PERFORMANCE EVALUATION IN REVERSE LOGISTICS WITH DATA ENVELOPMENT ANALYSIS

by

AKE TONANONT

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ABSTRACT

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Ake Tonanont, PhD.

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Supervising Professor: K.J. Rogers

Good reverse logistics design can save cost, increase revenues, and gain competitive edges over the rivals. Design of the optimized reverse supply chain model is a very important task to help enterprises save cost and gain benefits from their supply chains. In this study, reverse logistics is considered as a part of the Closed Loop Supply Chain (CLSC). CLSC combines forward and reverse flow together in the supply chain. Each component in a forward and reverse supply chain results in the efficiency of CLSC. Therefore, considering forward and reverse supply chain together as a CLSC will result in more benefits in improving efficiency of the supply chain than considering it separately. Since most data in the reverse supply chain are very difficult to obtain and many companies do not want to provide their reverse supply chain data due to business reasons, the data is secretly kept. Due to these reasons, there is a need to create a simulation model of CLSC to get reasonable data that can be used in this study.

This research proposes a methodology to design a good reverse supply chain by using the specified parameters. The statistical experiments with Data Envelopment Analysis (DEA) were applied to obtain an optimized model. This model is used to evaluate efficiency of the reverse logistics model and also provides the opportunity to improve efficiency by varying the significant parameters. Two case studies of carpet recycling were provided as the examples to show how to apply this methodology.

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CHAPTER 1

INTRODUCTION

1.1 Overview

Nowadays, the role of reverse logistics (RL) or reverse supply chain (used interchangeably) is increasing in many industries such as in the automobile industry, consumer electronics, book publishers, catalog retailers and so on. The value of product returns in the United States (U.S.) has increased every year from $40 billion in 1992 to over $100 billion in 2002 [1]. Many companies pay more attention to their reverse logistics strategies because they realize that a good reverse supply chain can lead to significant cost saving. Reverse logistics is defined 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 of proper disposal" [2]. Reverse logistics also includes processing returned merchandise due to damage, seasonal inventory, restock, salvage, recalls, and excess inventory. It also includes recycling programs, hazardous material programs, obsolete equipment disposition, and asset recovery [3]. A well organized reverse logistics not only reduces costs but also increases customer satisfaction. Many companies try to improve their reverse logistics strategy to gain competitive advantages. For example, Kodak has been selling remanufactured single-use photo cameras for more than a decade. Coca-Cola uses refillable bottles. These companies gain more profit from their reverse logistics strategies. The products in the reverse flow can come from different players in each supply chain, not necessarily from the end user or customer only. Sometimes retailers need to return their goods to the manufacturer even though there is nothing wrong with the products because those products are out of date or hard to sell. Products are returned for many reasons, such as defective product, end of useful life, or the product does not meet the customer's needs. Figure 1.1 illustrates a Generic Supply Chain for both forward and reverse logistics.

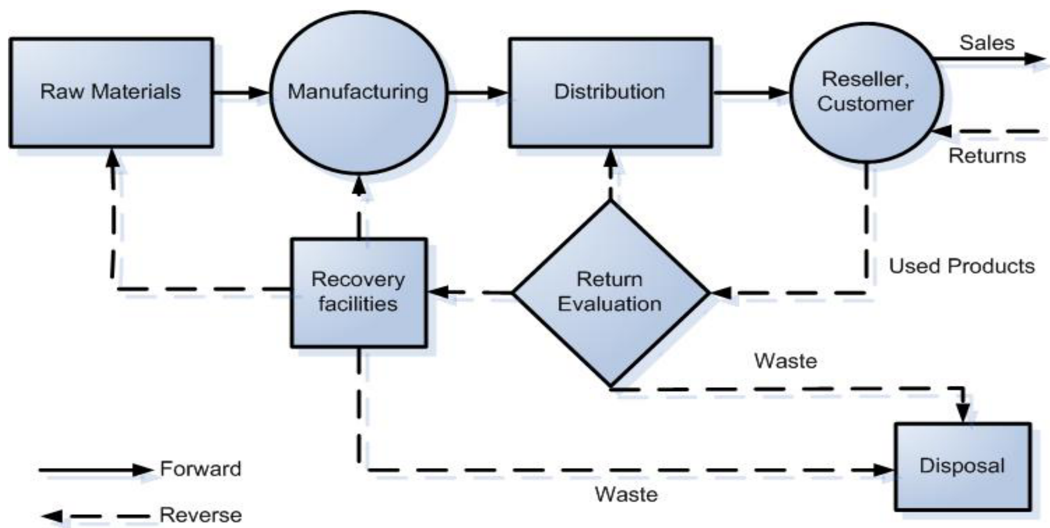

Fig 1.1 Generic Supply Chain

The rate of returns varies by industry. Some industries have high percentages of returns such as apparel, internet retailers, or computer manufacturers while others have lower percentages. Sample Return Percentages in different industries are shown in Table 1.1.

Table 1.1 Percentages of return by industry, [3]

Industry	Percent
Magazine Publishing	50%
Book Publishers	20-30%
Book Distributors	10-20%
Greeting Cards	20-30%
Catalog Retailers	18-35%
Electronic Distributors	10-12%
Computer Manufacturers	10-20%
CD-ROMs	18-25%
Printers	4-8%
Mail Order Computer Manufacturers	2-5%
Mass Merchandisers	4-15%
Auto Industry (Parts)	4-6%
Consumer Electronics	4-5%
Household Chemicals	2-3%

1.2 Background

Volumes of product returns are increasing every day in several industries. A good reverse logistics strategy is needed to cope with this return to gain the most benefits. Although many firms already have strategies to deal with this problem, some of them are not good enough. Every strategy can be improved. These strategies need continuous improvement to help companies build more competitive advantages. Performance measurement is a tool that helps firms better understanding advantages and disadvantages of their strategies and provides an opportunity for improvement. A performance measure is used to measure the efficiency and/or effectiveness of the system, or to compare with the benchmark.

1.2.1 Logistics Performance Measures

Performance measurement is defined as an assignment process where numbers are assigned to represent some attribute of an object or event of interest for those responsible for deciding the fate of a business entity [4]. Enterprises need to measure their logistics performance to improve their revenue growth, reduce their operation cost, and increase their shareholder value. Most companies do performance measurement but some of them do not gain many advantages. They do not completely understand what they are measuring and how they could employ this information to improve their logistics performance [5].

1.2.2 Reverse Logistics Performance Measures

Although a number of performance measurement methodologies were developed in the past, few of them focus on reverse supply chain. The existing measures are inadequate in capturing the dual extended supply chain objectives [6]. This identifies a need to develop new methodology to describe reverse logistics performance. This research considers reverse logistics as a part of the Closed Loop Supply Chain (CLSC) because each component in a forward supply chain results in the efficiency of the reverse supply chain. This research will utilize a Data Envelopment Analysis (DEA) technique together with statistical process to evaluate the performance of CLSC and also provide the opportunity to improve efficiency by varying the significant parameters.

1.2.3 Closed Loop Supply Chain (CLSC)

As mentioned earlier, reverse logistics is a part of CLSC. Normally, CLSC is composed of five main components which are supplier, manufacturing plant, distribution center/warehouse, retailers/customers and recovery facility. Figure 1.2 shows the components of CLSC.

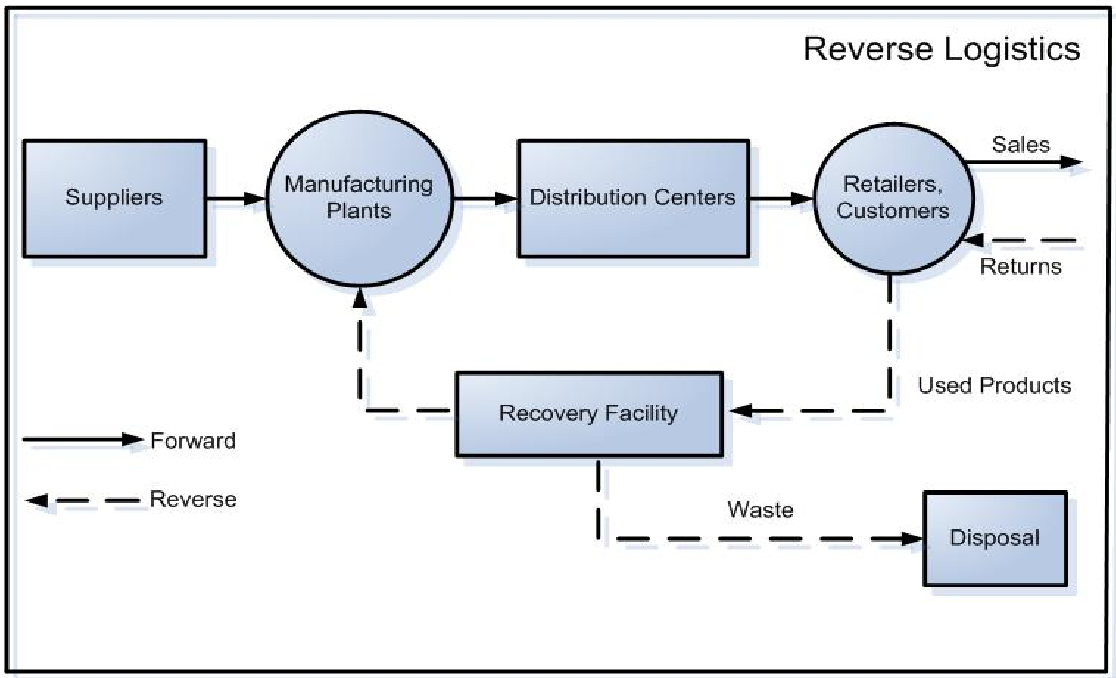

Fig 1.2 Closed Loop Supply Chain

The function of each component in the Closed Loop Supply Chain can be briefly described as follows:

1. Suppliers

Manufacturing plants need to get raw materials to produce the products. To get the raw materials, plants need to order them from suppliers. Thus the main function of the supplier is to deliver raw materials to manufacturers.

2. Manufacturing Plants

Manufacturing plants manufacture the products by using raw materials from the suppliers and also employ returned parts or assemblies from the recovery facility in order to reduce costs. Manufacturing plants need to specify the quantity and type of the materials that they need to buy from the suppliers at each period. Products from manufacturers will be delivered to distribution centers or warehouses. Not all of the produced products are delivered to distribution centers. Plants can decide to deliver all products or part of them because plants can keep some in their inventories, which can be a finished good or just materials used to manufacture products. Manufacturing plants could use the parts, materials, or assemblies from previous inventory, together with new materials purchased from the suppliers, to produce new products.

3. Distribution Centers

Distribution centers collect the demands from customers and retailers and then inform manufacturing plants. After receiving products from manufacturers, distribution centers will distribute them to retailers or customers to fulfill the demand.

4. Retailers or Customers

Retailers get products from manufacturers via distribution centers or warehouses while customers can get the products via retailers or directly from the distribution center.

5. Recovery Facility

Recovery facility collects returned products from customers or retailers then consider disposal options for those returns. Some products will be disassembled then be sent back to manufacturing plants to be remanufactured. The rest will be resold or disposed. The returns may be fully disassembled or partially disassembled, depending on the quality of the returns. Assemblies consist of many types of materials. An example of the classification process of returns at a recovery facility is shown in figure 1.3

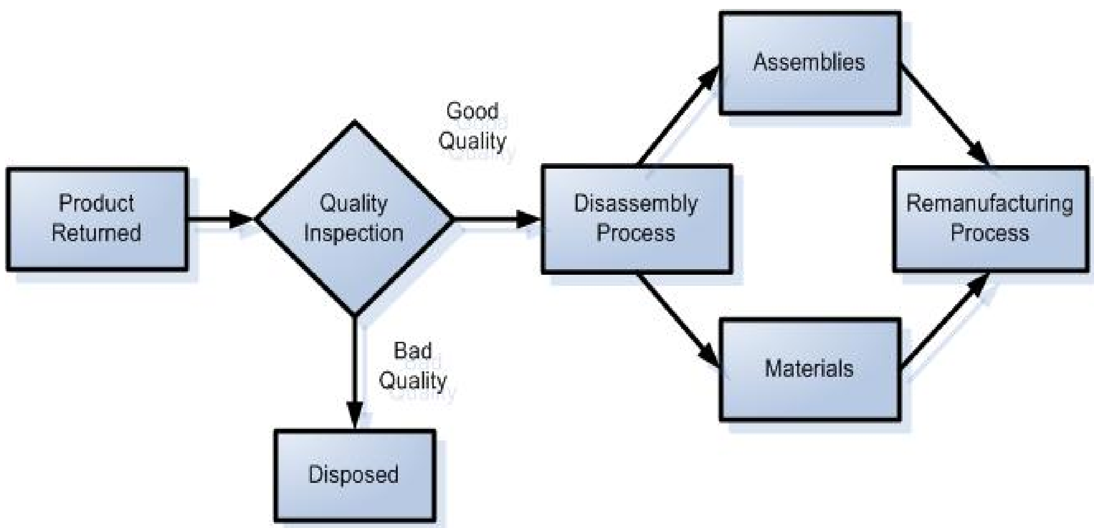

Fig 1.3 Classification process of return at Recovery Facility (adapted from Juan, [7])

1.3 Simulation model

Since most data in the reverse supply chain are very difficult to obtain and many companies do not want to provide their reverse supply chain data due to business reasons, the data is kept secret. For this reason, there is a need to create a simulation model of CLSC to get reasonable data that can be used to evaluate its performance. The created model will employ some reasonable parameters close to real data from sources such as literatures and the internet as input data to generate the completed reverse supply chain data that are sufficient to be used to evaluate the performance of CLSC. Also, those parameters used will be tested by statistical process to obtain correctly significant parameters that can be used to analyze. In this study, Design of Experiment (DOE) technique will be employed. The objective of the simulation model is to minimize the total cost of CLSC while satisfying the demand. This model consists of the main components as mentioned earlier. Each component will relate to many cost factors which will be used as inputs/outputs in evaluating efficiency by DEA model. With this simulation model, various reverse supply chain scenarios can be developed and easily altered. This model will provide feasible outputs that are reasonable to be used in testing performance evaluation with DEA.

1.3.1 Cost components

This simulation model focuses on cost. There are many different cost factors at each component in this model, which can be classified as follows:

At manufacturing plants, these costs are:

1. Purchase cost of materials from suppliers.

Purchase cost is what manufacturing plants need to pay for buying raw materials from suppliers. This cost is calculated from the summation of the product of purchase cost per unit of material and the number of units of materials that need to be purchased at the beginning of the period.

2. Total production cost of all products at all manufacturing plants.

Production cost is what manufacturers need to spend to produce the product. This cost is calculated from the summation of the product of the number of units produced at all manufacturing plants and production cost per unit on that period.

3. Total holding cost of products at all manufacturing plants.

Normally, manufacturing plants will manufacture more products than the demand requested from distributors or customers. Some of the products will be shipped to distribution centers or warehouses to serve the demand while the rest of the finished products will be kept in inventory at the plants to prevent the fluctuation of demand, in case the real demand is more than forecasted. Stocking finished products in plants incurs holding cost or inventory cost. This cost is calculated from the summation of the product of holding cost per unit of product at manufacturing plants and inventory units at the end of that period.

4. Total holding cost of materials at all manufacturing plants.

Manufacturing plants can provide inventories for raw materials to use immediately in case the inventory of finished products is not enough to serve the demands. Plants can use raw materials from their inventories to manufacture products in time while waiting for raw materials from suppliers. Stocking raw materials in plants can help plants to produce the product in time, but the plants will need to pay for holding cost of these materials. This cost is calculated from the summation of the product of holding cost per unit of materials at plants and inventory units of material in plants at the end of that period.

5. Total transportation cost of products

This is the cost that manufacturers need to pay to ship their products to distribution centers/warehouses. Normally, this cost depends on the shipping distance, but in this model this cost is assumed to be constant per unit of the product. This cost is calculated from the summation of the product of transportation cost per unit shipped from plants to warehouses on that period and quantity of products shipped to warehouses from plants at the same period.

At distribution centers/warehouses, these costs are:

6. Total holding cost of products at distribution centers/warehouses.

There are inventories of finished products at distribution centers/warehouses. These inventories are used to serve the high level of the demands which exceed the demand forecasted. This cost is calculated from the summation of the product of unit holding cost at warehouses and inventory units of product at warehouses at that period.

7. Total stock out cost of products at distribution centers/warehouses.

In the case that demands are very high and inventories at the warehouses are not enough to fulfill the demands, it will incur stock-out or shortage of products. This stock-out cost is calculated from the summation of the product of stock-out cost per unit and stock-out unit at warehouse.

8. Total transportation cost of products

This is the cost that distribution centers/warehouses need to pay for shipping the products to customers/retailers. Normally, this cost depends on the shipping distance, but in this model, this cost is assumed to be constant per unit of the product. This cost is calculated from the summation of the product of transportation cost per unit shipped from distribution centers/warehouses and quantity of products shipped to retailers/customers.

At Retailers/Customers, this cost is:

9. Total transportation cost of returned products from retailers/customers to recovery facility

This is the cost that retailers/customers need to pay for shipping the returned products from customers/retailers to the recovery facility to disassemble, reuse, or dispose properly. Normally, this cost depends on the shipping distance, but in this model, this cost is assumed to be constant per unit of the product. This cost is calculated from the summation of the product of transportation cost per unit of returns and quantity of returns at the same period.

At the recovery facility, these costs are:

10. Total disassembly cost at recovery facility.

This is the cost that recovery facility needs to pay for disassembling the returned products to get the reusable parts or assemblies which can be remanufactured at manufacturing plants. This cost is calculated from the summation of the product of the following terms which are: the probability of material resulting from the disassembly process of product is of good quality for remanufacturing. This probability will stay between 0 and 1 and will be specified. The second term used to calculate cost is the number of units of product returned to recovery facility on the same period which is expected quantity, usually coming from statistical data in the past. The third term is the number of units of materials or assemblies that can be obtained from returned product. The last term is disassembly cost per unit of returned products at that period.

11. Total holding cost of returned materials at recovery facility.

After good quality returned products are disassembled, some of the reusable materials or assemblies will be shipped to manufacturing plants depending on demands requested from plants, while the rest will be kept in inventory at the recovery facility itself. This inventory will incur holding cost at the recovery facility. This cost is calculated from the summation of the product of holding cost of materials per unit and inventory units of material on the same period at the recovery facility.

12. Total transportation cost of returned products to manufacturing plants.

This is the cost that the recovery facility needs to pay for shipping the reusable materials or assemblies to the plant to be remanufactured. Normally, shipping cost is based on the shipping distance, but in this model, this cost is assumed to be constant per unit of the product. This cost is calculated from the summation of the product of transportation cost per unit of reusable materials and quantity of reusable materials at the same period.

The objective of this simulation model is to minimize all of the total cost with feasible parameters, inputs and outputs.

1.4 Data Envelopment Analysis (DEA)

DEA was first proposed by Charnes, Cooper and Rhodes in 1978 [8]. At first, it was named the CCR model (combination of the first letter from each author's name). CCR model is the first basic model of the DEA model. The DEA model was adapted from a nonlinear programming model by using fractional programming techniques. DEA is used to evaluate the efficiency of decision making units (DMUs). DMUs can be banks, hospitals, schools, profit or nonprofit organizations, and any elements in the process in which multiple inputs and multiple outputs are involved. The basic concept of DEA is to evaluate performance of DMUs. DEA can identify the "best" performing or the most efficient DMU and measures the efficiency of other units based on the deviation from the efficient DMU [9]. The concept of the DEA model is to provide input and output elements in term of non-parametric linear programming and evaluate efficiency from the ratio between output and input. Efficiency values stay between 0 and 1. After setting up the DEA model, weight input and output values (that maximize the efficiency or ratio of DMU_0 of the model) and the satisfaction of all constraints of input and output will be evaluated. The basic model of DEA can be shown as follows:

$$\text{Max } \theta = \frac{\sum_{r=1}^{s} u_r y_{ro}}{\sum_{i=1}^{m} v_i x_{io}}$$

$$\text{Subject to} \qquad \frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \leq 1; \quad j = 1, \ldots, n.$$

$$u_r, v_i \geq 0; \quad r = 1, \ldots, s; \quad i = 1, \ldots, m.$$

Where:

θ : the relative efficiency score of DMU_0 which is the objective function value that maximizes the ratio of DMU_0

u_r : weight of output r or the virtual multiplier of the rth output value;

y_{ro} : value for output y of DMU_0 or the rth output value of DMU_0;

v_i : weight of input i or the virtual multiplier of the ith input value;

x_{io} : value for input x of DMU_0 or the ith input value of DMU_0;

n : the number of DMUs

This linear model is then replaced by the following linear program

$$\text{Max} \ \sum_{r=1}^{s} u_r y_{ro} \tag{1}$$

Subject to $$\sum_{i=1}^{m} v_i x_{io} = 1$$

$$\sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \leq 0, \qquad j = 1,2,\ldots,n$$

$$u_r, v_i \geq \varepsilon > 0; \quad r = 1, \ldots, s; \quad i = 1, \ldots, m.$$

The dual model will be obtained as follows:

Min θ

Subject to $$\theta x_{io} - \sum_{j=1}^{n} \lambda_j x_{ij} - s_i = 0, \qquad i = 1,2,\ldots,m$$

$$y_{ro} - \sum_{j=1}^{n} \lambda_j y_{rj} + \sigma_r = 0, \qquad r = 1,2,...,s$$

$$\lambda_j \geq 0, \forall j, s_i \geq 0, \sigma_r \geq 0, \forall\, i, r$$

Where s_i and σ_r represent the slack variables of the ith input item and the rth output item respectively. If the presented DMU values are inefficient, the dual model can provide suggestions for its improvement.

The quality of inputs can be improved as shown in the following formula:

$$x_{io}^{*} = \theta^{*} x_{io} - s_i$$

The quality of outputs can be improved as shown in the following formula:

$$y_{ro}^{*} = y_{ro} + \sigma_r$$

If the efficiency value of DMU is equal to 1, this efficient is called CCR-efficient, and there is at least one optimal solution for this model.

The advantages of the basic DEA model can be summarized as follows:

- DEA can deal with multiple inputs and outputs.
- Inputs and outputs do not need to have the same units of measurement.
- DEA assigns the score for each unit, making it easy to point out efficient and inefficient units.
- Input and output data can be applied without any modification [9].
- DEA does not require any assumptions or prior information for inputs and outputs but can be included when needed.

Although DEA has many advantages, this methodology has some limitations. The disadvantages of DEA can be summarized as follows [10]:

- DEA is a point technique; therefore poor measurement data can cause significant error.
- DEA provides relative efficiency of DMU, not exact efficiency for the unit itself.
- Since DEA is a non-parametric technique, statistical hypothesis tests are difficult to do.
- A basic DEA will create a separate linear program for each DMU; large and complicated problems may consume huge computational time.

1.5 Dissertation Objective

Due to increasing values of reverse logistics in recent years, many enterprises pay more attention to their reverse supply chain. These firms need to gain the most benefits from their reverse logistics. They continuously improve their reverse supply chain to save costs, increase revenues, meet customers' expectations, and gain competitive edges over their rivals. Performance measurement is an important tool to help them identify the problems and improve the existing reverse logistics strategy.

The objective of this research is to provide the methodology used to evaluate performance of the reverse supply chain, using DEA and statistical process. By considering the supply chain as a CLSC, and by providing a generic algorithm for CLSC, this algorithm can be used to simulate the set of feasible data that can be used to test with this new DEA model. This generic algorithm and DEA model can be adapted to any supply chain depending on specified attributes or constraints.

1.6 Data Collection

Due to the difficulty of obtaining completed reverse supply chain data because of business reasons, the data in this research will be created using a simulation model. Specifying feasible parameters, which come from many sources (such as literature, books, and internet,) as input data to generate the completed reverse supply chain output data is sufficient to be used to evaluate performance of CLSC. Those parameters used will be tested by statistical process to get correctly significant parameters that can be used to analyze. In this study Design of Experiment (DOE) technique will be employed. The objective of the simulation model is to minimize total cost of the CLSC while satisfying the demand. With this simulation model, various reverse supply chain scenarios can be developed and altered easily. This model will provide feasible outputs that are reasonable to be used in testing performance evaluation with DEA.

1.7 Organization of the Dissertation

This dissertation is composed of five chapters. A brief description of each chapter is presented as follows:

Chapter 1 consists of seven sections. The first section explains an overview of reverse logistics, the importance of reverse supply chain, and identifies the necessity of performance measurement. The second part provides background information about logistics performance measures, reverse logistics performance measures, and Closed Loop Supply Chain (CLSC). The third section talks about the simulation model that is used to simulate the data, and also mentions cost components related to the model. The fourth section previews the techniques applied in this research Data Envelopment Analysis (DEA) to evaluate the performance of reverse supply chain. The fifth section describes the objective of this research. The sixth section describes the data used in this research, simulated and optimized from generic the CLSC model. The organization of the dissertation is depicted in the final part.

Chapter 2 reviews many useful published articles related to reverse logistics to point out the importance of reverse supply chain and the necessity of performance measurement for reverse logistics. As well, a review of the algorithms that were employed in the past to evaluate the performance of the reverse logistics will be mentioned. DEA will be discussed. The existing algorithms will be adapted and modified to fulfill the objectives of this dissertation.

Chapter 3 provides the methodology that is employed in this dissertation. The CLSC simulation model used to simulate the supply chain data are proposed. The DEA model that is employed in this study to evaluate the efficiency of the CLSC model, including mathematical relations, is shown. The DOE technique, which is used couple with the CLSC model and the DEA model to obtain the statistical results, along with the optimized model (which are the objective of this study) is explained. The process of doing the experiments is concluded in the flow chart proposed in this chapter.

Chapter 4 illustrates how to apply the methodology proposed in chapter 3 with two case studies. Both of them are related to carpet manufacturing CLSC and the main process will be the same, only with differences in parameters, number of components and operation costs. Case study 1 illustrates simple scenarios which consist of few parameters while case study 2 shows complex scenarios which are composed of more parameters and more components in CLSC.

Chapter 5 provides an overview of this study and discusses the case studies, including advantages and disadvantages of the methodology proposed. The conclusion and contribution of this dissertation will be mentioned. Future research direction will be recommended.

CHAPTER 2

LITERATURE REVIEW

2.1 What is reverse logistics?

The field of reverse logistics has been studied for a long time. In the past, reverse logistics gained little attention, as many enterprises focused on their forward supply chain only. Recently interest in reverse logistics has increased because many firms have started to realize the many benefits of the reverse supply chain. Many literatures have provided the definition of reverse logistics in different ways. Lambert and Stock [11], for example, have defined reverse logistics as “going the wrong way on a one-way street because the great majority of product shipments flow in one direction.” This description is similar to Murphy’s [12] and Murphy and Poist’s [13] who described reverse logistics as “movement of goods from a consumer towards a producer in channel of distribution.” Throughout the 1980s, the scope of reverse logistics was limited to the movement of material against the primary flow, from the customer toward the producer [14]. Kroon [15] and Pohlen [16] defined Reverse Logistics (RL) or Reverse Distribution (RD) as “the logistics management skills and activities involved in reducing, managing, and disposing of hazardous waste from packing and products.” Reverse distribution causes goods and information to flow in the opposite direction from normal logistics activities. Stock [17] defined reverse logistics as “the term most often used to refer to the role of logistics in product returns, source reduction, recycling materials substitution, reuse of materials, waste disposal, and refurbishing, repair and remanufacturing." Carter and Ellram [18] called reverse logistics as "the process whereby companies can become more environmentally efficient through recycling, and reducing the amount of material used." Rogers and Tibben-Lembke [3] provided the definition of 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 or creating value or proper disposal." Many people confuse green logistics and reverse logistics because they are similar. Green logistics or environmental logistics is primarily motivated by environmental considerations which could be defined as "efforts to measure and minimize the environmental impact of logistics activities"[14].

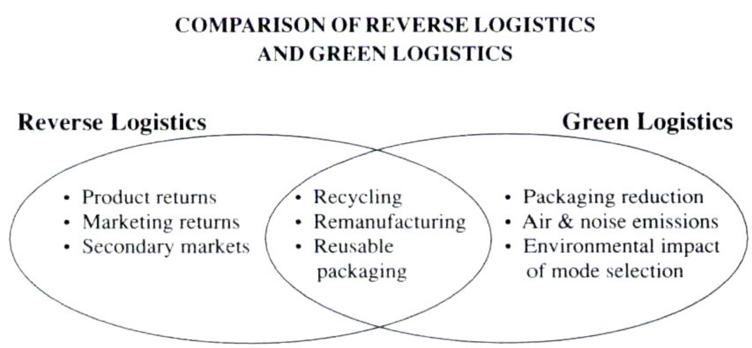

Fig 2.1 Comparison of reverse logistics and green logistics [14]

Figure 2.1 illustrates the resemblance and the difference between reverse logistics and green logistics. The term "reverse logistics" should be reserved for the flow of products and material going "the wrong way on a one-way street" [14].

2.1.1 Importance of reverse logistics

The following are some statistics that show interesting data about reverse logistics. Reverse logistics costs accounted for $37 billion in 1999 [14], amounting to between 0.5% and 1% of the total U.S. gross domestic product [3]. Twelve percent of the US $5 billion worth of products sold online during the two-month Christmas season of 1999 was returned, (Bizrate.com, Stock [1]). Ninety-five percent of consumers would rather return a product purchased over the internet to a physical location; 43% would always use that option if it were available; 37% of online buyers and 54% of online browsers refused to purchase online products due to the difficulty of returning or exchanging items (Jupiter Research , Stock [1]). The return processing cost is about two to three times that of an outbound shipment, (Returns Online, Inc., Stock [1]). The returns amount from catalogue and Web retailers is about US $3.2 billion in 2001 (R.R. Donneley Logistics, Stock [1]). Many companies continue to improve their reverse logistics to reduce reverse logistics costs. There are some successful examples of firms that have applied reverse logistics strategies, including the following: Levi Strauss cooperated with Genco, a third party reverse logistics service provider, to develop a returns-processing method that computed estimated costs, generated paperwork in advance of the product being return, matched the item automatically with the prepared paperwork and processed the item within 72 hours (Levi Strauss 2000, Stock [1]). Canon Computers reduced return value from US $37 million in 1997 to US $15 million in 2000 (Chargebacks Solutions Monitor 2001, Stock [1]). Buy.com, an internet superstore, uses major transportation providers, such as; FedEx, United Parcel Service of America, Inc. (UPS) and the U.S. Postal Service, which provide e-tailer customers with online return labels, and saves customers and companies both time and money (Logistics Management & Distribution Report 2001, Stock [1]). These successful reverse logistics strategies have helped firms reduce costs, increase revenues and increase customer satisfaction. The environment issue is another crucial aspect of reverse logistics. Environmental concerns, legislative actions and increasing product disposal costs have led many companies to adopt "green manufacturing" practices, such as the recovery and remanufacturing of used products. These practices lead to challenging reverse logistics problems, where the return flows of used products need to be taken into account [19]. Hewlett-Packard (HP), a leading company in electronics manufacturing, developed HP's hardware Product Take Back program (PTB) that allows consumers and businesses to conveniently recycle obsolete computers and equipment from any manufacturer for a minimal fee. These programs are available around the world and allow individuals and commercial customers to return both HP LaserJet and inkjet cartridges at no charge. PTB was created for many reasons, foremost, to fulfill government and individual requirements which require environmentally responsible end-of-life solutions for electronics hardware and ink cartridges. The second reason is to conform with environmental procurement guidelines and the European Directive on Waste Electrical and Electronic Equipment (WEEE) [20]. In 1998, IBM established the Global Asset Recovery Services organization (GARS) to provide a single, global focus for managing the disposal of returned, surplus, and excess computer and related hardware inventory. About 10,000 "preowned" computers were returned to manufacturers each week at the end of lease agreements, as well as products ranging from PCs to servers [21]. The Environmental Protection Administration (EPA) of Taiwan announced a Scrap Home Appliances and Computers Recycling Regulation in March 1998 that mandates manufacturers and importers to take-back their products [22].

Kokkinaki [23] concluded that reverse logistics is necessary for the following reasons:

- Positive environmental impact: legislations acts, also called "producer responsibility laws," require manufacturers to develop a policy for the collection and reuse of products at the end of their life cycle.
- Competitiveness advancement: efficient handling of returns leads to reduced costs, increased profits and improved customer service.
- Regaining value: efficient reverse logistics can capture values from reusing products or parts or recycling materials. There are at least 70,000 re-manufacturing firms in the U.S. for jet and car engines, auto parts and copiers that amount to total sales of US $53 billion [24].

Tibben-Lembke [25] have provided the differences between reverse and forward logistics as shown in table 2.1

Table 2.1 The differences between reverse and forward logistics

Forward	Reverse
Forecasting relatively straightforward	Forecasting more difficult
One to many transportation	Many to one transportation
Product quality uniform	Product quality not uniform
Product packaging uniform	Product packaging often damaged
Destination/routing clear	Destination/routing unclear
Standardized channel	Exception driven
Disposition options clear	Disposition not clear
Pricing relatively uniform	Pricing dependent on many factors
Importance of speed recognized	Speed often not considered a priority
Forward distribution costs closely monitored by accounting systems	Reverse costs less directly visible
Inventory management consistent	Inventory management not consistent
Product lifecycle manageable	Product lifecycle issues more complex
Negotiation between parties straightforward	Negotiation complicated by additional considerations
Marketing methods well-known	Marketing complicated by several factors
Real-time information readily available to track product	Visibility of process less transparent

2.1.2 Components of reverse logistics and reverse logistics activities

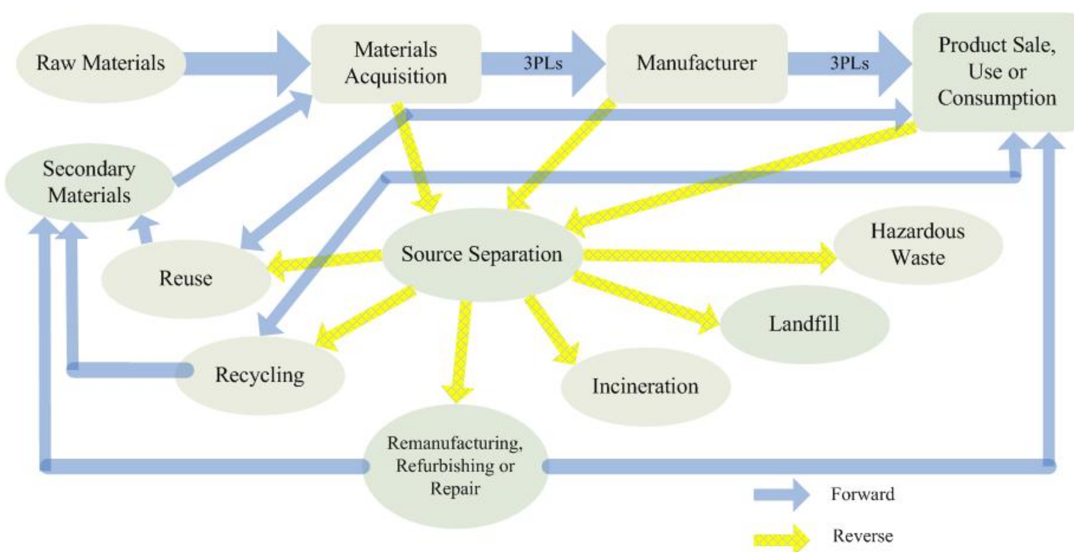

Fig 2.2 Reverse logistics within a supply chain (Adapted from [26])

Stock [1] illustrated components and activities of reverse logistics within one portion of a typical supply chain as shown in figure 2.2

Rogers [14] concluded common reverse logistics activities as shown in table 2.2

Table 2.2 Common reverse logistics activities, [14]

Material	Reverse Logistics Activities
Products	Return to supplier Resell Sell via outlet Salvage Recondition Refurbish Remanufacture Reclaim materials Recycle Donate Landfill
Packaging	Reuse Refurbish Reclaim materials Recycle Salvage Landfill

Amini and Bayles [27, 28] have provided brief definitions of each disposal option of reverse supply chain as follows:

- Reuse – the packaging is reused or a product is sent back for resale to another customer.
- Repair/repackage – where a moderate amount of repair and/or repacking will allow the product to be reused.
- Recycling – where the product is broken down and "mined" for components that can be reused or resold.

- Reconditioning – When a product is cleaned to its basic elements, which are reused.
- Refurbishing – Similar to reconditioning, except with perhaps more work involved in repairing the product.
- Remanufacturing – Similar to reconditioning, but requiring more extensive work; often requires completely disassembling the product.

Motivation for returns

Returns can be divided in two types. The first type is unplanned or undesired returns called “traditional returns” and the second one is “desired” or “planned returns”. Amini [27] has provided some reasons of product returns. The reasons for unplanned product returns include:

- The customers changed their minds.
- The product was defective.
- The customer perceived product to be defective.
- The product was damaged in transit.
- A vendor error (such as wrong item or quantity shipped).
- Warranty returns or product recalls.

The prediction for unplanned product returns is difficult because companies do not know what will be returned or when.

The reasons for planned product returns may include:

- Trade-in programs – Firms offer their customers to exchange old products for partial credit on a new one.

- Company take-backs – Companies take back end of life products from their customers due to economic or environment reasons.
- Leased or rented products – Customers return products at the end of lease.
- Service work - The products are shipped to serviced location to be fixed after that they were returned to customers.

Planned returns are much easier for the firms to predict and design their reverse supply chain because they know what is coming back and when.

2.2 Reverse Logistics Network Design

Fleischmann [29] proposed a recovery network model (RNM) which is a general quantitative model for reverse logistics network design. This model was adapted from the warehouse location model (WLM) by adding the recovery network part. He integrated forward and reverse logistics together in his model using the balance constraints that restrict the volume of returns is not greater than production volumes. For the forward chain, there are three levels of facility starting from Manufacturing Plants to the second level, Warehouses then to customers which are the final level for forward flow. For reverse flow, the levels start from customers to disassembly centers then go back to Manufacturing Plants. The Recovery Network Structure from Fleischmann is shown in figure 2.3. The objective of his model is to minimize total cost of the integrated supply chain by employing the mixed integer linear programming technique (MILP) which satisfies all balance constraints at each level of facilities. Many case studies were applied with his model. He found that forward flow has much more influence on cost saving than reverse flow does. He also pointed out that his model can be easily adapted to apply to any recovery network design for different industries.

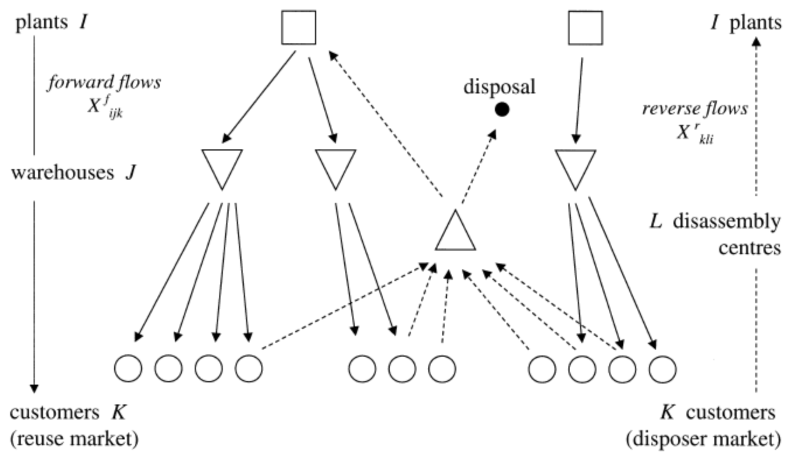

Fig 2.3 Recovery Network Structure [29]

Salema [30] tried to improve RNM model (Fleischmann's model). This study corrected some limitations of the original model such as production/storage capacity, multi-product production and demand/returns uncertainty. The MILP technique is still applied to the model but adds more characteristics to the model. A case study of an Iberian company was used to test the new model.

MAO [31] used the integration of genetic algorithms and the random simulation technique to model the reverse logistics networks. The logistics intelligent simulating software (RaLC) was used to simulate the reverse logistics network with uncertainty of time, place, and quantity of return products, but did not consider the uncertainty of the quality of product returns.

Krikke [32] designed a reverse logistic network to optimize total operational costs for reverse supply chain of the copier machine. The idea of his model is balancing between supply and demand in recovery strategy. The model is based on the recovery strategy. The cost parameters used in the model are investment costs, constant costs such as space cost, processing costs, distribution costs related to transportation, inventory costs, and overall costs. Supply and demand also need to be specified. A network graph for the returned machine was created first. After that the optimization model was formulated related to this graph. Considering uncertainty in quantity, quality and timing for demand and supply, three scenarios were created to test the model. Lindo software was used to optimize the model. The researchers recommended that other than trying to minimize cost the copier company should consider other performance factors such as JIT and reliability to support their reverse strategy.

Juan[7] proposed a reverse logistics model using the concept of medium term production planning. Production planning is categorized in three types: strategic planning, tactical planning, and finally, operative planning [7]. Strategic planning is considered as long term planning as related to business planning, while tactical planning is considered medium term planning related to production level. Several techniques are used at this level, for example, Master Production Schedule (MPS) and Capacity Planning. The final type of planning, Operative Planning or short term planning is related to some activities such as job-shop scheduling and Material Requirement Planning (MRP). The multi plant production planning model with returns was developed. All returns are assumed to be processed at a centralized facility which can dispose, disassemble and ship returned parts or assemblies back to be remanufactured at plants, depending on the quality of these returns. The objective of this CLSC is to minimize total cost, which includes production cost, processing cost, transportation cost, disassembly cost, holding cost, and purchased cost. The idea of this model is balancing flow in and out at each facility while satisfying the demand based on cheapest cost that will also satisfy all of constraints. This model is specified as the integer linear programming model. The summary of this model can be shown as follows;

$$\text{Min} \sum_{a=1}^{A}\sum_{j=1}^{M}\sum_{i=1}^{n}\sum_{t=1}^{T} C_{aijt}X_{aijt} + \sum_{j=1}^{M}\sum_{i=1}^{n}\sum_{t=1}^{T} H_{ij}I_{ijt} + \sum_{i=1}^{n}\sum_{t=1}^{T} S_{it}Y_{it}^{-}$$

$$+ \sum_{j=1}^{M}\sum_{p=1}^{P}\sum_{t=1}^{T} R_{jpt}P_{jpt} + \sum_{j=1}^{M}\sum_{p=1}^{P}\sum_{t=1}^{T} L_{jpt}M_{jpt} + \sum_{j=1}^{M}\sum_{i=1}^{n}\sum_{t=1}^{T} T_{ijt}q_{ijt}$$

$$+ \sum_{i=1}^{n}\sum_{t=1}^{T} W_{it}Y_{it}^{+} + \sum_{j=1}^{M}\sum_{p=1}^{P}\sum_{t=1}^{T} G_{jpt}O_{jpt} + \sum_{p=1}^{P}\sum_{t=1}^{T} HO_{pt}IN_{pt}$$

$$+ \sum_{t=1}^{T}\sum_{i=1}^{n}\sum_{p=1}^{P} PROB_{ip}[QU_{ip}]*CF_{ip}*E[F_{it}]*DC_{ipt}$$

Subject to:

1. $IN_{pt} = IN_{p(t-1)} + \sum_{i=1}^{n}(PROB_{ip}[QU_{ip}]*CF_{ip}*E[F_{it}]) - \sum_{j=1}^{M} O_{jpt}$

Where: p = (n+1),…,P ; t = 1…T ;

2. $\sum_{j=1}^{M} O_{jpt} \leq IN_{p(t-1)}$

Where: p = (n+1),…,P ; t = 1…T ;

3. $IN_{pt} \leq MRM_{p}$

Where: p = (n+1),…,P ; t = 1…T ;

4. $M_{jpt} = M_{jp(t-1)} + P_{jpt} - [\sum_{i=1}^{n}\sum_{a=1}^{A} K_{aip}X_{aijt}] + O_{jpt}$

Where: j = 1,…,M ; t = 1…T ; p = 1,…,n ;

5. $M_{jpt} = M_{jp(t-1)} - [\sum_{i=1}^{n}\sum_{a=1}^{A} K_{aip}X_{aijt}] + O_{jpt}$

Where: j = 1,…,M ; t = 1…T ; p = (n+1),…,P ;

6. $V_{jp} \le M_{jpt} \le W_{jp}$

Where: j = 1,…,M ; t = 1…T ; p = 1,…,P ;

7. $\sum_{i=1}^{n}\sum_{a=1}^{A} K_{aip}X_{aijt} \le M_{jp(t-1)} + P_{jpt}$

Where: j = 1,…,M ; t = 1…T ; p = 1,…,P ;

8. $I_{ijt} = I_{ij(t-1)} + \sum_{a=1}^{A} X_{aijt} - q_{ijt}$

Where: i = 1,…,n ; j = 1…M ; t = 1,…,T ;

9. $\sum_{a=1}^{A} X_{aijt} + I_{ij(t-1)} \ge q_{ijt}$

Where: i = 1,…,n ; j = 1…M ; t = 1,…,T ;

10. $SS_{ij} \le I_{ijt} \le B_{ij}$

Where: i = 1,…,n ; j = 1…M ; t = 1,…,T ;

11. $Y_{i(t-1)} + \sum_{j=1}^{M} q_{ijt} - d_{it} = Y_{it}$

Where: i = 1,…,n ; t = 1,…,T ;

12. $Y_{it} = Y_{it}^{+} + Y_{it}^{-}$

Where: i = 1,…,n ; t = 1,…,T ;

13. $\sum_{a=1}^{A}\sum_{i=1}^{n} PT_{ai} X_{aijt} \leq U_{jt}$

Where: j = 1…,M ; t = 1,…,T ;

14. $X_{aijt} \geq 0$ and integer;

15. $P_{pt} \geq 0$ and integer;

16. $I_{ijt} \geq 0$ and integer;

17. $Y_{it}^{+} \geq 0$ and integer;

18. $Y_{it}^{-} \geq 0$ and integer;

19. $M_{jpt} \geq 0$ and integer;

20. $q_{ijt} \geq 0$ and integer;

21. $O_{jpt} \geq 0$ and integer;

22. $IN_{pt} \geq 0$ and integer;

Parameters:

A = Number of production processes that have the product with the maximum number of production processes.

n = Type of products.

P = Type of materials (including assemblies and reusable parts)

M = Number of Manufacturing Plants.

T = Number of periods of time to planning (normally represents one week)

C_{aijt} = Production cost of one unit of product i at Manufacturing Plant j by process a on period t.

H_{ij} = Holding cost per unit of product i at Manufacturing Plant j.

S_{it} = Stock-out cost per unit of product i at period t.

R_{jpt} = Cost of purchase of one unit of material p at Manufacturing Plant j at period t

L_{jpt} = Holding cost per unit of material p at Manufacturing Plant j at period t

SS_{ij} = Security stock of product i at Manufacturing Plant j.

B_{ij} = Maximum allowed stock of product i at Manufacturing Plant j.

K_{aip} = Quantity of material p needed to manufacture one unit of product i by process a.

CF_{ip} = Number of units of material p that can be obtained from returned product i.

W_{jp} = Maximum allowed stock of material p at Manufacturing Plant j.

V_{jp} = Security stock of material p at Manufacturing Plant j.

T_{ijt} = Transportation cost per unit of product i shipped from Manufacturing Plant j to Distribution Center/Warehouse on period t.

G_{pjt} = Transportation cost per unit of material p (including all assemblies) shipped from Recovery Facility to Manufacturing Plant j on period t

d_{it} = Demand of product i at period t.

W_{it} = Holding cost of product i at period t on Distribution Center/Warehouse.

PT_{ai} = Production time (hours) for manufacturing one unit of product i by process a.

U_{jt} = Hours of production capacity in Manufacturing Plant j at period t.

HO_{pt} = Holding cost of material p at period t at Recovery Facility.

$PROB_{ip}[QU_p]$ = Probability of material p resulting from the disassembly process of product i is of quality QU_p for remanufacturing

DC_{ipt} = Disassembly cost for material of assembly p from product i at period t

Variables:

X_{aijt} = Number of units of product i to produce in plant j by process a on period t.

P_{jpt} = Number of units of material p to purchase in plant j at the beginning of period t.

q_{ijt} = Quantity of product i shipped to warehouse from plant j at period t.

I_{ijt} = Inventory units of product I in plant j at the end of period t.

M_{jpt} = Inventory units of material p in plant j at the end of period t.

Y_{it}^{-} = Number of units of stock-out of product i at warehouse at period t.

Y_{it}^{+} = Inventory units of product i at warehouse at period t.

O_{jpt} = Quantity of material p shipped from central recovery plant to plant j on period t.

IN_{pt} = Inventory units of material p at period t on central recovery plant.

MRM_p = Holding capacity of reusable material or assembly p at central recovery plant.

Random Variables:

$E[F_{it}]$ = Number of units of product i returned to central recovery plant on period t.

QU_{ip} = 1 if material p obtained from product i is of good quality for the remanufacturing process

= 0 if material p obtained from product i is not of good quality for the remanufacturing process

After running the model, optimal production schedule, and optimal purchasing strategy estimated inventory levels and total costs for the planning will come out as a result. In this study, our model is developed based on this model to obtain the completed data for performance evaluation in reverse logistics with DEA.

2.3 Reverse Logistics Performance

There are many literatures which are related to reverse logistics performance including:

Autry [33] found that reverse logistics performance is significantly impacted by sales volume and that customers' satisfaction with reverse logistics service varies by industry. They found that neither the location of nor the responsibility for disposal affects either reverse logistics performance or the customers' level of satisfaction.

Richey [34] discovered that resource commitment makes reverse logistics more efficient and more effective if it is used to develop innovative capabilities/approaches to handling returns. Large firms can provide greater resources than small firms in the automotive aftermarket industry.

Marien [35] has pointed out six categories of companies who have dealt with their reverse logistics in different ways. For example, high-tech companies such as Motorola or Hewlett-Packard invested a lot in their new products which led to less waste generation and lower reverse logistics costs, while firms with low costs of goods sold have little motivation to improve their reverse supply chain. This paper identified that industry segments react in different ways with their reverse supply chain; as a result reverse logistics performance varies by industry.

Langley [36] explained that logistics creates customer value in three dimensions: effectiveness, efficiency, and differentiation. Effectiveness refers to level of performance of logistics and whether the logistics function meets customer requirements in critical result areas. Efficiency refers to the ability of firms to provide the desired product or service that can satisfy customers, while differentiation means the ability of logistics to create value for the customer through the uniqueness and distinctiveness of logistical service.

Johnson [37] investigated factors that influenced scrap disposal strategies. They found that volume is one of the important drivers of reverse logistics. Each company reacts to their reverse supply chain in different ways. Some firms hire third party logistics companies to take care of their reverse products, while others handle it themselves. Whether in-house operations or outsource strategies, an effective reverse supply chain lead to overall cost reduction.

Johnson [38] stated that many organizations started to realize the importance of effective reverse logistics systems. Volume plays an important role for reverse logistics strategies because when firms receive high volumes of return, they need to improve their reverse supply chain to handle their return flows efficiently and effectively.

Blumberg [39] explained that due to legislation imposed by governments and increasing customer concerns about the environment, firms need effective reverse supply chains to handle the waste and hazardous materials. Effective transportation and distribution firms such as FedEx and UPS can help the organizations improve their reverse logistics services for rapid and efficient return shipping to the end-users or to the company for repair, recovery, or final disposal.

2.3.1 A framework of reverse logistics

Framework is "a basic concept structure" [40, 41]. De Brito [40] proposed a framework of reverse logistics which depends on five dimensions:

- The return reasons (why-returning).
- Driving forces (why-receiving).
- The type of products and their characteristics (what)
- The recovery processes and recovery options (how)
- The actors involved and their roles (who).

Figure 2.4 illustrates a framework for reverse logistics.

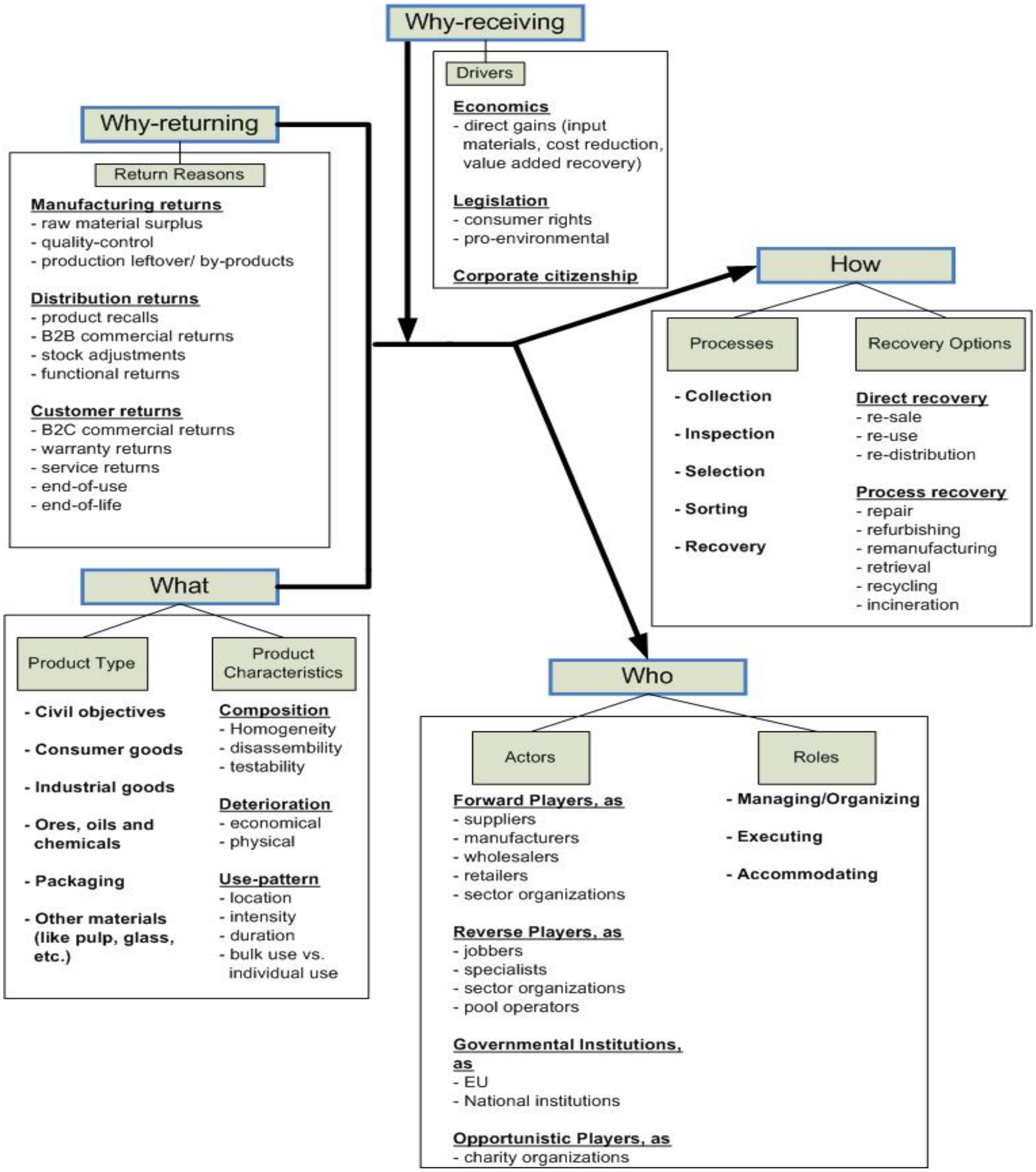

Fig 2.4 Framework for reverse logistics (Adapted from De Brito 2003)

Gilmour [42] proposed a framework for supply chain operations as shown in Figure 2.4.

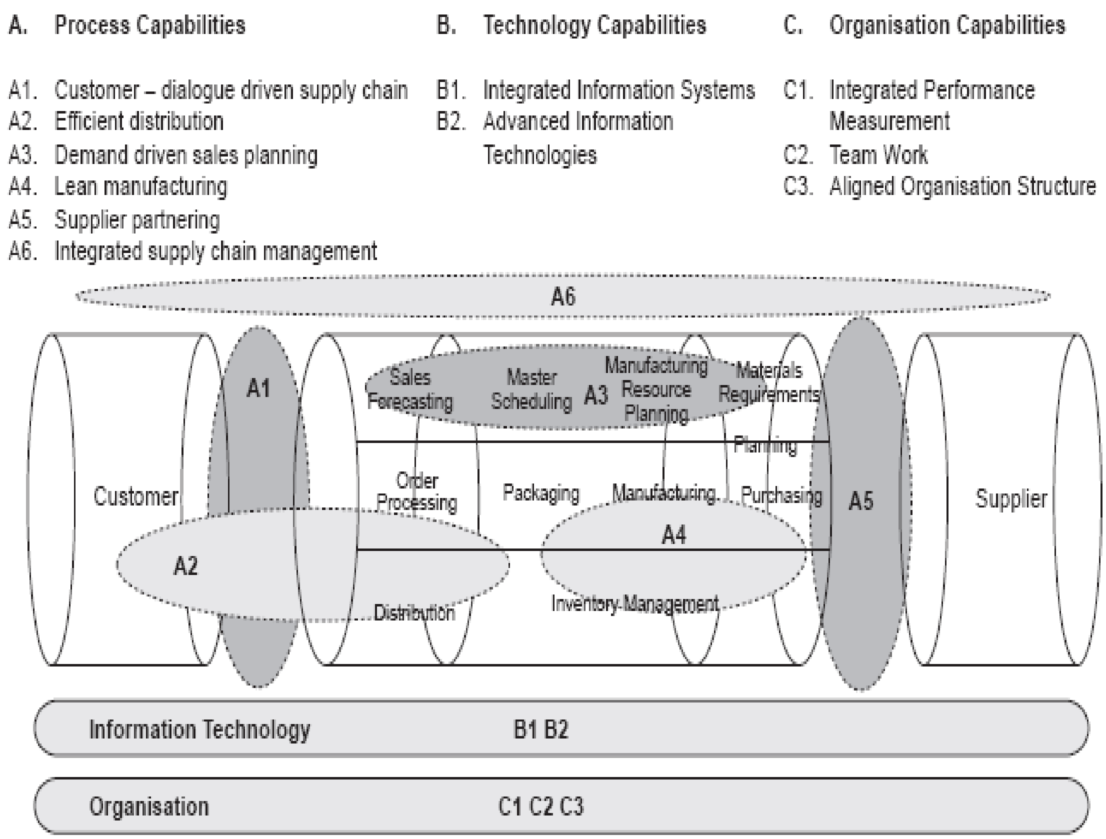

Fig 2.5 Supply chain operations framework model [42]

This model was used to investigate logistics operations of the companies in Gilmour's research. It was composed of six functional process capabilities, two technology capabilities and two organization capabilities as shown in figure 2.4. These eleven components were categorized in five dimensions in order to evaluate the logistic activities in the area of management. These dimensions are strategy and organization; planning; business process and information; product flow; and measurement. Gilmour also provides descriptions of capabilities as shown in Table 2.3.

Table 2.3 Logistics capabilities components [42]

Logistics capabilities	Description
Process capabilities	
1. Customer-driven supply chain	A customer-driven supply chain enables manufacturers to understand their customers' needs and proactively offer solutions that deliver increased values.
2. Efficient logistics	An ability to move products and materials from suppliers through manufacturing and to customers at lowest possible costs while meeting or exceeding customers requirements.
3. Demand-driven sales planning	Accuracy of projections for product volume and mix and their consistent use throughout the organization in production scheduling, vendor management and sales and operations planning.
4. Lean manufacturing	Effective utilization of the manufacturing asset base (achieving high equipment reliability, minimal rework, low inventories, short changed over times) while maintaining high levels of flexibility and quality.
5. Supplier partnering	Integration of manufacturers' and suppliers' supply chain activities to maximize the value and cost efficiency of purchased material and services.
6. Integrated supply chain management	Management of the supply chain at two levels: tactical management across functional and company boundaries; and strategic consideration of cost and performance options.
Information technology capabilities	
1. Integrated information systems	Improved quality and timeliness of business data to drive supply chain planning, execution and performance monitoring from a common base, resulting in high integrity and consistency of decision making.
2. Advanced technology	To improve the efficiency of workflows and to enable new ways to manage the supply chain.
Organization capabilities	
1. Integrated performance measurement	Enables the translation of business objectives into specific operational and financial targets for elements in the supply chain. Regular measurement and analysis of supply chain performance benefits suppliers and customers.
2. Teamwork	A focus on building the knowledge base of individuals enhances the ability of employees to work together effectively in achieving broader business goals and improving performance.
3. Aligned organization structure	A cross-functional structure with the objective to support business processes.

Dowlatshahi [43] provided five strategic factors that are important for reverse supply chain, as follows:

1. Costs – Costs are related to every part of reverse supply chain design, for example, the cost of building a customer service center for remanufacturing operations.
2. Quality – Strategic quality focuses on quality of remanufactured, recycled or repaired product.
3. Customer service – The point of this strategy is to meet customer expectations, for instance, how fast the firm can fix or replace defective product.
4. Environmental concerns – Communities and customers require that the firms should be responsible to the environmental impact from their production, delivery or final disposal of their products [43, 44]. Reverse logistics strategies should conform to environmental regulations and requirements.
5. Political/legal concerns – Due to increasing government legislations, reverse logistics strategies need to be more efficient to conform to these regulations and need to be able to handle waste and hazardous materials from final disposal or end-of-life products.

2.4 Data Envelopment Analysis (DEA)

DEA was first introduced by Charnes, Cooper and Rhodes [8]. DEA is a linear programming-based technique that converts multiple input and output measures into a single comprehensive measure of productivity efficiency [4, 45]. DEA is a nonparametric method for quantitative analysis [4]. DEA is employed to evaluate the efficiency of decision making units (DMUs). DEA's concept was successfully applied to measure operational efficiency in many fields, including banks [46], hospitals [47], purchasing departments [48], cellular manufacturing [49], travel demand [50], information technology investments [51], motor carriers [52], and international ports [53].

Yang [54] proposed the facilities layout design methodology by applying Analytic Hierarchy Process (AHP) together with DEA. Layout alternatives were generated by a computer-aided, layout-planning tool. Quantitative decision making unit (DMU) outputs were computed by the same tool. AHP technique was used to evaluate qualitative DMU outputs, and then modified DEA was applied to identify the performance of each alternative.

Chih-Ming Liu [55] modified the DEA method with AHP and fuzzy set theory to develop a more effective performance evaluation method. Normally, the traditional DEA method cannot be used with a small number of business units but their proposed methodology is very efficient when used for comparing and choosing among many small units.

Zhang [56] proposed a model for selecting a Third Party Logistics (3PL) vendor in Fourth Party Logistics (4PL). 4PL is a single organization that provides an entire set of supply chain process. The 3PL vendor is very important because it is a part of 4PL. The authors applied the concept of AHP together with a DEA framework. The procedure of this methodology is shown in the figure below.

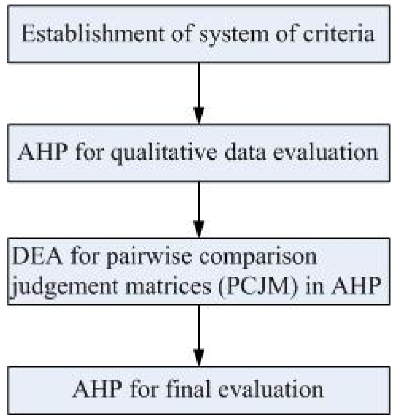

Fig 2.6 Procedure of the AHP/DEA methodology [56]

Both subjective opinions (qualitative data) from decision-makers and quantitative data can be evaluated at the same time with this proposed method.

Tavares [57] collected the data about DEA publications from 1978 to 2001. He found more than 3200 publications, including research papers, dissertations, journal papers, and book chapters, related to DEA in many areas. Some of them related to logistics and performance measurement, but there were very few related to reverse logistics.

Zhang [58] proposed a multi-phase methodology to design a reverse logistics network considering the risks by applying the fuzzy DEA model and location-allocation model solved by a hybrid genetic algorithm framework. The advantages of this method are dealing with uncertainty in the risk measure and considering reverse logistics demand for every reverse logistics supplier together with risk measure value.

Haas [59] applied DEA to reverse supply chains to aid logistics managers in better understanding the cost interactions and efficiencies of the channel members. The authors applied this methodology with municipal solid waste management systems to find out the benefits from this method. The results showed that the efficiency of municipal reverse logistics operations can be evaluated with DEA and this also provided valuable diagnostic information that can be analyzed and applied by each member of the evaluation field.

Li [4] collected the data about the method of performance evaluation of logistics activities. Many methods had been proposed in the past but there are some most frequently used methods, such as AHP, DEA, statistical methods (cluster analysis, principal component analysis, and factor analysis), fuzzy evaluation methods (fuzzy comprehensive evaluation, fuzzy cluster, and fuzzy AHP) and methods similar to those above. Every method has its own advantages and disadvantages. AHP can handle both qualitative and quantitative data but the result is greatly influenced by subjectivity. Mathematical Statistics usually deals with quantitative data and the evaluation process is complicated. Fuzzy application has strong qualitative analysis ability. DEA is more suitable than the others for multi-input and multi-output complicated systems or logistics activities because DEA only focuses on the weights of input and output of DMU. Therefore, the DEA technique can eliminate a lot of subjective factors.

Jing-yuan [60] applied DEA and AHP together to develop a DEA/AHP model for evaluating the supply chain performance. They applied the concept of Balanced Scorecard (BSC) to evaluate the index system of the supply chain and then employed DEA to calculate the relative efficiency rate of DMUs and used AHP to rank all the DMUs. This DEA/AHP model can overcome the limits of the DEA model and also simplify AHP evaluation. A traditional DEA model can only classify the units into two categories, “efficient” and “inefficient types,” but cannot rank all the units under one standard. The authors applied AHP to correct this problem. Meanwhile AHP requires judging matrices by many experts. Different experts provided different judgments that may cause inaccuracies and AHP consumes much time to compare each pair of alternatives. The authors facilitate this problem by applying DEA to construct the judging matrices. It is less complicated and does not need a consistency test, so the DEA/AHP model is feasible and convenient to evaluate supply chain performance.

Hokey Min [61] proposed a set of financial benchmarks for measuring the operational efficiency of third party logistics providers (3PL) by using DEA. There is high competition among 3PL providers, so they need to continuously improve their financial performance to stay competitive. Benchmarking is the most effective method to help 3PL set a reliable financial standard and measure their operational efficiency. The authors applied DEA to measure competitiveness of 3PL services. This proposed methodology can identify inefficient units and assists 3PL providers in establishing detailed policy guidelines in prioritizing the use of financial resources and evaluating the effects of financial investment on the profitability of 3PL.

Zhu [62] proposed DEA methodology used to measure supply chain’s efficiency. Supply chain’s efficiency is evaluated as a whole system and each member individually. This model helps to find out how to improve the current model to reach the best practice. The advantage of this model is no requirement of ideal assumptions, such as constant demand and known lead-time for delivery. The general supply chain model, composed of suppliers, manufacturers, distributors, and retailers, was presented to test this methodology. Supply chain system is considered as an integrated input-output system. The supply chain model from Zhu can be shown in figure 2.7.

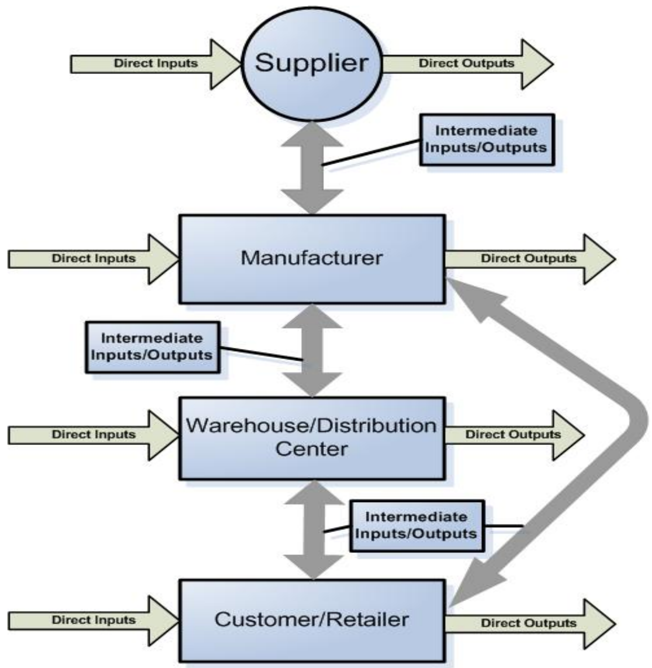

Fig 2.7 Supply Chain model [62]

To consider the performance of the supply chain, inputs and outputs of each member need to be considered. In this case, inputs and outputs are classified in two categories, direct inputs/outputs and intermediate inputs/outputs. Direct inputs/outputs are independent variables while intermediate inputs/outputs are dependent variables. For example, intermediate outputs of a supplier can be considered as intermediate inputs of a manufacturer.

The following notions were used to represent intermediate inputs/outputs in Zhu's model.

Z_t^{S-M} = t th intermediate output from Supplier to Manufacturer, t = 1,....,T;

Z_m^{M-S} = m th intermediate output from Manufacturer to Supplier, m = 1,…,M;

Z_f^{M-D} = f th intermediate output from Manufacturer to Distributor, f = 1,…,F;

Z_g^{D-M} = g th intermediate output from Distributor to Manufacturer, g = 1,…,G;

Z_l^{M-R} = l th intermediate output from Manufacturer to Retailer, l = 1,…,L;

Z_q^{R-M} = q th intermediate output from Retailer to Manufacturer, q= 1,…,Q;

Z_e^{D-R} = e th intermediate output from Distributor to Retailer, e = 1,…,E;

Z_n^{R-D} = n th intermediate output from Retailer to Distributor, n = 1,…,N;

In this model, intermediate outputs will only be specified because this output can be used as an input to an associated member. For example, Z_f^{M-D} (output of Manufacturing Plants) also represents an input to Distributor.

Let w_i be the weights reflecting the preference over the supply chain member's performance; w_i can be specified by users. Let Ω^* be the efficiency of the supply chain and the efficiency of component i is represented by Ω_i. The DEA model for the supply chain was developed following linear programming [62]:

$$\Omega^* = \underset{\Omega_i,\lambda_j,\beta_j,\delta_j,\gamma_j,\tilde{z}}{\mathrm{Min}} \frac{\sum_{i=1}^{4} w_i \Omega_i}{\sum_{i=1}^{4} w_i}$$

Subject to:

Constraints for Supplier S

1. $\sum_{j=1}^{J} \lambda_j X_{ij}^{supplier} \leq \Omega_1 X_{ij_0}^{supplier} \quad , \quad i \in DI^{supplier}$

2. $\sum_{j=1}^{J} \lambda_j Y_{rj}^{supplier} \geq Y_{rj_0}^{supplier} \quad , \quad r \in DR^{supplier}$

3. $\sum_{j=1}^{J} \lambda_j Z_{tj}^{S-M} \geq \tilde{Z}_{tj_0}^{S-M} \quad , \quad t = 1,\ldots, T$

4. $\sum_{j=1}^{J} \lambda_j Z_{mj}^{M-S} \leq \tilde{Z}_{mj_0}^{M-S} \quad , \quad m = 1,\ldots, M$

5. $\lambda_j \geq 0 \quad , \quad j = 1,\ldots, J$

Constraints for Manufacturer M

7. $\sum_{j=1}^{J} \beta_j X_{ij}^{manufacturer} \leq \Omega_2 X_{ij_0}^{manufacturer} \quad , \quad i \in DI^{manufacturer}$

8. $\sum_{j=1}^{J} \beta_j Y_{rj}^{manufacturer} \geq Y_{rj_0}^{manufacturer} \quad , \quad r \in DR^{manufacturer}$

9. $\sum_{j=1}^{J} \beta_j Z_{tj}^{S-M} \leq \tilde{Z}_{tj_0}^{S-M} \quad , \quad t = 1,\ldots, T$

10. $\sum_{j=1}^{J} \beta_j Z_{mj}^{M-S} \geq \tilde{Z}_{mj_0}^{M-S} \quad , \quad m = 1,\ldots, M$

11. $\sum_{j=1}^{J} \beta_j Z_{fj}^{M-D} \geq \tilde{Z}_{fj_0}^{M-D} \quad , \quad f = 1,\ldots, F$

12. $\sum_{j=1}^{J} \beta_j Z_{gj}^{D-M} \leq \tilde{Z}_{gj_0}^{D-M} \quad , \quad g = 1,\ldots, G$

13. $\sum_{j=1}^{J} \beta_j Z_{lj}^{M-R} \leq \tilde{Z}_{lj_0}^{M-R}$, $l = 1,\ldots, L$

14. $\sum_{j=1}^{J} \beta_j Z_{qj}^{R-M} \geq \tilde{Z}_{qj_0}^{R-M}$, $q = 1,\ldots, Q$

15. $\beta_j \geq 0$, $j = 1,\ldots, J$

Constraints for Distributor D

16. $\sum_{j=1}^{J} \delta_j X_{ij}^{distributor} \leq \Omega_3 X_{ij_0}^{distributor}$, $i \in DI^{distributor}$

17. $\sum_{j=1}^{J} \delta_j Y_{rj}^{distributor} \geq Y_{rj_0}^{distributor}$, $r \in DR^{distributor}$

18. $\sum_{j=1}^{J} \delta_j Z_{fj}^{M-D} \leq \tilde{Z}_{fj_0}^{M-D}$, $f = 1,\ldots, F$

19. $\sum_{j=1}^{J} \delta_j Z_{gj}^{D-M} \leq \tilde{Z}_{gj_0}^{D-M}$, $g = 1,\ldots, G$

20. $\sum_{j=1}^{J} \delta_j Z_{ej}^{D-R} \leq \tilde{Z}_{ej_0}^{D-R}$, $e = 1,\ldots, E$

21. $\sum_{j=1}^{J} \delta_j Z_{nj}^{D-R} \leq \tilde{Z}_{nj_0}^{D-R}$, $n = 1,\ldots, N$

22. $\delta_j \geq 0$, $j = 1,\ldots, J$

Constraints for Retailer R

23. $\sum_{j=1}^{J} \gamma_j X_{ij}^{Retailer} \leq \Omega_4 X_{ij_0}^{Retailer}$, $i \in DI^{Retailer}$

24. $\sum_{j=1}^{J} \gamma_j Y_{rj}^{Retailer} \geq Y_{rj_0}^{Retailer}$, $r \in DR^{Customers}$

25. $\sum_{j=1}^{J} \gamma_j Z_{lj}^{M-R} \leq \tilde{Z}_{lj_0}^{M-R}$, $l = 1,\ldots, L$

26. $\sum_{j=1}^{J} \gamma_j Z_{qj}^{R-M} \geq \tilde{Z}_{qj_0}^{R-M}$, $q = 1,\ldots, Q$

27. $\sum_{j=1}^{J} \gamma_j Z_{ej}^{D-R} \leq \tilde{Z}_{ej_0}^{D-R}$, $e = 1,\ldots, E$

28. $\sum_{j=1}^{J} \gamma_j Z_{nj}^{R-D} \geq \tilde{Z}_{nj_0}^{R-D}$, $n = 1,\ldots, N$

29. $\gamma_j \geq 0$, $j = 1,\ldots, J$

The variables λ_j, β_j, δ_j, and γ_j are nonnegative scalar variables for DMU_j of supplier, manufacturer, distributor, and retailer respectively. This model is very flexible; additional constraints could be added depending on the data and limitations. If $\Omega^* = 1$, then it means there is an optimal solution that the optimal values of the following variables $\lambda, \beta, \delta, and\ \gamma$ are equal to 1 and all components are efficient. If $\Omega^* \neq 1$, all members are efficient with respect to $\Omega_1^* X_{ij_0}^{supplier}$ where $i \in DI^{supplier}$, $\Omega_2^* X_{ij_0}^{manufacturer}$ where $i \in DI^{manufacturer}$, $\Omega_3^* X_{ij_0}^{distributor}$ where $i \in DI^{distributor}$, $\Omega_4^* X_{ij_0}^{retailer}$ where $i \in DI^{retailer}$, $Y_{rj_0}^{supplier}$ where $r \in DR^{supplier}$, $Y_{rj_0}^{manufacturer}$ where $r \in DR^{manufacturer}$, $Y_{rj_0}^{distributor}$ where $r \in DR^{distributor}$, $Y_{rj_0}^{retailer}$ where $r \in DR^{retailer}$,

$\widetilde{Z}_{tj_0}^{S-M^*}$ where t = 1,…, T , $\widetilde{Z}_{mj_0}^{M-S^*}$ where m = 1,…, M , $\widetilde{Z}_{fj_0}^{M-D^*}$ where f = 1,…, F , $\widetilde{Z}_{gj_0}^{D-M^*}$ where g = 1,…, G, $\widetilde{Z}_{lj_0}^{M-R^*}$ where l = 1,…, L, $\widetilde{Z}_{qj_0}^{R-M^*}$ where q = 1,…, Q , $\widetilde{Z}_{ej_0}^{D-R^*}$ where e = 1,…, E , where (*) represents optimal value and (˜) represents unknown decision variables.

In this research, Zhu's model will be adapted to evaluate the performance of reverse logistics.

2.4.1 Weight restriction in DEA

The advantage of the traditional DEA model developed by Charnes in 1978 is the ability to evaluate the efficiency of DMUs with a mix of assigned weights on the variables (inputs and outputs). On the other hand, conventional DEA models have a severe limitation, which is their excessive weight flexibility, allowing DMU to seek maximum efficiency by selecting a mix of weights that either is impossible because it ignores one or more variables, or is unacceptable because it is inconsistent with the expert judgment available to the decision maker [63]. Many researchers proposed various methodologies for increasing discrimination in DEA to correct these drawbacks. Some of these interesting methodologies include:

The cone ratio model was developed by Charnes [64] and used by Kornbluth [65]. If the weights provided by DEA are not consistent with the objectives of each DMU then the efficiency scores of these DMUs may be overestimated. Applying additional restriction of the cone ratio will obtain better efficiency scores, which are consistent with their objectives. The cone ratio model always provides at least one efficient DMU, but this model needs a priori information by an expert or a decision-maker.

Assurance Regions (AR) was first introduced by Thompson [66]. The objective of AR is to deal with the infeasible solution of DEA by separating linear homogeneous restrictions on input and output weights. The AR boundaries are of the form:

$$a_r u_1 \leq u_r \leq b_r u_1$$

$$a_i v_1 \leq v_i \leq b_i v_1$$

The value of a and b must be specified by an expert or the decision-maker, which is the drawback of this method. The AR approach allows one to augment successively on AR until an efficiency refinement level is reached and satisfies the decision-maker [67].

Wong [68] used the proportion of constraints to restrict the weight flexibility in DEA. They restricted the proportion of output to the total virtual output instead of doing it directly on the weight. Although this methodology can be used in any situation and usually provides better efficiency scores than the classical DEA model does, this method can lead to infeasible efficiency scores for some DMUs due to some constraints that need to be added with the proportion.

Value efficiency analysis was developed by Halme [69]. The objective of this method is incorporating preference information into the analysis of DMUs. This methodology consists of two steps. The first step is identifying the decision-maker's Most Preferred Solution (MPS). MPS can be evaluated using multiple objective linear programming. This multiple objective model comes with many feasible solutions which will be chosen by the expert, depending on their preferences. The next step is determining the efficient frontier with preferred input/output level by the expert; the resulting efficiency scores of this new frontier are called “value efficient” [70]. The disadvantage of this model is the need of prior information from the expert and the efficiency score depends on the expert’s preference.

Per [71] presented the method for ranking efficient DMUs. Their concept is to compare the unit under evaluation with a linear combination of all other DMUs in the sample while the observed DMU itself is excluded. Efficient DMUs will be ranked very high by this model and can have an efficiency score greater than one. The advantage of this method is easily discriminating among efficient DMUs and providing ranking for each unit. But this model cannot deal with unreal weight [70].

Weight restriction with a multiple criteria approach is another interesting methodology. First introduced by Li [72], a Multiple Criteria Data Envelopment Analysis (MCDEA) model improves discriminating efficient DMUs from inefficient ones. The difference between this method and classical DEA is that this model provides many criteria. Each criterion can be viewed as an independent objective function and each of them provides different efficiency scores for DMUs. The advantage of this model is no prior information is needed.

CHAPTER 3

METHODOLOGY

3.1 Overview

To simulate the methodology for evaluating the performance of the reverse supply chain, many tasks need to be done. The first step is creating a reverse supply chain model to use for simulating the data. In this study, the reverse supply chain will be considered as a part of the Closed Loop Supply Chain model (CLSC), thus the model that will be used in this study is viewed as a CLSC. Normally, the model will be designed based on levels of production planning. Production planning is categorized in three levels [7]: strategic planning (long term), tactical planning (medium term), and operative planning (short term). Tactical planning is good for a combination level of products. The examples of this medium term planning are the Master Production Schedule (MPS) and Approximated Capacity Planning. The operative planning works with the Material Requirement Planning (MRP) or job-shop scheduling. For this dissertation, CLSC will be developed at the medium term planning (tactical level). To design a CLSC, each component in the model needs to be specified correctly, including inputs and outputs of each component. After designing the model, mathematical equations, together with some constraints, will be applied to each component to illustrate the input and output for that component and interaction among components.

After finishing with the CLSC, the next step is designing a DEA model that is used to evaluate performance of the CLSC. In this step, attributes for each component must be specified carefully because it will result the performance of CLSC. In this DEA model, inputs and outputs of the components will be classified in two categories, direct and intermediate inputs/outputs. Direct inputs/outputs are independent variables, while intermediate inputs/outputs are dependent variables. For example, intermediate output of a supplier can be considered as intermediate input of a manufacturer.

3.2 Design Reverse Logistics Model

As mentioned earlier, reverse logistics is a part of CLSC. In this step, CLSC will be designed. Before designing CLSC, the components in the supply chain will be specified. In this study, CLSC consists of the components as shown in the figure 1.2

3.2.1 Components of CLSC

From figure 1.2, CLSC is composed of 5 main components which are Supplier, Manufacturing Plant, Distribution Center/Warehouse, Retailers/Customers and Recovery Facility. The function and assumption of each component's function in this model will be explained as follows:

Supplier – will deliver raw materials to manufacturing plants.

Manufacturing Plant – will manufacture the products by using raw materials from suppliers and will employ returned parts or assemblies from the Recovery Facility. Manufacturing Plants need to specify the quantity and type of the materials that they need to buy from suppliers at each period that could be determined by the model. Products from manufacturers will be delivered to the Distribution Centers or

Warehouses. Not all of the produced products are delivered to the Distribution Center. Plants can decide to deliver all products, or part of them, because plants can keep some inventory (which could be finished goods or just materials used to manufacture products). Manufacturing Plants could use the parts, materials or assemblies from a previous period that are kept in inventories, together with new materials purchased from suppliers to produce the products at that period. We assume that products will be manufactured within the period.

Distribution Center – will collect the demands from customers and retailers and then inform Manufacturing Plants. After receiving products from manufacturers, the Distribution Center will distribute them to retailers or customers to fulfill the demand. In this model, stock-out can happen to the Distribution Center when demands exceed the inventory level. In a stock-out event, this model assumes that insufficient demands will be fulfilled at the next period.

Retailers or Customers – get products from manufacturers via Distribution Centers or Warehouses. Quantities of products depend on demands.

Recovery Facility – collects returned products from customers or retailers then considers disposal options for those returns. Some products will be disassembled then sent back to manufacturing plants to be manufactured again. The rest will be resold or disposed. The returns may be fully disassembled or partially disassembled so the parts that come from the facility can be assemblies or just single parts, depending on the quality of the returns. Assemblies consist of many types of materials. An example of the classification process of returns at the Recovery Facility is shown in figure 1.3

This model implies that those assemblies and returned parts that are shipped from the Recovery Facility can be used to manufacture new products but employ different processes. In this case, we need to know the bill of materials for each product. For example, Product X could be divided into assembly A and material B in the first level, while assembly A is composed of material C and D and can be disassembled at the second level. So Product X can be manufactured by all new material B, C and D or reused assembly A and new material B. Fig 3.3 shows an example of the bill of materials for product X.

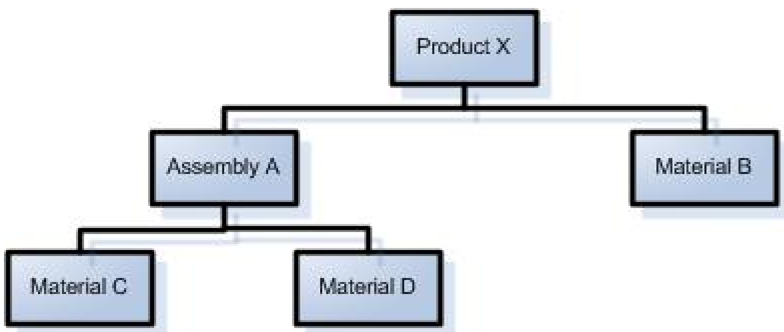

Fig 3.1 An example of bill of materials for product X

This model is adapted from Soto's model [7] which needs to include the following assumptions:

- The new product can be manufactured with new and/or reused parts and/or assemblies depending on the bill of materials.
- The new product can be manufactured with different processes depending on the bill of materials.
- The quantity of reusable parts or assemblies affects the quantity of new material purchased.

- The cost of the assemblies includes inspection cost, disassembly cost and transportation cost.
- Demand for each period comes from the sale forecast.

Figure 3.2 illustrates CLSC design model for this study in more detail.

3.2.2 Formulation of the model

The objective of this model is to minimize the total production cost of the CLSC. This model is adapted and improved from Soto's model [7] to fit this study. In the case that products have many production process options and many types of materials need to be purchased, this model will choose the process that minimizes the cost to manufacture the products. The quantity of reusable parts or assemblies shipped from the Recovery Facility will be calculated by the model based on the most benefit criteria. The Total Production Costs of this model consists of the following components:

1. Total production cost of all products at all Manufacturing Plants. This cost is calculated by the summation of the product of number of units of product i to produce in plant m by process Ω on period t ($Q1_{\Omega imt}$) and production cost of one unit of article i at plant m by process Ω on period t ($A_{\Omega imt}$). This term can be written in mathematical term as follows: $\sum_{\Omega=1}^{\Omega}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} A_{\Omega imt}Q1_{\Omega imt}$

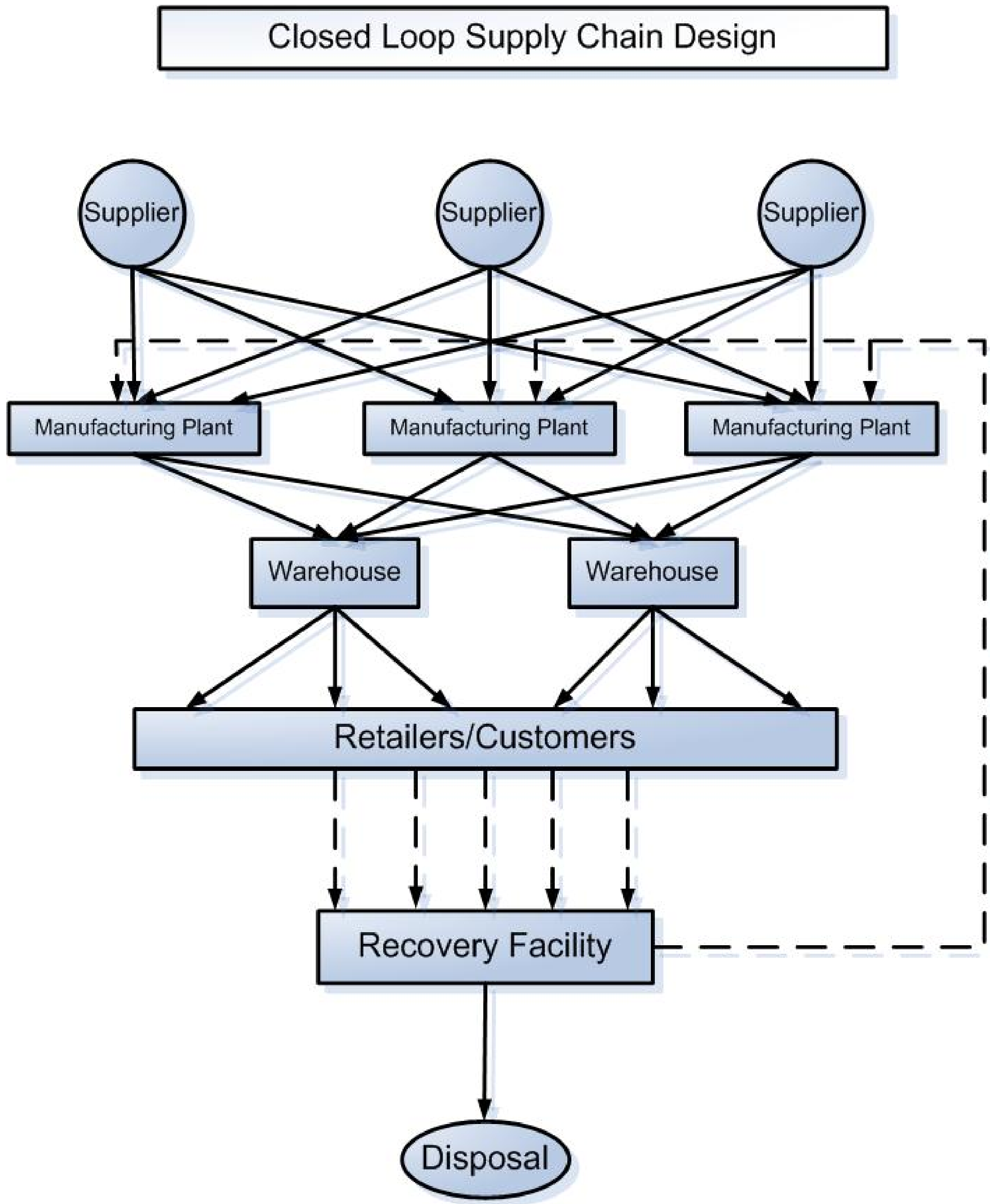

Fig 3.2 Closed Loop Supply Chain Design Model

2. Total holding cost of products at all Manufacturing Plants. This cost is calculated by the summation of the product of the holding cost per unit of article

i at plant m and inventory units of product i in plant m at the end of period t ($Q4_{imt}$). This term can be written in mathematical term as follows: $\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} B_{im}Q4_{imt}$

3. Total stock-out cost of products. This cost is calculated by the summation of the product of stock out cost per unit of product i at warehouse w at period t (Q_{iwt}) and the number of units of stock out of product i at warehouse w at period t ($Q6^{-}_{iwt}$). This term can be written in mathematical term as follows: $\sum_{i=1}^{I}\sum_{w=1}^{W}\sum_{t=1}^{T} Q_{iwt}Q6^{-}_{iwt}$

4. Total purchase cost of materials from suppliers. This cost is calculated by the summation of the product of the cost of purchasing one unit of material p from supplier s to plant m at period t (E_{smpt}) and the number of units of material p to purchase from supplier s in plant m at the beginning of period t ($Q2_{smpt}$). This term can be written in mathematical term as follows: $\sum_{s=1}^{S}\sum_{m=1}^{M}\sum_{p=1}^{P}\sum_{t=1}^{T} E_{smpt}Q2_{smpt}$

5. Total holding cost of materials at all Manufacturing Plants. This cost is calculated by the summation of the product of the holding cost per unit of material p at plant m at period t (D_{mpt}) and inventory units of material p in plant m at the end of period t ($Q5_{mpt}$). This term can be written in mathematical term as follows: $\sum_{m=1}^{M}\sum_{p=1}^{P}\sum_{t=1}^{T} D_{mpt}Q5_{mpt}$

6. Total transportation cost of product shipped from Manufacturing Plants to Distribution Center/Warehouse. This cost is calculated by the summation of the product of the transportation cost per unit of product i shipped from plant m to warehouse w on period t (F_{iwmt}) and the quantity of product i shipped to warehouse w from plant m at period t ($Q3_{iwmt}$).This term can be written in mathematical term as follows: $\sum_{i=1}^{I}\sum_{w=1}^{W}\sum_{m=1}^{M}\sum_{t=1}^{T} F_{iwmt}Q3_{iwmt}$

7. Total holding cost of product at Distribution Center/Warehouse. This cost is calculated by the summation of the product of the holding cost of product i at period t on warehouse w (C_{iwt}) and inventory units of product i at warehouse w at period t ($Q6^{+}_{iwt}$). This term can be written in mathematical term as follows: $\sum_{i=1}^{I}\sum_{w=1}^{W}\sum_{t=1}^{T} C_{iwt}Q6^{+}_{iwt}$

8. Total transportation cost of all materials shipped from Recovery Facility to Manufacturing Plants. This cost is calculated by the summation of the product of the transportation cost per unit of material p shipped from recovery facility to Manufacturing Plant m on period t (U_{mpt}) and the quantity of material p shipped from central recovery plant to plant m on period t ($Q7_{mpt}$).This term can be written in mathematical term as follows: $\sum_{m=1}^{M}\sum_{p=1}^{P}\sum_{t=1}^{T} U_{mpt}Q7_{mpt}$

9. Total holding cost of materials at Recovery Facility. This cost is calculated by the summation of the product of the holding cost of material p at period t at

central recovery plant (V_{pt}) and the inventory units of material p at period t on central recovery plant ($Q8_{pt}$). This term can be written in mathematical term as follows: $\sum_{p=1}^{P}\sum_{t=1}^{T} V_{pt}Q8_{pt}$

10. Total disassembly cost at Recovery Facility. This cost is calculated by the summation of the product of the probability of material p resulting from the disassembly process of product i being of good quality for remanufacturing (Pb_{ip}); this probability will stay between 0 and 1 and will be specified. The second term used to calculate cost is the number of units of product i returned to the Recovery Facility on period t. The third term is the number of units of material p that can be obtained from returned product i (RT_{ip}). Another factor is the number of units of product i returned to central recovery plant on period t (Z_{it}); the expected quantity usually comes from statistical data in the past. The last term is the disassembly cost for material of assembly p from product i at period t (X_{ipt}). Total disassembly cost can be written in mathematical term as follows: $\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{p=1}^{P} Pb_{ip}*RT_{ip}*Z_{it}*X_{ipt}$

In summary, the objective function of this model is to minimize all costs which is

Minimize (Total production cost of all products at all Manufacturing Plants + Total holding cost of products at all Manufacturing Plants + Total stock-out cost of products + Total purchase cost of materials from supplier + Total holding cost of materials at all

Manufacturing Plants + Total transportation cost from Manufacturing Plants to Distribution Center + Total holding cost of product at Distribution Center + Total transportation cost of all materials shipped from Recovery Facility to Manufacturing Plants + Total holding cost of materials at Recovery Facility + Total disassembly cost at Recovery Facility).

Besides this objective function, this model will be subjected to the following constraints:

1. Inventory equation for reusable materials and assemblies: This constraint relates to reusable materials or assemblies that are obtained from returned product. Before setting up this constraint, materials will be separated into two groups. The first group contains new materials (material 1 to material n) while the second group contains reusable materials and assemblies from the returned process (material n+1 to material p). Parameter p represents the type of materials (type of new materials plus type of reusable materials and assemblies). The inventory of material p in period t ($Q8_{pt}$) must be equal to the inventory of material p from the previous period ($Q8_{p(t-1)}$) plus the amount of returned materials during the present period t, minus the quantity of material p shipped to Manufacturing Plant m at period t ($Q7_{mpt}$). The estimated returned materials quantity will be calculated from the following equation:

$$Q8_{pt} = Q8_{p(t-1)} + \sum_{i=1}^{I}(Pb_{ip} * RT_{ip} * Z_{it}) - \sum_{m=1}^{M} Q7_{mpt}$$

Where i = 1,...,I ; m = 1,…,M ; p = (n+1),…,P ; t = 1…T

2. Control of shipments: this model assumes all good quality returned parts or assembly at the current period will be shipped to Manufacturing Plants in the next period. So the quantity of returned material p to plant m at period t ($Q7_{mpt}$) must be less than or equal to the inventory of materials p at the recovery facility in the previous period ($Q8_{p(t-1)}$). This constraint can be written as follow:

$$\sum_{m=1}^{M} Q7_{mpt} \leq Q8_{p(t-1)}$$

Where p = (n+1),…,P ; t = 1…T

3. Inventory capacity for reusable materials and assemblies: The inventory of material p at period t in the recovery facility ($Q8_{pt}$) must be less than or equal to maximum stock quantity (Y_p) and must be greater than or equal to 0. This constraint can be written as follows:

$$Q8_{pt} \leq Y_p$$

Where p = (n+1),…,P ; t = 1…T

4. Inventory equation for materials: This constraint relates to the amount of materials purchased from suppliers. The inventory of material p at Manufacturing Plant m at the end of period t ($Q5_{mpt}$) must be equal to the inventory of the previous period ($Q5_{mp(t-1)}$) plus the purchased quantity of this material p from suppliers at plant m during the period t ($\sum_{s=1}^{S} Q2_{smpt}$), minus the summation of the units produced by all production processes Ω of product i at

plant m at period t ($Q1_{\Omega imt}$) times the amount of materials p needed to produce one unit of product i by process Ω ($G_{\Omega ip}$) plus returned material p to plant m at period t ($Q7_{mpt}$).This constraint can be written as follows:

$$Q5_{mpt} = Q5_{mp(t-1)} + \sum_{s=1}^{S} Q2_{smpt} - [\sum_{i=1}^{I}\sum_{\Omega=1}^{\Omega} G_{\Omega ip} Q1_{\Omega imt}] + Q7_{mpt}$$

Where i = 1,…,I ; m = 1,…,M ; t = 1…T ; p = 1,…,n ; s = 1,…,S ; Ω = 1,…, Ω

5. Inventory equation for assemblies: This constraint is similar to the inventory equation for materials. The slight difference is that the assemblies cannot be purchased from suppliers. The assemblies can be obtained from the Recovery Facility only. The constraint of the inventory equation for assemblies can be written as follows:

$$Q5_{mpt} = Q5_{mp(t-1)} - [\sum_{i=1}^{I}\sum_{\Omega=1}^{\Omega} G_{\Omega ip} Q1_{\Omega imt}] + Q7_{mpt}$$

Where i = 1,…,I ; m = 1,…,M ; t = 1…T ; p = (n+1),…,P ; Ω = 1,…, Ω

6. Inventory capacity for materials: Each Manufacturing Plant m has maximum holding capacity for material p (J_{mp}) and security stock (H_{mp}) for material p. Therefore, inventory of material p at plant m at period t ($Q5_{mpt}$) must stay between maximum holding capacity and security stock. This constraint can be written as follows:

$$H_{mp} \le Q5_{mpt} \le J_{mp}$$

Where m = 1,…,M ; t = 1…T ; p = 1,…,P

7. Control of materials: this constraint limits the number of products that can be manufactured from available materials only. The quantity of available materials at the present period, which is the summation of the product of the quantity of units to be manufactured by all processes Ω of product i at plant m at period t ($Q1_{\Omega imt}$) and the amount of materials p needed to produce one unit of product i by process Ω ($G_{\Omega ip}$), must be less than or equal to the inventory of materials p at plant m at the previous period ($Q5_{mp(t-1)}$) plus the quantity of material p purchased from suppliers at Manufacturing Plant m on the current period ($\sum_{s=1}^{S} Q2_{smpt}$). This constraint can be written as follows:

$$\sum_{i=1}^{I}\sum_{\Omega=1}^{\Omega} G_{\Omega ip} Q1_{\Omega imt} \leq Q5_{mp(t-1)} + \sum_{s=1}^{S} Q2_{smpt}$$

Where i = 1,…,I ; m = 1,…,M ; t = 1…T ; p = 1,…,P ; s = 1,…,S ; Ω = 1,…, Ω

8. Inventory equation for products: The inventory of product i at Manufacturing Plant m at the end of period t ($Q4_{imt}$) must be equal to the inventory of product i in this plant m at the end of the previous period ($Q4_{im(t-1)}$), plus the production quantity of the product i at plant m by all the production processes Ω during the period t ($Q1_{\Omega imt}$) minus summation of the quantity of product i shipped from plant m to all Distribution Centers at period t ($Q3_{wimt}$).This constraint can be written as follows:

$$Q4_{imt} = Q4_{im(t-1)} - \sum_{\Omega=1}^{\Omega} Q1_{\Omega imt} - \sum_{w=1}^{W} Q3_{wimt}$$

Where i = 1,…,I ; m = 1…M ; t = 1,…,T ; w = 1,…,W ; Ω = 1,…, Ω ;

9. Shipment control: The amount of product i that is shipped from the Manufacturing Plants to Distribution Centers must be less than or equal to the inventory of product i at plant m at the end of the previous period ($Q4_{im(t-1)}$) plus the quantity manufactured at plant m at period t by all the production processes Ω ($Q1_{\Omega imt}$). This constraint can be written as follows:

$$\sum_{\Omega=1}^{\Omega} Q1_{\Omega imt} + Q4_{im(t-1)} \geq \sum_{w=1}^{W} Q3_{wimt}$$

Where i = 1,…,I ; m = 1…M ; t = 1,…,T ; w = 1,…,W ; Ω = 1,…, Ω

10. Inventory capacity for products: Each Manufacturing Plant m has maximum holding capacity for product i (JJ_{im}) and security stock (HH_{im}) for product i. Therefore, inventory of product i at plant m on period t ($Q4_{imt}$) must stay between the maximum holding capacity and security stock. This constraint can be written as follows:

$$HH_{im} \leq Q4_{imt} \leq JJ_{im}$$

Where i = 1,…,I ; m = 1,…, M ; t = 1,…,T

11. Stock out or Inventory units on Distribution Centers/Warehouses: This constraint allows stock out or inventory units at Distribution Centers/Warehouses. Stock-out or Inventory units of product i on all

Distribution Centers/Warehouses at period t ($\sum_{w=1}^{W} Q6_{iwt}$) is calculated from the inventory of product i at all Distribution Centers from the previous period ($\sum_{w=1}^{W} Q6_{iw(t-1)}$) plus the total quantity of product i shipped from all the Manufacturing Plant m to all Distribution Centers w at period t ($\sum_{w=1}^{W}\sum_{m=1}^{M} Q3_{wimt}$), minus the demand of product i at period t (R_{it}).This constraint can be written as follows:

$$\sum_{w=1}^{W} Q6_{iw(t-1)} + \sum_{w=1}^{W}\sum_{m=1}^{M} Q3_{wimt} - R_{it} = \sum_{w=1}^{W} Q6_{iwt}$$

Where i = 1,…,I ; t = 1,…,T ; w = 1,…,W ; m = 1,…, M

12. Stock-out or inventory units relation: The difference between stock-out and inventory units is if $R_{it} > \sum_{w=1}^{W} Q6_{iw(t-1)} + \sum_{w=1}^{W}\sum_{m=1}^{M} Q3_{wimt}$ it means there are units of stock-out, and if $R_{it} \leq \sum_{w=1}^{W} Q6_{iw(t-1)} + \sum_{w=1}^{W}\sum_{m=1}^{M} Q3_{wimt}$, there are inventory units. The variable $\sum_{w=1}^{W} Q6_{iw(t-1)}$ could be positive or negative, which is difficult to specify in the model. To make it easier, $Q6_{iwt}$ will be divided into two variables: Inventory units of product i at warehouse w at period t ($Q6^{+}_{iwt}$) and Number of stock-out units of product i at warehouse w at period t ($Q6^{-}_{iwt}$). When $Q6^{+}_{iwt} = 0$ and $Q6^{-}_{iwt} > 0$, it means there are stock out units of product i at Distribution

Center w at period t. If $Q6^{+}_{iwt} \geq 0$ and $Q6^{-}_{iwt} = 0$, it means there are inventory units of product i at Distribution Center w at period t. And the relation among $Q6_{iwt}$, $Q6^{+}_{iwt}$ and $Q6^{-}_{iwt}$ is

$$Q6_{iwt} = Q6^{+}_{iwt} + Q6^{-}_{iwt}$$

Where i = 1,…,I ; t = 1,…,T ; w = 1,…,W

13. Production capacity: The production capacity is limited by hours of production available at each Manufacturing Plant m at period t (O_{mt}). And the summation of the product of the hours of production used to produce one unit of product i ($N_{\Omega i}$) and the quantity of product i manufactured at plant m by process Ω at period t ($Q1_{\Omega imt}$) must be less than or equal to the production capacity (O_{mt}). This constraint can be written as follows:

$$\sum_{\Omega=1}^{\Omega}\sum_{i=1}^{I} N_{\Omega i} Q1_{\Omega imt} \leq O_{mt}$$

Where i = 1,…,I ; m = 1…M ; t = 1,…,T ; Ω = 1,…, Ω

14. Integer constraints: Other than the constraints above most of the parameters and variables must be greater than or equal to 0 and must be integers except all cost parameters.

In summary the model will be specified as follows:

$$\text{Min} \sum_{\Omega=1}^{\Omega}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} A_{\Omega imt} Q1_{\Omega imt} + \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} B_{im} Q4_{imt} + \sum_{i=1}^{I}\sum_{w=1}^{W}\sum_{t=1}^{T} Q_{iwt} Q6^{-}_{iwt}$$

$$+ \sum_{s=1}^{S}\sum_{m=1}^{M}\sum_{p=1}^{P}\sum_{t=1}^{T} E_{smpt} Q2_{smpt} + \sum_{m=1}^{M}\sum_{p=1}^{P}\sum_{t=1}^{T} D_{mpt} Q5_{mpt} + \sum_{i=1}^{I}\sum_{w=1}^{W}\sum_{m=1}^{M}\sum_{t=1}^{T} F_{iwmt} Q3_{iwmt}$$

$$+ \sum_{i=1}^{I}\sum_{w=1}^{W}\sum_{t=1}^{T} C_{iwt}Q6^{+}_{iwt} + \sum_{m=1}^{M}\sum_{p=1}^{P}\sum_{t=1}^{T} U_{mpt}Q7_{mpt} + \sum_{p=1}^{P}\sum_{t=1}^{T} V_{pt}Q8_{pt}$$

$$+ \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{p=1}^{P} Pb_{ip}*RT_{ip}*Z_{it}*X_{ipt}$$

Subject to:

1. $Q8_{pt} = Q8_{p(t-1)} + \sum_{i=1}^{I}(Pb_{ip}*RT_{ip}*Z_{it}) - \sum_{m=1}^{M}Q7_{mpt}$

Where i = 1,...,I ; m = 1,…,M ; p = (n+1),…,P ; t = 1…T

2. $\sum_{m=1}^{M}Q7_{mpt} \leq Q8_{p(t-1)}$

Where p = (n+1),…,P ; t = 1…T

3. $Q8_{pt} \leq Y_{p}$

Where p = (n+1),…,P ; t = 1…T

4. $Q5_{mpt} = Q5_{mp(t-1)} + \sum_{s=1}^{S}Q2_{smpt} - [\sum_{i=1}^{I}\sum_{\Omega=1}^{\Omega} G_{\Omega ip}Q1_{\Omega imt}] + Q7_{mpt}$

Where i = 1,…,I ; m = 1,…,M ; t = 1…T ; p = 1,…,n ; s = 1,…,S ; Ω = 1,…, Ω

5. $Q5_{mpt} = Q5_{mp(t-1)} - [\sum_{i=1}^{I}\sum_{\Omega=1}^{\Omega} G_{\Omega ip}Q1_{\Omega imt}] + Q7_{mpt}$

Where i = 1,…,i ; m = 1,…,m ; t = 1…T ; p = (n+1),…,P ; Ω = 1,…, Ω

6. $H_{mp} \leq Q5_{mpt} \leq J_{mp}$

Where m = 1,…,M ; t = 1…T ; p = 1,…,P

7. $\sum_{i=1}^{I}\sum_{\Omega=1}^{\Omega} G_{\Omega ip}Q1_{\Omega imt} \leq Q5_{mp(t-1)} + \sum_{s=1}^{S}Q2_{smpt}$

Where i = 1,…,I ; m = 1,…,M ; t = 1…T ; p = 1,…,P ; s = 1,…,S ; Ω = 1,…, Ω

8. $Q4_{imt} = Q4_{im(t-1)} - \sum_{\Omega=1}^{\Omega} Q1_{\Omega imt} - \sum_{w=1}^{W} Q3_{wimt}$

Where i = 1,…,I ; m = 1…M ; t = 1,…,T ; w = 1,…,W ; Ω = 1,…, Ω

9. $\sum_{\Omega=1}^{\Omega} Q1_{\Omega imt} + Q4_{im(t-1)} \geq \sum_{w=1}^{W} Q3_{wimt}$

Where i = 1,…,I ; m = 1…M ; t = 1,…,T ; w = 1,…,W ; Ω = 1,…, Ω

10. $HH_{im} \leq Q4_{imt} \leq JJ_{im}$

Where i = 1,…,I ; m = 1,…, M ; t = 1,…,T

11. $\sum_{w=1}^{W} Q6_{iw(t-1)} + \sum_{w=1}^{W}\sum_{m=1}^{M} Q3_{wimt} - R_{it} = \sum_{w=1}^{W} Q6_{iwt}$

Where i = 1,…,I ; t = 1,…,T ; w = 1,…,W ; m = 1,…, M

12. $Q6_{iwt} = Q6^{+}_{iwt} + Q6^{-}_{iwt}$

Where i = 1,…,I ; t = 1,…,T ; w = 1,…,W

13. $\sum_{\Omega=1}^{\Omega}\sum_{i=1}^{I} N_{\Omega i} Q1_{\Omega imt} \leq O_{mt}$

Where i = 1,…,I ; m = 1…M ; t = 1,…,T ; Ω = 1,…, Ω

14. $Q1_{\Omega imt} \geq 0$ and integer

15. $Q2_{smpt} \geq 0$ and integer

16. $Q3_{iwmt} \geq 0$ and integer

17. $Q4_{imt} \geq 0$ and integer

18. $Q5_{mpt} \geq 0$ and integer

19. $Q6^{+}_{iwt} \geq 0$ and integer

20. $Q6^{-}_{iwt} \geq 0$ and integer

21. $Q7_{mpt} \geq 0$ and integer

22. $Q8_{pt} \geq 0$ and integer

Parameters:

Ω = Number of production processes that have the product with the maximum number of production processes

I = Type of products

P = Type of materials (including assemblies and reusable parts)

M = Number of Manufacturing Plants

T = Number of periods of time to planning (normally represents week)

W = Number of Distribution Centers/Warehouses

S = Number of Suppliers

$A_{\Omega imt}$ = Production cost of one unit of product i at Manufacturing Plant m by process Ω on period t

B_{im} = Holding cost per unit of product i at Manufacturing Plant m

Q_{iwt} = Stock-out cost per unit of product i at Distribution Center/Warehouse w on period t

E_{smpt} = Cost of purchase of one unit of material p at Manufacturing Plant m from supplier s at period t

D_{mpt} = Holding cost per unit of material p at Manufacturing Plant m at period t

JJ_{im} = Security stock of product i at Manufacturing Plant m

HH_{im} = Maximum allowed stock of product i at Manufacturing Plant m

$G_{\Omega ip}$ = Quantity of material p needed to produce one unit of product i by process Ω

RT_{ip} = Number of units of material p that can be obtained from returned product i

J_{mp} = Maximum allowed stock of material p at Manufacturing Plant m

H_{mp} = Security stock of material p at Manufacturing Plant m

F_{imwt} = Transportation cost per unit of product i shipped from Manufacturing Plant m to Distribution Center/Warehouse w on period t

U_{mpt} = Transportation cost per unit of material p (including all assemblies) shipped from Recovery Facility to Manufacturing Plant m on period t

R_{it} = Demand of product i at period t

C_{iwt} = Holding cost of product i at period t on Distribution Center/Warehouse w

$N_{\Omega i}$ = Production time for manufacturing one unit of product i by process Ω

O_{mt} = Hours of production capacity in Manufacturing Plant m at period t

V_{pt} = Holding cost of material p at period t at Recovery Facility

Pb_{ip} = Probability that material p resulting from the disassembly process of product i is of good quality for remanufacturing

X_{ipt} = Disassembly cost for material or assembly p from product i at period t

Y_p = Holding capacity of reusable material or assembly p at central recovery plant

Z_{it} = Number of units of product i returned to central recovery plant on period t

Variables:

$Q1_{\Omega imt}$ = Number of units of product i to produce in plant m by process Ω on period t

$Q2_{smpt}$ = Number of units of material p to purchase in plant m from supplier s at the beginning of period t

$Q3_{iwmt}$ = Quantity of product i shipped to warehouse w from plant m at period t

$Q4_{imt}$ = Inventory units of product i in plant m at the end of period t

$Q5_{mpt}$ = Inventory units of material p in plant m at the end of period t

$Q6^{+}_{iwt}$ = Inventory units of product i at warehouse w at period t

$Q6^{-}_{iwt}$ = Number of units of stock-out of product i at warehouse w at period t

$Q7_{mpt}$ = Quantity of material p shipped from central recovery to plant m on period t

$Q8_{pt}$ = Inventory units of material p at period t on central recovery plant

This model is an integer linear programming model and Lingo software is used to generate the code to solve this model.

After running this model, a set of inputs and outputs will be obtained. These inputs/outputs from this model will be used as inputs in the DEA model to obtain the efficiency score of the CLSC.

3.3 Performance evaluation with DEA

The next step, after designing the reverse logistics model, is to design a DEA model for CLSC that can be employed to evaluate the performance of the reverse supply chain. In this study, CLSC will be considered as a DMU. Each DMU consists of 4 main components which are Manufacturing Plants, Distribution Centers/Warehouses, Retailers/Customers, and Recovery Facility. Performance of each component in each DMU needs to be considered because each component has its own strategy to reach 100% efficiency and to reach 100% for the overall system. It does not require all components to have 100% efficiency. Sometimes, there are conflicts of efficiency between components in the same DMU. The efficiency of one component may cause the inefficiency of the other components. For instance, the Recovery Facility can increase the efficiency by processing more reusable parts to plants to be remanufactured. Increasing returns may reduce the efficiency of Manufacturing Plants because the cause of the return may come from unsatisfied products from customers that may reduce the demand volumes in the next period.

To consider the performance of the reverse supply chain, inputs and outputs of each member need to be considered. In this case, inputs and outputs are classified in two categories: direct inputs/outputs and intermediate inputs/outputs. Direct input/output are independent variables, while intermediate input/output are dependent variables. For example, intermediate output of Manufacturing Plants can be considered as intermediate input of Distribution Centers/Warehouses. Properly specified inputs/outputs for each member in the reverse supply chain is very important and will affect the performance evaluation of reverse logistics. In this study, inputs and outputs of each component are specified as shown in table 3.1

Table 3.1 Inputs/outputs for each component in DEA model

Components	Direct Inputs	Direct Output	Intermediate Inputs/Outputs	Type
Manufacturing Plants	Purchasing cost (materials)		# return materials from Recovery to Plants	Input
	Production cost			
	Holding Cost of products		# products from Plants to WHs	Output
	Holding Cost of Materials			
	Transportation cost (Plants to WHs)			
Distribution Centers/WHs	Transportation cost (WHs to Retailers)		# products from Plants to WHs	Input
	Holding Cost of products		# products from WHs to Retailers	Output
	Stock out Cost			
Retailers/ Customers	Transportation cost	Demand	# products from WHs to Retailers	Input
	(Retailers to Recovery)			
Recovery Facility	Disassembly Cost		# return materials	Output
	Transportation cost (Recovery to Plants)		from Recovery to Plants	
	Holding Cost			

Because holding costs of products and materials at Manufacturing Plants and transportation costs from Plants to Warehouses are very small compared to purchasing and production costs, the holding cost and transportation cost will be combined with the production cost and be considered as one direct input at Manufacturing Plants in this DEA model. In the same manner, transportation cost from the Recovery Facility to the Warehouse and the holding cost at the Recovery Facility are very small compared to the disassembly cost; therefore, disassembly cost, transportation cost and holding cost will be combined and considered as one direct input cost at the recovery facility. Figure 3.3 illustrates the relation among components in each DMU.

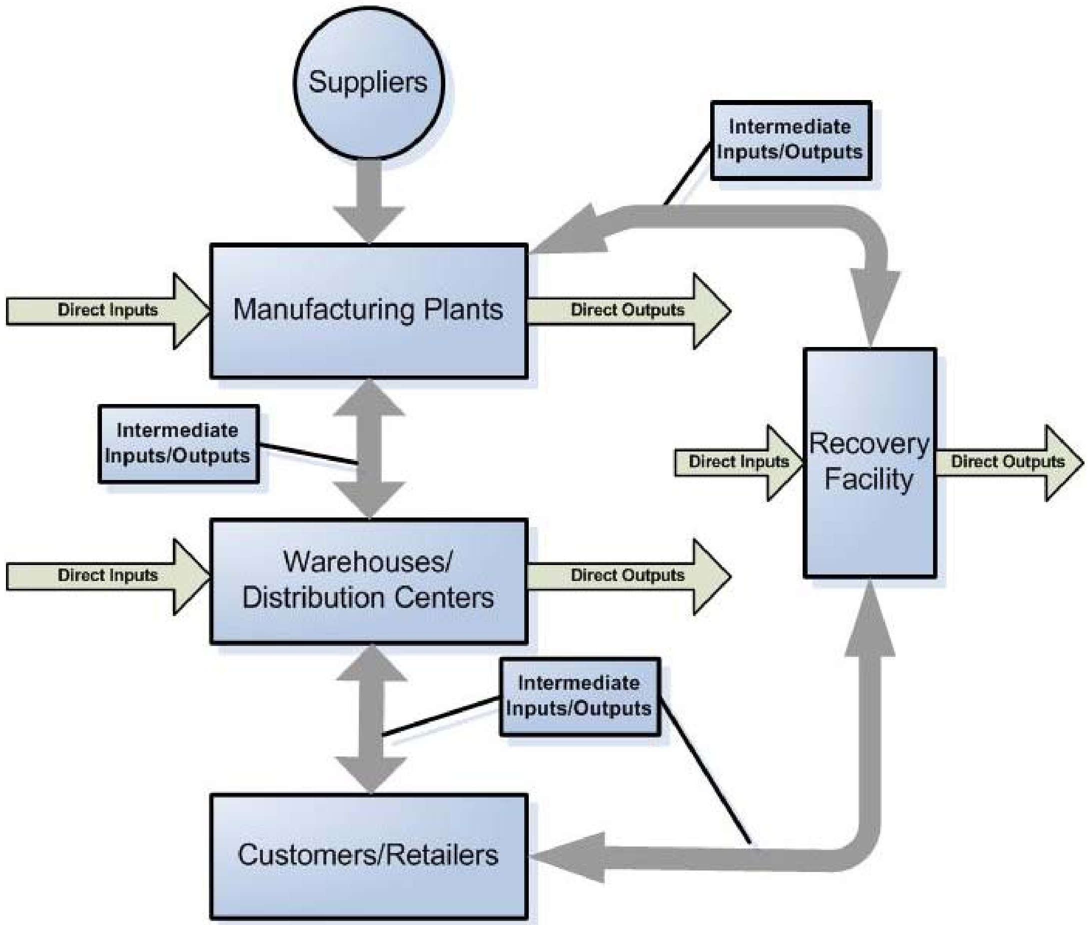

Fig 3.3 Relation among components in each DMU

This DEA model can be expressed in a linear programming model as follows:

$$\theta^* = \min_{\theta_i, \Omega_j, \beta_j, \alpha_j, \gamma_j, \tilde{K}} \frac{\sum_{i=1}^{4} w_i \theta_i}{\sum_{i=1}^{4} w_i} \quad \ldots\ldots (3.1)$$

Subject to:

Constraints for Manufacturing Plants, M

1. $\sum_{j=1}^{J} \Omega_j Q_{ij}^{M} \leq \theta_1 Q_{ij_0}^{M} \quad , \quad i \in DI^{M}$

2. $\sum_{j=1}^{J}\Omega_j S_{rj}^{M} \geq S_{ij_0}^{M}$, $r \in DR^{M}$

3. $\sum_{j=1}^{J}\Omega_j K_{aj}^{M-D} \geq \tilde{K}_{aj_0}^{M-D}$, $a = 1,\ldots, A$

4. $\sum_{j=1}^{J}\Omega_j K_{bj}^{D-M} \leq \tilde{K}_{bj_0}^{D-M}$, $b = 1,\ldots, B$

5. $\sum_{j=1}^{J}\Omega_j K_{cj}^{R-M} \leq \tilde{K}_{cj_0}^{R-M}$, $c = 1,\ldots, C$

6. $\sum_{j=1}^{J}\Omega_j Z_{dj}^{M-R} \geq \tilde{Z}_{dj_0}^{M-R}$, $d = 1,\ldots, D$

7. $\Omega_j \geq 0$, $j = 1,\ldots, J$

Constraints for Distribution Centers/Warehouses, D

8. $\sum_{j=1}^{J}\beta_j Q_{ij}^{D} \leq \theta_2 Q_{ij_0}^{D}$, $i \in DI^{D}$

9. $\sum_{j=1}^{J}\beta_j S_{rj}^{D} \geq S_{ij_0}^{D}$, $r \in DR^{D}$

10. $\sum_{j=1}^{J}\beta_j K_{aj}^{M-D} \geq \tilde{K}_{aj_0}^{M-D}$, $a = 1,\ldots, A$

11. $\sum_{j=1}^{J}\beta_j K_{bj}^{D-M} \leq \tilde{K}_{bj_0}^{D-M}$, $b = 1,\ldots, B$

12. $\sum_{j=1}^{J}\beta_j K_{ej}^{D-C} \leq \tilde{K}_{ej_0}^{D-C}$, $e = 1,\ldots, E$

13. $\sum_{j=1}^{J}\beta_j K_{fj}^{C-D} \geq \tilde{K}_{fj_0}^{C-D}$, $f = 1,\ldots, F$

14. $\beta_j \geq 0$, $j = 1,\ldots, J$

Constraints for Customers/Retailers, C

15. $\sum_{j=1}^{J}\alpha_j Q_{ij}^{C} \leq \theta_3 Q_{ij_0}^{C}$, $i \in DI^C$

16. $\sum_{j=1}^{J}\alpha_j S_{rj}^{C} \geq S_{ij_0}^{C}$, $r \in DR^C$

17. $\sum_{j=1}^{J}\alpha_j K_{ej}^{D-C} \leq \tilde{K}_{ej_0}^{D-C}$, $e = 1,\ldots, E$

18. $\sum_{j=1}^{J}\alpha_j K_{fj}^{C-D} \geq \tilde{K}_{fj_0}^{C-D}$, $f = 1,\ldots, F$

19. $\sum_{j=1}^{J}\alpha_j K_{gj}^{C-R} \leq \tilde{K}_{gj_0}^{C-R}$, $g = 1,\ldots, G$

20. $\sum_{j=1}^{J}\alpha_j K_{hj}^{R-C} \geq \tilde{K}_{hj_0}^{R-C}$, $h = 1,\ldots, H$

21. $\alpha_j \geq 0$, $j = 1,\ldots, J$

Constraints for Recovery Facility, R

22. $\sum_{j=1}^{J}\gamma_j Q_{ij}^{R} \leq \theta_4 Q_{ij_0}^{R}$, $i \in DI^R$

23. $\sum_{j=1}^{J} \gamma_j S_{rj}^{R} \geq S_{ij_0}^{R}$, $r \in DR^R$

24. $\sum_{j=1}^{J} \gamma_j K_{gj}^{C-R} \leq \widetilde{K}_{gj_0}^{C-R}$, $g = 1, \ldots, G$

25. $\sum_{j=1}^{J} \gamma_j K_{hj}^{R-C} \geq \widetilde{K}_{hj_0}^{R-C}$, $h = 1, \ldots, H$

26. $\sum_{j=1}^{J} \gamma_j K_{cj}^{R-M} \leq \widetilde{K}_{cj_0}^{R-M}$, $c = 1, \ldots, C$

27. $\sum_{j=1}^{J} \gamma_j K_{dj}^{M-R} \geq \widetilde{K}_{dj_0}^{M-R}$, $d = 1, \ldots, D$

28. $\gamma_j \geq 0$, $j = 1, \ldots, J$

The following notions are used to represent intermediate inputs/outputs in the model.

K_a^{M-D} = a th intermediate output from Manufacturing Plants to Distribution Centers/Warehouses, a = 1,…,A

K_b^{D-M} = b th intermediate output from Distribution Centers/Warehouses to Manufacturing Plants, b = 1,…,B

K_e^{D-C} = e th intermediate output from Distribution Centers/Warehouses to Customers/Retailers, e = 1,…,E

K_f^{C-D} = f th intermediate output from Customers/Retailers to Distribution Centers/Warehouses, f = 1,…,F

K_g^{C-R} = g th intermediate output from Customers/Retailers to Recovery Facility, g = 1,…,G

K_h^{R-C} = h th intermediate output from Recovery Facility to Customers/Retailers, h = 1,…,H

K_c^{R-M} = c th intermediate output from Recovery Facility to Manufacturing Plants, c = 1,…,C

K_d^{M-R} = d th intermediate output from Manufacturing Plants to Recovery Facility, d = 1,…,D

In this model, intermediate outputs will only be specified because this output can be used as an input to an associated member. For example, K_a^{M-D} (output of Manufacturing Plants) also represents an input to Distribution Centers/Warehouses.

Let w_i be the weight reflecting the preference over the reverse supply chain member's performance (operation); w_i will be specified by users. Let θ^* be the efficiency of the DMU and the efficiency of component i is represented by θ_i. The variables Ω_j, β_j, α_j, and γ_j are nonnegative scalar variables for DMU_j of Manufacturing Plants, Distribution Centers/Warehouses, Customers/Retailers, and Recovery Facility respectively. This model is very flexible, additional constraints could be added depending on the data and limitations. If θ^*= 1, then it means there is an optimal solution and that the optimal values of the following variables $\Omega, \beta, \alpha,$ and γ are equal to 1 and all reverse logistics components are efficient. If $\theta^{*} \neq 1$, all members are efficient with respect to $\theta_1^{*} Q_{ij_0}^{M}$ where $i \in DI^{M}$, $\theta_2^{*} Q_{ij_0}^{D}$ where $i \in DI^{D}$, $\theta_3^{*} Q_{ij_0}^{C}$ where $i \in DI^{C}$, $\theta_4^{*} Q_{ij_0}^{R}$ where $i \in DI^{R}$, $S_{rj_0}^{M}$ where $r \in DR^{M}$, $S_{rj_0}^{D}$ where $r \in DR^{D}$, $S_{rj_0}^{C}$ where $r \in DR^{C}$, $S_{rj_0}^{R}$ where $r \in DR^{R}$, $\tilde{K}_{aj_0}^{M-D^*}$ where a = 1,…, A , $\tilde{K}_{bj_0}^{D-M^*}$ where b = 1,…, B, $\tilde{K}_{ej_0}^{D-C^*}$ where e = 1,…, E, $\tilde{K}_{fj_0}^{C-D^*}$ where f = 1,…, F , $\tilde{K}_{gj_0}^{C-R^*}$ where g = 1,…, G , $\tilde{K}_{hj_0}^{R-C^*}$ where h = 1,…, H , $\tilde{K}_{cj_0}^{R-M^*}$ where c = 1,…, C , $\tilde{K}_{dj_0}^{M-R^*}$ where d = 1,…, D, and (*) represents optimal value and (˜) represents unknown decision variables.

3.4 Design of experiment

Design of experiment (DOE) is a statistical technique used to investigate a system. DOE creates an experimentation strategy used to test the significant parameters that result in the response. DOE only applies a few resources but can provide a clear picture of the system in statistical aspects. It helps analysts in planning and testing the process in cost-effective ways and also helps in predicting the response from the inputs specified. There are many types of experimental design, for example, Plackett-Burman designs, full factorial designs, fractional factorial designs, central composite designs, and Box-Behnken designs. Each design has their advantages and disadvantages. In this study, the two levels full factorial designs technique will be used. Two levels designs is generally good enough to test all possible interactions of factors at each level and also point out parameters that can significantly affect the response. Design of experiment software (DOE++) will be used to do the two levels full factorial designs in this study.

To do the experiment, parameters will be divided into two levels: low and high. Any interaction among significant parameters will be tested and the final model will be obtained related to significant parameters and interactions.

Figure 3.4 illustrates the idea of how to design the experiment in this study to get the optimized reverse supply chain model that can be used to evaluate the efficiency of the systems.

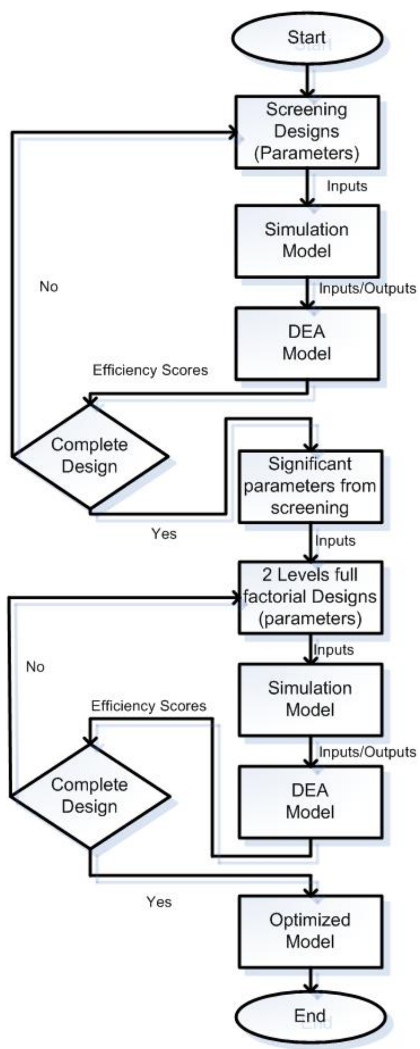

Fig 3.4 Flow chart of the methodology to optimize and evaluate efficiency of the reverse logistics model

The process of doing the experiment in figure 3.4 can be explained as follows:

1. Design the parameters with screening test

Due to many parameters involved in the models, to test all of them with 2 levels full factorial design not only consumes a lot of time but is also costly in real life scenarios. Screening tests are needed to help roughly eliminate non-significant parameters. In this study, fractional factorial design is used for screening the parameters. This design is not only good enough to identify the significant parameters among many, but also provides many options of the number of experiments which can be decided by the experimenter. The process of screening design starts with choosing parameters to be tested, then putting these parameters in the simulation model to get all the optimized inputs/outputs for each scenario. In the next step, these inputs/outputs will be put into the DEA model to get the relative efficiency scores. After that, these scores will be put back into the screening test models as the responses for each scenario. Finally, the screening test will be completed to obtain the significant parameters.

2. Do the experiments with significant parameters from step 1 by two levels full factorial designs

After receiving the significant parameters from the screening designs, these parameters will be tested in two levels full factorial designs experiments. The number of experiments is equal to 2^K where K is the number of tested parameters. The process of experiments is similar to the screening tests. The same simulation model and the same DEA model will be used to get inputs/outputs and relative efficiency scores, respectively. After obtaining all the responses (efficiency scores) for all scenarios, the experiments will be completed to get the optimized model and statistical information.

CHAPTER 4

CASE STUDY AND DATA ANALYSIS

4.1 Overview

In 2003, five billion pounds of carpet were sent to landfills and 500 million pounds of old carpet have been recovered since 2002 (Carpet America Recovery Effort, CARE). U.S. annual landfill cost for carpet is about $65 million. Complete carpet recycling can recover a value of about $750 million in lost material from landfills [73]. Designing a good reverse logistics for carpet recycling is a challenging task for a company. Not only can it save a lot of money and increase revenue from using recycled materials from returned carpets, but it also encourages environmental concerns.

In this study, we assume that returned carpets are sent back from retailers/customers to a central recovery to sort, dispose, or disassemble, depending on the condition of the returns. The mechanical and chemical process will convert the nylon carpet to raw materials. The conversion process in this study, referred to as the disassembly process, will convert nylon polymer from used carpet to monomer units which can be used as raw materials to produce the carpet again. This process is also called depolymerization. There are three main types of materials related to carpet manufacturing: yarn, which is nylon; chemical products such as polypropylene and polyester; and finally, the package. For the return part, assume that only nylon can be used to remanufacture; all else needs to be disposed. Manufacturers will purchase raw materials from suppliers then ship finished products to the Warehouse via the demand requested, then the products will be shipped to retailers/customers. All of the returns due to end of use or end of life will be shipped to the Recovery Facility. The Recovery Facility will process the returns and send the reusable part to Manufacturers, depending on the demand requested from them. The CLSC of this carpet manufacturing is identical to the CLSC in figure 3.2.

4.2 Case Study

In this study, two case studies will be conducted. Both of them are related to carpet manufacturing CLSC and the main process will be the same, but some parameters for each case will be varied.

4.2.1 Case Study 1- Simple Scenarios

The process of each case study will follow the flow chart in figure 3.4. In case study 1, there is one Supplier, one Manufacturing Plant, one Distribution Center/Warehouse and one Recovery Facility. The design parameters related to the model are first divided into two levels: low and high, for fitting the two levels full factorial designs. The parameters are designed based on the real data of carpet manufacturing from a previous study, books and internet. All of the parameters specified are shown in appendix A. The first step is to design the parameters. The following parameters will be chosen to be tested in the screening design (two levels fractional factorial designs). The chosen parameters are essentially based on the significant effects in the simulation model. In this case, nine factors are picked to be tested. The designed parameters are shown in table 4.1.

Table 4.1 Specified parameters for screening test

Name	Units	Type	Low Level	High Level
Purchase cost/unit	$	Qualitative	low	high
Production cost/unit	$	Quantitative	1	3
Disassembly cost/unit	$	Quantitative	0.2	0.4
Demand Volume	unit	Quantitative	50000	100000
Return Volume	unit	Quantitative	2500	20000
Holding Cost of product at plant	$	Quantitative	0.1	0.4
Holding Cost/unit of Materials at plant	$	Qualitative	low	high
Transportation cost/unit from plant to warehouse	$	Quantitative	0.05	0.1
Transportation cost/unit from recovery facility to plant	$	Quantitative	0.05	0.1

Parameters are divided into two types: qualitative and quantitative. Normally, the purchase cost is quantitative but in this model purchase cost/unit relates to many materials. For example, in this case study, purchase cost refers to cost of purchase of one unit of yarn plus cost of purchase of chemicals and the package. Therefore, it is more convenient to categorize the type of purchase cost to low and high. When the purchase cost/unit is specified low, it means all the purchase costs per unit of all materials are low. In the same manner, when it mentions high, all of the purchase costs per unit are high. For the simulation model, the purchase cost/unit still uses the quantitative value. These parameters will be put in the statistical software (DOE++) to generate the number of experiments for screening test by applying the 2 level fractional factorial designs technique. For nine factors, resolution III, IV, V and above will be available for screening test. Resolution V and above will provide the most details for experiments (more resolutions means more experiments) but will take more time.

Resolution III will prevent the effects of the factors and can be used with two-factor interactions only (provides the least information compared to the others). Resolution IV is reasonable to use for screening test as the main effects can be free of aliasing with two-factor interactions even though there is some loss of detail information. In this test, resolution IV will be used for screening test and options of fractions are $1/2^3$ and $1/2^4$. Fraction $1/2^4$ is employed to reduce the number of experiments (more number of experiments). The total number of experiments will be equal to $2^9 * (1/2^4)$ or 32 experiments. The parameters for each experiment are shown in table 4.2 when each run order represents each experiment. The parameters of each experiment will be used as inputs in the simulation model in chapter 3 to get the set of outputs for each experiment.

Table 4.2 Parameters for each experiment for screening test

Run Order	Standard Order	Purchase cost/unit ($)	Production cost/unit ($)	Disassembly cost/unit ($)	Demand Volume (unit)	Return Volume (unit)	Holding cost (product)/ unit @plant ($)	Holding cost (material)/ unit @plant ($)	Transportation cost/unit from plant to WH ($)	Transportation cost/unit from recovery to plant ($)
1	30	high	1	0.4	100000	20000	0.1	low	0.05	0.1
2	19	low	3	0.2	50000	20000	0.1	high	0.1	0.05
3	32	high	3	0.4	100000	20000	0.4	high	0.1	0.1
4	3	low	3	0.2	50000	2500	0.1	low	0.05	0.1
5	14	high	1	0.4	100000	2500	0.1	high	0.1	0.05
6	7	low	3	0.4	50000	2500	0.4	high	0.05	0.05
7	17	low	1	0.2	50000	20000	0.4	low	0.05	0.05
8	15	low	3	0.4	100000	2500	0.1	high	0.1	0.1
9	31	low	3	0.4	100000	20000	0.1	low	0.05	0.05
10	12	high	3	0.2	100000	2500	0.1	high	0.05	0.1
11	25	low	1	0.2	100000	20000	0.1	low	0.1	0.1
12	1	low	1	0.2	50000	2500	0.4	high	0.1	0.1
13	6	high	1	0.4	50000	2500	0.4	high	0.05	0.1
14	16	high	3	0.4	100000	2500	0.4	low	0.05	0.05
15	9	low	1	0.2	100000	2500	0.1	high	0.05	0.05
16	21	low	1	0.4	50000	20000	0.1	high	0.05	0.1
17	28	high	3	0.2	100000	20000	0.1	low	0.1	0.05
18	24	high	3	0.4	50000	20000	0.1	high	0.05	0.05
19	18	high	1	0.2	50000	20000	0.1	high	0.1	0.1
20	10	high	1	0.2	100000	2500	0.4	low	0.1	0.1
21	26	high	1	0.2	100000	20000	0.4	high	0.05	0.05
22	4	high	3	0.2	50000	2500	0.4	high	0.1	0.05
23	29	low	1	0.4	100000	20000	0.4	high	0.1	0.05
24	13	low	1	0.4	100000	2500	0.4	low	0.05	0.1
25	5	low	1	0.4	50000	2500	0.1	low	0.1	0.05
26	2	high	1	0.2	50000	2500	0.1	low	0.05	0.05
27	27	low	3	0.2	100000	20000	0.4	high	0.05	0.1
28	11	low	3	0.2	100000	2500	0.4	low	0.1	0.05
29	22	high	1	0.4	50000	20000	0.4	low	0.1	0.05
30	20	high	3	0.2	50000	20000	0.4	low	0.05	0.1
31	8	high	3	0.4	50000	2500	0.1	low	0.1	0.1
32	23	low	3	0.4	50000	20000	0.4	low	0.1	0.1

In the next step, inputs and outputs of each experiment will be put in the DEA model in chapter 3 (model 3.1) to be evaluated for the relative efficiency for each experiment. Efficiency of each experiment will be considered as a response for each experiment. Statistical software will evaluate significant parameters from setup parameters and responses of all experiments. Table 4.3 illustrates the setup parameters and a response (efficiency) of each experiment.

Table 4.3 Parameters and a response for each experiment for screening test

Run Order	Standard Order	Purchase cost/unit ($)	Production cost/unit ($)	Disassembly cost/unit ($)	Demand Volume (unit)	Return Volume (unit)	Holding cost (product)/ unit @plant ($)	Holding cost (material)/ unit @plant ($)	Transportation cost/unit from plant to WH ($)	Transportation cost/unit from recovery to plant ($)	Efficiency
1	30	high	1	0.4	100000	20000	0.1	low	0.05	0.1	0.668
2	19	low	3	0.2	50000	20000	0.1	high	0.1	0.05	0.572
3	32	high	3	0.4	100000	20000	0.4	high	0.1	0.1	0.422
4	3	low	3	0.2	50000	2500	0.1	low	0.05	0.1	0.72
5	14	high	1	0.4	100000	2500	0.1	high	0.1	0.05	0.873
6	7	low	3	0.4	50000	2500	0.4	high	0.05	0.05	0.684
7	17	low	1	0.2	50000	20000	0.4	low	0.05	0.05	0.572
8	15	low	3	0.4	100000	2500	0.1	high	0.1	0.1	0.887
9	31	low	3	0.4	100000	20000	0.1	low	0.05	0.05	0.679
10	12	high	3	0.2	100000	2500	0.1	high	0.05	0.1	0.84
11	25	low	1	0.2	100000	20000	0.1	low	0.1	0.1	0.752
12	1	low	1	0.2	50000	2500	0.4	high	0.1	0.1	0.72
13	6	high	1	0.4	50000	2500	0.4	high	0.05	0.1	0.626
14	16	high	3	0.4	100000	2500	0.4	low	0.05	0.05	0.767
15	9	low	1	0.2	100000	2500	0.1	high	0.05	0.05	1
16	21	low	1	0.4	50000	20000	0.1	high	0.05	0.1	0.546
17	28	high	3	0.2	100000	20000	0.1	low	0.1	0.05	0.436
18	24	high	3	0.4	50000	20000	0.1	high	0.05	0.05	0.395
19	18	high	1	0.2	50000	20000	0.1	high	0.1	0.1	0.47
20	10	high	1	0.2	100000	2500	0.4	low	0.1	0.1	0.961
21	26	high	1	0.2	100000	20000	0.4	high	0.05	0.05	0.537
22	4	high	3	0.2	50000	2500	0.4	high	0.1	0.05	0.612
23	29	low	1	0.4	100000	20000	0.4	high	0.1	0.05	0.679
24	13	low	1	0.4	100000	2500	0.4	low	0.05	0.1	0.887
25	5	low	1	0.4	50000	2500	0.1	low	0.1	0.05	0.684
26	2	high	1	0.2	50000	2500	0.1	low	0.05	0.05	0.741
27	27	low	3	0.2	100000	20000	0.4	high	0.05	0.1	0.752
28	11	low	3	0.2	100000	2500	0.4	low	0.1	0.05	1
29	22	high	1	0.4	50000	20000	0.4	low	0.1	0.05	0.487
30	20	high	3	0.2	50000	20000	0.4	low	0.05	0.1	0.4
31	8	high	3	0.4	50000	2500	0.1	low	0.1	0.1	0.555
32	23	low	3	0.4	50000	20000	0.4	low	0.1	0.1	0.546

After running the program, five of nine factors were found to have significant effects to the response in the screening test. Five significant factors are return volume, demand volume, purchase cost, production cost, and disassembly cost. There are some significant interactions among these factors, but in this step, only significant factors will be chosen to test because all the interactions among these factors will be evaluated again in the full factorial test. Figure 4.1 shows the Pareto chart of all factors and interactions from the screening test while figure 4.2 shows the Pareto chart of only significant factors and interactions obtained from the screening test.

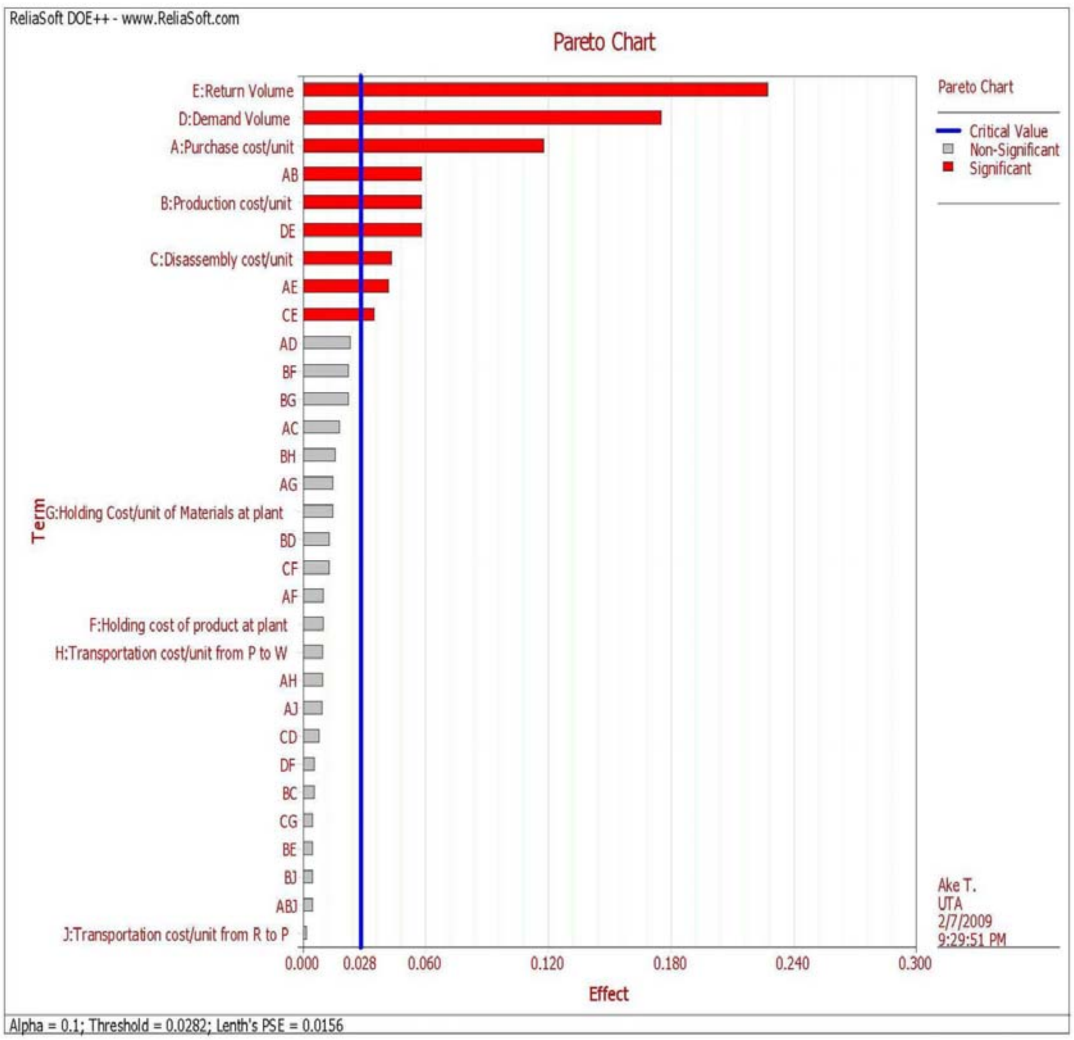

Fig 4.1 Pareto Chart of all factors and interactions from screening test

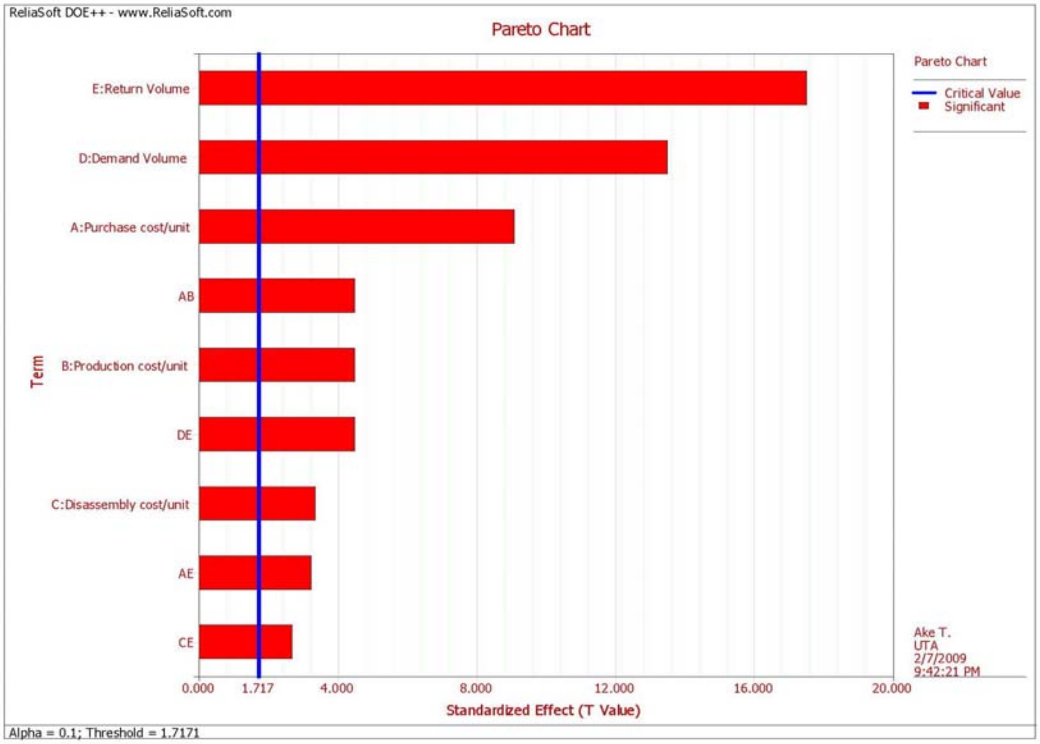

Fig 4.2 Pareto Chart of significant factors and significant interactions

All five significant parameters will be analyzed again with the 2 level full factorial designs to obtain more information and better results. For five factors, 32 experiments will be conducted. Setup parameters are shown in table 4.4.

Table 4.4 Setup parameters for 2 level full factorial test

Name	Units	Type	Low Level	High Level
Purchase cost/unit	$	Qualitative	low	high
Production cost/unit	$	Quantitative	1	3
Disassembly cost/unit	$	Quantitative	0.2	0.4
Demand Volume	unit	Quantitative	50000	100000
Return Volume	unit	Quantitative	2500	20000

The process of doing experiments is similar to the screening test process. All of the non-significant parameters from the screening test earlier will be averaged and used in the simulation model to calculate the outputs. Sets of inputs and outputs of each experiment will be put in the DEA model to obtain relative efficiency. Parameters and responses (relative efficiency) are shown in table 4.5.

Table 4.5 Parameters and responses of each experiment

Run Order	Standard Order	Purchase cost/unit ($)	Production cost/unit ($)	Disassembly cost/unit ($)	Demand Volume (unit)	Return Volume (unit)	Efficiency
1	21	low	1	0.4	50000	20000	0.550
2	13	low	1	0.4	100000	2500	0.905
3	8	high	3	0.4	50000	2500	0.564
4	4	high	3	0.2	50000	2500	0.612
5	26	high	1	0.2	100000	20000	0.562
6	23	low	3	0.4	50000	20000	0.550
7	1	low	1	0.2	50000	2500	0.735
8	30	high	1	0.4	100000	20000	0.551
9	22	high	1	0.4	50000	20000	0.491
10	3	low	3	0.2	50000	2500	0.735
11	17	low	1	0.2	50000	20000	0.572
12	32	high	3	0.4	100000	20000	0.424
13	27	low	3	0.2	100000	20000	0.781
14	11	low	3	0.2	100000	2500	1.000
15	29	low	1	0.4	100000	20000	0.686
16	25	low	1	0.2	100000	20000	0.781
17	20	high	3	0.2	50000	20000	0.402
18	5	low	1	0.4	50000	2500	0.687
19	14	high	1	0.4	100000	2500	0.905
20	12	high	3	0.2	100000	2500	0.869
21	7	low	3	0.4	50000	2500	0.687
22	6	high	1	0.4	50000	2500	0.668
23	10	high	1	0.2	100000	2500	1.000
24	15	low	3	0.4	100000	2500	0.905
25	19	low	3	0.2	50000	20000	0.572
26	9	low	1	0.2	100000	2500	1.000
27	18	high	1	0.2	50000	20000	0.497
28	24	high	3	0.4	50000	20000	0.396
29	28	high	3	0.2	100000	20000	0.436
30	31	low	3	0.4	100000	20000	0.686
31	2	high	1	0.2	50000	2500	0.716
32	16	high	3	0.4	100000	2500	0.774

After all inputs and responses needed are completed, DOE software will evaluate all significant parameters and interactions. The ANOVA Table and regression information of significant parameters and significant interactions can be shown in table 4.6-4.7

Table 4.6 ANOVA Table of reduced model (all significant parameters and interactions)

ANOVA Table					
Source of Variation	Degrees of Freedom	Sum of Squares [Partial]	Mean Squares [Partial]	F Ratio	P Value
Model	12	0.985	0.0821	342.7285	1.50E-19
Main Effects	5	0.8765	0.1753	731.9072	4.95E-21
2-Way Interaction	6	0.0999	0.0167	69.5406	6.56E-12
3-Way Interaction	1	0.0086	0.0086	35.9629	9.04E-06
Residual	19	0.0046	0.0002		
Lack of Fit	19	0.0046	0.0002		
Total	31	0.9896			

S = 0.0155
R-sq = 99.54%
R-sq(adj) = 99.25%

Table 4.7 Regression information of significant factors and interactions

Regression Information							
Term	Effect	Coefficient	Standard Error	Low CI	High CI	T Value	P Value
Intercept		0.6781	0.0027	0.6734	0.6828	247.8606	0
A:Purchase cost/unit	-0.1228	-0.0614	0.0027	-0.0661	-0.0567	-22.4456	3.89E-15
B:Production cost/unit	-0.0571	-0.0285	0.0027	-0.0333	-0.0238	-10.4289	2.66E-09
C:Disassembly cost/unit	-0.0526	-0.0263	0.0027	-0.031	-0.0216	-9.6065	1.00E-08
D:Demand Volume	0.1769	0.0885	0.0027	0.0837	0.0932	32.3376	0
E:Return Volume	-0.2391	-0.1195	0.0027	-0.1243	-0.1148	-43.6917	0
AB	-0.0571	-0.0285	0.0027	-0.0333	-0.0238	-10.4289	2.66E-09
AD	-0.0301	-0.015	0.0027	-0.0198	-0.0103	-5.4943	2.67E-05
AE	-0.0546	-0.0273	0.0027	-0.032	-0.0226	-9.972	5.51E-09
CD	-0.0216	-0.0108	0.0027	-0.0155	-0.0061	-3.9408	0.0009
CE	0.0189	0.0095	0.0027	0.0047	0.0142	3.4611	0.0026
DE	-0.0673	-0.0337	0.0027	-0.0384	-0.0289	-12.3022	1.70E-10
ADE	-0.0328	-0.0164	0.0027	-0.0211	-0.0117	-5.9969	9.04E-06

From table 4.6 – 4.7, five factors, six 2-way interactions, and one 3-way interaction are found as having a significant effect on the response. These factors are purchase cost (A), production cost (B), disassembly cost (C), demand volume (D), and return volume (E). The six 2-way interactions are AB, AD, AE, CD, CE, and DE. A 3-way interaction is ADE. The regression table provides very useful information. It helps analysts to better understand the effects of each significant parameter and interactions. For example, if production cost is varied from high ($3/unit) to low ($1/unit) the efficiency of the CLSC will be increased by an average 11.42% (effect of B+AB) if the rest of parameters remain the same. In this case study, the efficiency of the CLSC model can be predicted by a linear regression model (no transformation needed) from the data in the regression table. The predicted model is:

$$\begin{aligned}\text{Efficiency} = {} & 0.678 - (0.0614*A) - (0.0285*B) - (0.0263*C) + (0.0885*D) \\ & - (0.1195*E) - (0.0285*AB) - (0.015*AD) - (0.0273*AE) - (0.0108*CD) \\ & + (0.0095*CE) - (0.0337*DE) - (0.0164*ADE)\end{aligned}$$

Where all of the variables in this regression model are ranged between -1 (low) and +1 (high)

The model that uses the real data can be obtained by interpolation which is:

$$\text{Efficiency} = 0.512 + (0.0125*A) - (0.0285*B) - (0.0611*C) + (6.5334E\text{-}6*D) - (5.3679E\text{-}6*E) - (0.0285*AB) + (2.4250E\text{-}7*AD) + (2.5071E\text{-}6*AE) - (4.3125E\text{-}6*CD) + (1.0821E\text{-}5*CE) - (1.5386E\text{-}10*DE) - (7.5E\text{-}11*ADE)$$

Both models will provide the same results but the second model can put the real data in directly. The predicted model is very useful in improving the efficiency of the CLSC by just varying the setup parameters. Figure 4.3 shows the comparison between predicted data and actual value.

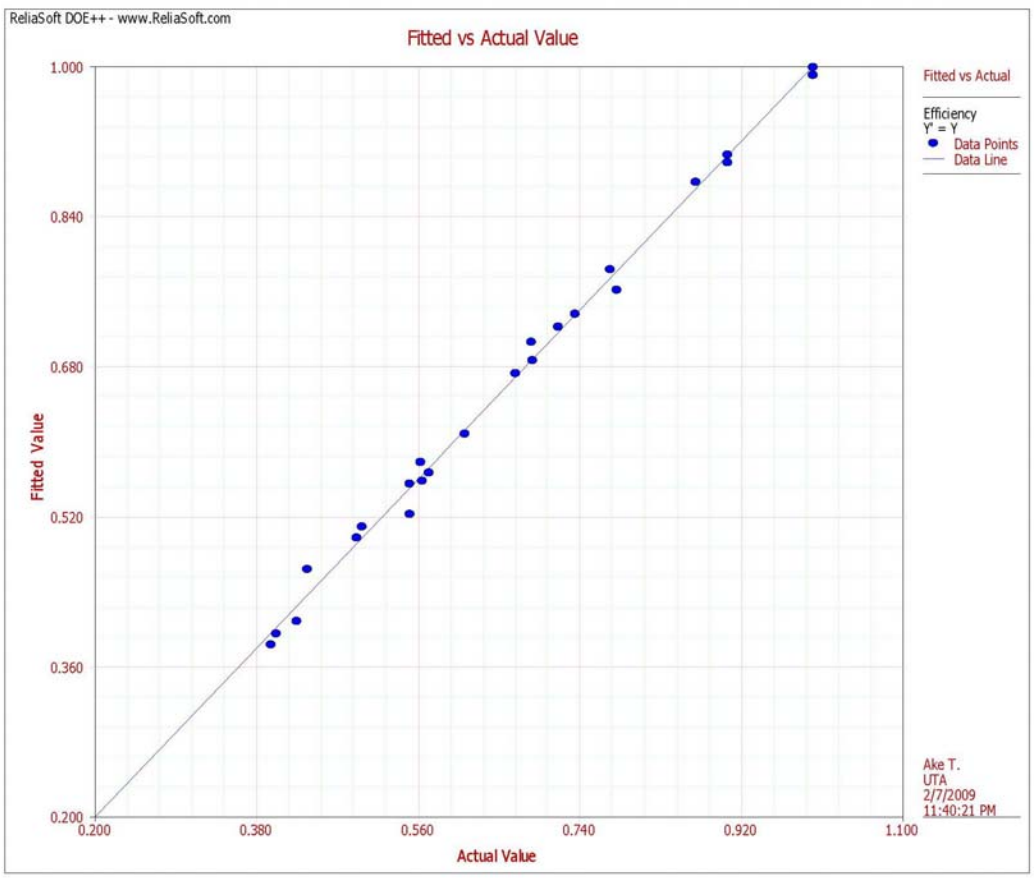

Fig 4.3 Fitted values versus actual values

From figure 4.3, the predicted model fits the actual values from the experiment very well.

4.2.2 Case Study 2- Complex Scenarios

In case study 1, there is only one Supplier, one Manufacturing Plant, one Distribution Center/Warehouse, and one Recovery Facility. In case study 2, more components will be added to the model to provide an insight of how to apply the same methodology to analyze in case the CLSC system is more complicated. The manufacturing process will be the same for this case study but the number of Manufacturing Plants, Distribution Centers/Warehouses will be increased. As well, operation costs, transportation costs, and production capacity among Plants are different. In this case study, there are three Manufacturing Plants, three Distribution Centers/Warehouses, and a Recovery Facility. Table 4.8 shows costs and production capacity of three Manufacturing Plants specified in this case study.

Table 4.8 Costs and production capacity of Manufacturing Plants

	Plant1	Plant2	Plant3
Purchase cost	Low	Medium	High
Production cost	High	Medium	Low
Production Capacity	Medium	Low	High
Transportation cost from Plant to Warehouses	High	Low	Medium

The other parameters are similar to the parameters specified in case study 1. The details of specified parameters of this case study are in Appendix B. The design parameters in this study are still divided into two levels: low and high. The steps to do this case study are as same as case study 1 following the flow chart in figure 3.4. The first step is to design parameters. The chosen parameters are similar to parameters in case study 1 but the number is greater. The chosen parameters for the screening test (two levels fractional factorial design) are shown in table 4.9.

Table 4.9 Specified parameters for screening test

Name	Units	Type	Low Level	High Level
Purchase cost/unit for plant 1	$	Qualitative	low	high
Purchase cost/unit for plant 2	$	Qualitative	low	high
Purchase cost/unit for plant 3	$	Qualitative	low	high
Production cost/unit for plant 1	$	Quantitative	3	5
Production cost/unit for plant 2	$	Quantitative	2	4
Production cost/unit for plant 3	$	Quantitative	1	3
Disassembly cost/unit	$	Quantitative	0.2	0.4
Demand Volume	unit	Quantitative	50000	200000
Return Volume	unit	Quantitative	2500	20000
Transportation cost/unit from plant 1 to warehouses	$	Quantitative	0.075	0.125
Transportation cost/unit from plant 2 to warehouses	$	Quantitative	0.025	0.075
Transportation cost/unit from plant 3 to warehouses	$	Quantitative	0.05	0.1

Parameters are divided into two types: qualitative and quantitative. Normally, the purchase cost is quantitative but in this model purchase cost/unit relates to many materials (same as case study 1). It is more convenient to categorize the type of purchase cost to a qualitative type (low and high). When the purchase cost/unit is specified low, it means all the purchase costs per unit of all materials are low. In the same manner, when it mentions high, all of the purchase costs per unit are high. For the simulation model (model 3.1), the purchase cost/unit still uses the quantitative value. The parameters in table 4.9 will be put in the statistical software (DOE++) to generate the number of experiments for the screening test by applying the 2 level fractional factorial designs technique. In this case, there are twelve factors. The screening test with resolution IV will be used to do the test and options of fractions are $1/2^5$, $1/2^6$, and $1/2^7$. Fraction $1/2^6$ is used to reduce the number of experiments (more number of experiments). The total number of experiments will be equal to $2^{12} * (1/2^6)$ or 64 experiments. The parameters for each experiment are shown in table 4.10 when each run order represents each experiment. The parameters of each experiment will be used as inputs in the simulation model in chapter 3 to get the set of outputs for each experiment.

Table 4.10 Parameters for each experiment for screening test for case study 2

Run Order	Standard Order	Purchase cost/unit ($), plant 1	Purchase cost/unit ($), plant 2	Purchase cost/unit ($), plant 3	Production cost/unit ($), plant 1	Production cost/unit ($), plant 2	Production cost/unit ($), plant 3	Disassembly cost/unit ($)	Demand Volume (unit)	Return Volume (unit)	Transportation cost/unit from plant 1 to WH ($)	Transportation cost/unit from plant 2 to WH ($)	Transportation cost/unit from plant 3 to WH ($)
1	58	high	low	low	5	4	3	0.4	50000	2500	0.075	0.025	0.1
2	16	high	high	high	5	2	1	0.4	200000	2500	0.075	0.075	0.1
3	31	low	high	high	5	4	1	0.2	50000	2500	0.125	0.075	0.05
4	50	high	low	low	3	4	3	0.4	200000	20000	0.125	0.025	0.05
5	2	high	low	low	3	2	1	0.4	200000	2500	0.075	0.025	0.05
6	26	high	low	low	5	4	1	0.4	50000	2500	0.125	0.075	0.05
7	38	high	low	high	3	2	3	0.2	200000	20000	0.075	0.075	0.05
8	51	low	high	low	3	4	3	0.4	200000	2500	0.075	0.025	0.1
9	6	high	low	high	3	2	1	0.2	200000	20000	0.125	0.025	0.1
10	29	low	low	high	5	4	1	0.4	200000	2500	0.125	0.025	0.1
11	10	high	low	low	5	2	1	0.4	50000	20000	0.125	0.025	0.1
12	34	high	low	low	3	2	3	0.4	200000	2500	0.125	0.075	0.1
13	28	high	high	low	5	4	1	0.2	200000	2500	0.125	0.025	0.1
14	15	low	high	high	5	2	1	0.2	50000	20000	0.125	0.025	0.1
15	27	low	high	low	5	4	1	0.4	50000	20000	0.075	0.075	0.1
16	25	low	low	low	5	4	1	0.2	200000	20000	0.075	0.025	0.05
17	14	high	low	high	5	2	1	0.2	50000	2500	0.075	0.025	0.05
18	3	low	high	low	3	2	1	0.4	200000	20000	0.125	0.025	0.1
19	62	high	low	high	5	4	3	0.2	50000	20000	0.125	0.025	0.05
20	17	low	low	low	3	4	1	0.2	50000	2500	0.125	0.025	0.1
21	9	low	low	low	5	2	1	0.2	200000	2500	0.075	0.075	0.1
22	35	low	high	low	3	2	3	0.4	200000	20000	0.075	0.075	0.05
23	4	high	high	low	3	2	1	0.2	50000	2500	0.075	0.075	0.1
24	43	low	high	low	5	2	3	0.4	50000	2500	0.125	0.075	0.1
25	19	low	high	low	3	4	1	0.4	200000	2500	0.125	0.075	0.05
26	21	low	low	high	3	4	1	0.4	50000	20000	0.075	0.025	0.05
27	11	low	high	low	5	2	1	0.4	50000	2500	0.075	0.025	0.05
28	57	low	low	low	5	4	3	0.2	200000	20000	0.125	0.075	0.1
29	20	high	high	low	3	4	1	0.2	50000	20000	0.075	0.025	0.05
30	59	low	high	low	5	4	3	0.4	50000	20000	0.125	0.025	0.05
31	8	high	high	high	3	2	1	0.4	50000	20000	0.125	0.075	0.05
32	1	low	low	low	3	2	1	0.2	50000	20000	0.125	0.075	0.05
33	52	high	high	low	3	4	3	0.2	50000	20000	0.125	0.075	0.1
34	24	high	high	high	3	4	1	0.4	50000	2500	0.125	0.025	0.1
35	45	low	low	high	5	2	3	0.4	200000	20000	0.075	0.025	0.1
36	44	high	high	low	5	2	3	0.2	200000	20000	0.075	0.025	0.1
37	32	high	high	high	5	4	1	0.4	200000	20000	0.075	0.025	0.05
38	13	low	low	high	5	2	1	0.4	200000	20000	0.125	0.075	0.05
39	5	low	low	high	3	2	1	0.4	50000	2500	0.075	0.075	0.1
40	55	low	high	high	3	4	3	0.2	200000	20000	0.125	0.025	0.05
41	60	high	high	low	5	4	3	0.2	200000	2500	0.075	0.075	0.05
42	40	high	high	high	3	2	3	0.4	50000	20000	0.075	0.025	0.1
43	18	high	low	low	3	4	1	0.4	200000	20000	0.075	0.075	0.1
44	41	low	low	low	5	2	3	0.2	200000	2500	0.125	0.025	0.05
45	37	low	low	high	3	2	3	0.4	50000	2500	0.125	0.025	0.05
46	22	high	low	high	3	4	1	0.2	200000	2500	0.125	0.075	0.05
47	12	high	high	low	5	2	1	0.2	200000	20000	0.125	0.075	0.05
48	47	low	high	high	5	2	3	0.2	50000	20000	0.075	0.075	0.05
49	63	low	high	high	5	4	3	0.2	50000	2500	0.075	0.025	0.1
50	53	low	low	high	3	4	3	0.4	50000	20000	0.125	0.075	0.1
51	46	high	low	high	5	2	3	0.2	50000	2500	0.125	0.075	0.1
52	23	low	high	high	3	4	1	0.2	200000	20000	0.075	0.075	0.1
53	33	low	low	low	3	2	3	0.2	50000	20000	0.075	0.025	0.1
54	61	low	low	high	5	4	3	0.4	200000	2500	0.075	0.075	0.05
55	49	low	low	low	3	4	3	0.2	50000	2500	0.075	0.075	0.05
56	30	high	low	high	5	4	1	0.2	50000	20000	0.075	0.075	0.1
57	7	low	high	high	3	2	1	0.2	200000	2500	0.075	0.025	0.05
58	39	low	high	high	3	2	3	0.2	200000	2500	0.125	0.075	0.1
59	56	high	high	high	3	4	3	0.4	50000	2500	0.075	0.075	0.05
60	48	high	high	high	5	2	3	0.4	200000	2500	0.125	0.025	0.05
61	42	high	low	low	5	2	3	0.4	50000	20000	0.075	0.075	0.05
62	36	high	high	low	3	2	3	0.2	50000	2500	0.125	0.025	0.05
63	54	high	low	high	3	4	3	0.2	200000	2500	0.075	0.025	0.1
64	64	high	high	high	5	4	3	0.4	200000	20000	0.125	0.075	0.1

Table 4.11 Parameters and a response for each experiment for screening test

Run Order	Standard Order	Purchase cost/unit ($), plant 1	Purchase cost/unit ($), plant 2	Purchase cost/unit ($), plant 3	Production cost/unit ($), plant 1	Production cost/unit ($), plant 2	Production cost/unit ($), plant 3	Disassembly cost/unit ($)	Demand Volume (unit)	Return Volume (unit)	Transportation cost/unit from plant 1 to WH ($)	Transportation cost/unit from plant 2 to WH ($)	Transportation cost/unit from plant 3 to WH ($)	Efficiency
1	58	high	low	low	5	4	3	0.4	50000	2500	0.075	0.025	0.1	0.526
2	16	high	high	high	5	2	1	0.4	200000	2500	0.075	0.075	0.1	0.885
3	31	low	high	high	5	4	1	0.2	50000	2500	0.125	0.075	0.05	0.608
4	50	high	low	low	3	4	3	0.4	200000	20000	0.125	0.025	0.05	0.491
5	2	high	low	low	3	2	1	0.4	200000	2500	0.075	0.025	0.05	0.906
6	26	high	low	low	5	4	1	0.4	50000	2500	0.125	0.075	0.05	0.533
7	38	high	low	high	3	2	3	0.2	200000	20000	0.075	0.075	0.05	0.485
8	51	low	high	low	3	4	3	0.4	200000	2500	0.075	0.025	0.1	0.892
9	6	high	low	high	3	2	1	0.2	200000	20000	0.125	0.025	0.1	0.500
10	29	low	low	high	5	4	1	0.4	200000	2500	0.125	0.025	0.1	0.858
11	10	high	low	low	5	2	1	0.4	50000	20000	0.125	0.025	0.1	0.464
12	34	high	low	low	3	2	3	0.4	200000	2500	0.125	0.075	0.1	0.846
13	28	high	high	low	5	4	1	0.2	200000	2500	0.125	0.025	0.1	0.949
14	15	low	high	high	5	2	1	0.2	50000	20000	0.125	0.025	0.1	0.478
15	27	low	high	low	5	4	1	0.4	50000	20000	0.075	0.075	0.1	0.451
16	25	low	low	low	5	4	1	0.2	200000	20000	0.075	0.025	0.05	0.541
17	14	high	low	high	5	2	1	0.2	50000	2500	0.075	0.025	0.05	0.550
18	3	low	high	low	3	2	1	0.4	200000	20000	0.125	0.025	0.1	0.688
19	62	high	low	high	5	4	3	0.2	50000	20000	0.125	0.025	0.05	0.435
20	17	low	low	low	3	4	1	0.2	50000	2500	0.125	0.025	0.1	0.813
21	9	low	low	low	5	2	1	0.2	200000	2500	0.075	0.075	0.1	0.999
22	35	low	high	low	3	2	3	0.4	200000	20000	0.075	0.075	0.05	0.542
23	4	high	high	low	3	2	1	0.2	50000	2500	0.075	0.075	0.1	0.556
24	43	low	high	low	5	2	3	0.4	50000	2500	0.125	0.075	0.1	0.630
25	19	low	high	low	3	4	1	0.4	200000	2500	0.125	0.075	0.05	0.906
26	21	low	low	high	3	4	1	0.4	50000	20000	0.075	0.025	0.05	0.518
27	11	low	high	low	5	2	1	0.4	50000	2500	0.075	0.025	0.05	0.537
28	57	low	low	low	5	4	3	0.2	200000	20000	0.125	0.075	0.1	0.584
29	20	high	high	low	3	4	1	0.2	50000	20000	0.075	0.025	0.05	0.453
30	59	low	high	low	5	4	3	0.4	50000	20000	0.125	0.025	0.05	0.498
31	8	high	high	high	3	2	1	0.4	50000	20000	0.125	0.075	0.05	0.403
32	1	low	low	low	3	2	1	0.2	50000	20000	0.125	0.075	0.05	0.758
33	52	high	high	low	3	4	3	0.2	50000	20000	0.125	0.075	0.1	0.414
34	24	high	high	high	3	4	1	0.4	50000	2500	0.125	0.025	0.1	0.482
35	45	low	low	high	5	2	3	0.4	200000	20000	0.075	0.025	0.1	0.509
36	44	high	high	low	5	2	3	0.2	200000	20000	0.075	0.025	0.1	0.485
37	32	high	high	high	5	4	1	0.4	200000	20000	0.075	0.025	0.05	0.462
38	13	low	low	high	5	2	1	0.4	200000	20000	0.125	0.075	0.05	0.515
39	5	low	low	high	3	2	1	0.4	50000	2500	0.075	0.075	0.1	0.637
40	55	low	high	high	3	4	3	0.2	200000	20000	0.125	0.025	0.05	0.494
41	60	high	high	low	5	4	3	0.2	200000	2500	0.075	0.075	0.05	0.919
42	40	high	high	high	3	2	3	0.4	50000	20000	0.075	0.025	0.1	0.400
43	18	high	low	low	3	4	1	0.4	200000	20000	0.075	0.075	0.1	0.527
44	41	low	low	low	5	2	3	0.2	200000	2500	0.125	0.025	0.05	1.000
45	37	low	low	high	3	2	3	0.4	50000	2500	0.125	0.025	0.05	0.637
46	22	high	low	high	3	4	1	0.2	200000	2500	0.125	0.075	0.05	0.921
47	12	high	high	low	5	2	1	0.2	200000	20000	0.125	0.075	0.05	0.539
48	47	low	high	high	5	2	3	0.2	50000	20000	0.075	0.075	0.05	0.480
49	63	low	high	high	5	4	3	0.2	50000	2500	0.075	0.025	0.1	0.612
50	53	low	low	high	3	4	3	0.4	50000	20000	0.125	0.075	0.1	0.515
51	46	high	low	high	5	2	3	0.2	50000	2500	0.125	0.075	0.1	0.552
52	23	low	high	high	3	4	1	0.2	200000	20000	0.075	0.075	0.1	0.517
53	33	low	low	low	3	2	3	0.2	50000	20000	0.075	0.025	0.1	0.758
54	61	low	low	high	5	4	3	0.4	200000	2500	0.075	0.075	0.05	0.853
55	49	low	low	low	3	4	3	0.2	50000	2500	0.075	0.075	0.05	0.813
56	30	high	low	high	5	4	1	0.2	50000	20000	0.075	0.075	0.1	0.430
57	7	low	high	high	3	2	1	0.2	200000	2500	0.075	0.025	0.05	0.953
58	39	low	high	high	3	2	3	0.2	200000	2500	0.125	0.075	0.1	0.933
59	56	high	high	high	3	4	3	0.4	50000	2500	0.075	0.075	0.05	0.481
60	48	high	high	high	5	2	3	0.4	200000	2500	0.125	0.025	0.05	0.795
61	42	high	low	low	5	2	3	0.4	50000	20000	0.075	0.075	0.05	0.461
62	36	high	high	low	3	2	3	0.2	50000	2500	0.125	0.025	0.05	0.516
63	54	high	low	high	3	4	3	0.2	200000	2500	0.075	0.025	0.1	0.908
64	64	high	high	high	5	4	3	0.4	200000	20000	0.125	0.075	0.1	0.437

In the next step, inputs and outputs of each experiment will be put in the DEA model in chapter 3 (model 3.1) to be evaluated for the relative efficiency for each experiment. Efficiency of each experiment will be considered as a response for each experiment. Statistical software will evaluate significant parameters from setup parameters and responses of all experiments. Table 4.11 illustrates the setup parameters and a response (efficiency) of each experiment. After running the program, nine of twelve factors were found to have significant effects to the response in the screening test. Nine significant parameters are purchase cost/unit for plant 1, purchase cost/unit for plant 2, purchase cost/unit for plant 3, production cost/unit for plant 1, production cost/unit for plant 2, production cost/unit for plant 3, disassembly cost/unit, demand volume, and return volume. There are some significant interactions among these factors, but in this step, only significant factors will be chosen to test because all the interactions among these factors will be thoroughly evaluated again in the next step.

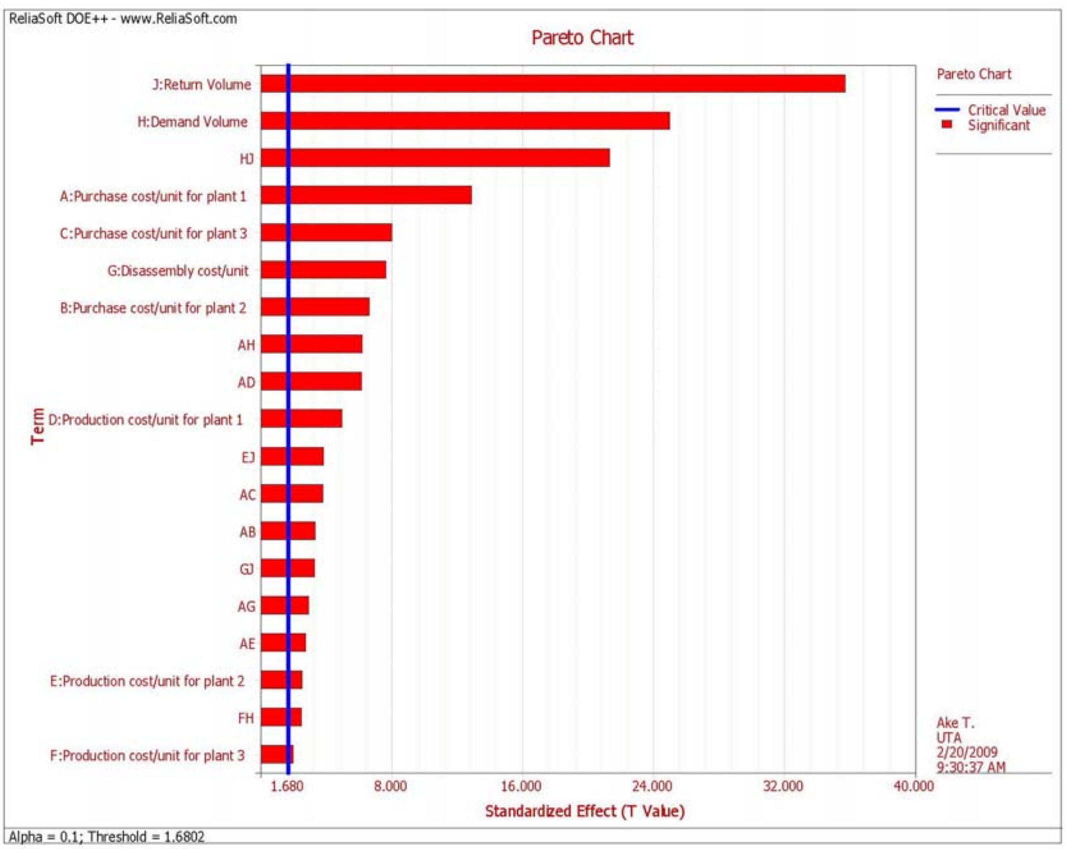

Fig 4.4 Pareto Chart of significant factors and significant interactions

Figure 4.4 shows the Pareto chart of only significant factors and interactions obtained from the screening test in order of importance. Normally, all significant parameters should be analyzed again with the 2 level full factorial designs but in this case study there are too many significant parameters (nine parameters). If we did the 2 level full factorial test, the number of experiments would be equal to 2^9 or 512 experiments which consumes a lot of time to do and it is not practical in real life to do too many experiments (waste both time and money). In this case, 2 level fractional factorial design with higher resolution (V or above) can be employed again to thoroughly evaluate the model. Even though this method is not as good as 2 level full factorial designs, it saves a lot of time and the results are still reasonable to use. Therefore, all nine significant parameters will be analyzed again with 2 level fractional factorial design using resolution VI with $1/2^2$ fraction. For nine factors, 128 experiments ($2^9 * 1/2^2$) will be conducted. Setup parameters for these experiments are shown in table 4.12.

Table 4.12 Setup parameters for 2 level fractional factorial test resolution VI

Name	Units	Type	Low Level	High Level
Purchase cost/unit for plant 1	$	Qualitative	low	high
Purchase cost/unit for plant 2	$	Qualitative	low	high
Purchase cost/unit for plant 3	$	Qualitative	low	high
Production cost/unit for plant 1	$	Quantitative	3	5
Production cost/unit for plant 2	$	Quantitative	2	4
Production cost/unit for plant 3	$	Quantitative	1	3
Disassembly cost/unit	$	Quantitative	0.2	0.4
Demand Volume	unit	Quantitative	50000	200000
Return Volume	unit	Quantitative	2500	20000

The process of doing experiments is similar to the screening test process. All of the non-significant parameters from the screening test earlier will be averaged and used in the simulation model to calculate the outputs. Sets of inputs and outputs of each experiment will be put in the DEA model to obtain relative efficiency. Parameters and responses (relative efficiency) are shown in table 4.13

Table 4.13 Parameters and responses of each experiment

Run Order	Standard Order	Purchase cost/unit ($), plant 1	Purchase cost/unit ($), plant 2	Purchase cost/unit ($), plant 3	Production cost/unit ($), plant 1	Production cost/unit ($), plant 2	Production cost/unit ($), plant 3	Disassembly cost/unit ($)	Demand Volume (unit)	Return Volume (unit)	Efficiency
1	84	high	high	low	3	4	1	0.4	200000	20000	0.525
2	93	low	low	high	5	4	1	0.4	200000	2500	0.853
3	113	low	low	low	3	4	3	0.4	200000	2500	0.906
4	57	low	low	low	5	4	3	0.2	50000	20000	0.538
5	97	low	low	low	3	2	3	0.4	50000	2500	0.719
6	5	low	low	high	3	2	1	0.2	200000	20000	0.538
7	125	low	low	high	5	4	3	0.4	200000	20000	0.499
8	41	low	low	low	5	2	3	0.2	200000	20000	0.584
9	36	high	high	low	3	2	3	0.2	50000	20000	0.410
10	121	low	low	low	5	4	3	0.4	50000	2500	0.716
11	127	low	high	high	5	4	3	0.4	50000	2500	0.588
12	20	high	high	low	3	4	1	0.2	200000	2500	0.971
13	59	low	high	low	5	4	3	0.2	200000	2500	0.970
14	4	high	high	low	3	2	1	0.2	50000	2500	0.558
15	73	low	low	low	5	2	1	0.4	200000	20000	0.553
16	111	low	high	high	5	2	3	0.4	200000	2500	0.825
17	21	low	low	high	3	4	1	0.2	50000	20000	0.526
18	103	low	high	high	3	2	3	0.4	50000	2500	0.588
19	126	high	low	high	5	4	3	0.4	50000	2500	0.511
20	64	high	high	high	5	4	3	0.2	200000	2500	0.880
21	88	high	high	high	3	4	1	0.4	50000	2500	0.481
22	96	high	high	high	5	4	1	0.4	200000	2500	0.823
23	56	high	high	high	3	4	3	0.2	50000	2500	0.503
24	69	low	low	high	3	2	1	0.4	200000	2500	0.877
25	77	low	low	high	5	2	1	0.4	50000	2500	0.544
26	58	high	low	low	5	4	3	0.2	200000	2500	0.931
27	53	low	low	high	3	4	3	0.2	50000	2500	0.686
28	87	low	high	high	3	4	1	0.4	200000	20000	0.505
29	13	low	low	high	5	2	1	0.2	50000	20000	0.466
30	6	high	low	high	3	2	1	0.2	50000	2500	0.552
31	108	high	high	low	5	2	3	0.4	200000	2500	0.826
32	90	high	low	low	5	4	1	0.4	200000	2500	0.876
33	105	low	low	low	5	2	3	0.4	200000	2500	0.906
34	89	low	low	low	5	4	1	0.4	50000	20000	0.443
35	123	low	high	low	5	4	3	0.4	200000	20000	0.687
36	15	low	high	high	5	2	1	0.2	200000	2500	0.923
37	70	high	low	high	3	2	1	0.4	50000	20000	0.446
38	128	high	high	high	5	4	3	0.4	200000	20000	0.434
39	22	high	low	high	3	4	1	0.2	200000	2500	0.920
40	44	high	high	low	5	2	3	0.2	200000	20000	0.484
41	66	high	low	low	3	2	1	0.4	200000	2500	0.906
42	32	high	high	high	5	4	1	0.2	200000	20000	0.475
43	106	high	low	low	5	2	3	0.4	50000	20000	0.457
44	47	low	high	high	5	2	3	0.2	200000	20000	0.486
45	43	low	high	low	5	2	3	0.2	50000	2500	0.671
46	29	low	low	high	5	4	1	0.2	200000	20000	0.516
47	63	low	high	high	5	4	3	0.2	50000	20000	0.499
48	102	high	low	high	3	2	3	0.4	50000	2500	0.527
49	45	low	low	high	5	2	3	0.2	50000	2500	0.567
50	118	high	low	high	3	4	3	0.4	200000	2500	0.813
51	8	high	high	high	3	2	1	0.2	200000	20000	0.485
52	109	low	low	high	5	2	3	0.4	50000	20000	0.467
53	27	low	high	low	5	4	1	0.2	200000	20000	0.535
54	33	low	low	low	3	2	3	0.2	50000	20000	0.758
55	42	high	low	low	5	2	3	0.2	50000	2500	0.561
56	100	high	high	low	3	2	3	0.4	50000	2500	0.489
57	119	low	high	high	3	4	3	0.4	200000	2500	0.829
58	10	high	low	low	5	2	1	0.2	50000	20000	0.463
59	91	low	high	low	5	4	1	0.4	200000	2500	0.878
60	3	low	high	low	3	2	1	0.2	200000	20000	0.578
61	65	low	low	low	3	2	1	0.4	50000	20000	0.634
62	46	high	low	high	5	2	3	0.2	200000	20000	0.465
63	76	high	high	low	5	2	1	0.4	200000	20000	0.529
64	35	low	high	low	3	2	3	0.2	200000	2500	0.980

Table 4.13 - continued

Run Order	Standard Order	Purchase cost/unit ($), plant 1	Purchase cost/unit ($), plant 2	Purchase cost/unit ($), plant 3	Production cost/unit ($), plant 1	Production cost/unit ($), plant 2	Production cost/unit ($), plant 3	Disassembly cost/unit ($)	Demand Volume (unit)	Return Volume (unit)	Efficiency
65	60	high	high	low	5	4	3	0.2	50000	20000	0.411
66	37	low	low	high	3	2	3	0.2	200000	2500	0.956
67	120	high	high	high	3	4	3	0.4	50000	20000	0.396
68	52	high	high	low	3	4	3	0.2	200000	20000	0.485
69	116	high	high	low	3	4	3	0.4	200000	2500	0.827
70	40	high	high	high	3	2	3	0.2	200000	2500	0.906
71	17	low	low	low	3	4	1	0.2	200000	2500	1.000
72	54	high	low	high	3	4	3	0.2	200000	20000	0.471
73	110	high	low	high	5	2	3	0.4	200000	2500	0.805
74	49	low	low	low	3	4	3	0.2	200000	20000	0.599
75	80	high	high	high	5	2	1	0.4	50000	2500	0.483
76	51	low	high	low	3	4	3	0.2	50000	2500	0.686
77	67	low	high	low	3	2	1	0.4	200000	2500	0.905
78	61	low	low	high	5	4	3	0.2	200000	2500	0.941
79	81	low	low	low	3	4	1	0.4	200000	20000	0.579
80	55	low	high	high	3	4	3	0.2	200000	20000	0.490
81	11	low	high	low	5	2	1	0.2	50000	20000	0.450
82	75	low	high	low	5	2	1	0.4	50000	2500	0.536
83	114	high	low	low	3	4	3	0.4	50000	20000	0.441
84	115	low	high	low	3	4	3	0.4	50000	20000	0.513
85	38	high	low	high	3	2	3	0.2	50000	20000	0.449
86	94	high	low	high	5	4	1	0.4	50000	20000	0.423
87	79	low	high	high	5	2	1	0.4	200000	20000	0.479
88	39	low	high	high	3	2	3	0.2	50000	20000	0.505
89	18	high	low	low	3	4	1	0.2	50000	20000	0.450
90	9	low	low	low	5	2	1	0.2	200000	2500	1.000
91	7	low	high	high	3	2	1	0.2	50000	2500	0.612
92	14	high	low	high	5	2	1	0.2	200000	2500	0.985
93	48	high	high	high	5	2	3	0.2	50000	2500	0.502
94	24	high	high	high	3	4	1	0.2	50000	20000	0.403
95	98	high	low	low	3	2	3	0.4	200000	20000	0.491
96	1	low	low	low	3	2	1	0.2	50000	2500	0.812
97	83	low	high	low	3	4	1	0.4	50000	2500	0.635
98	85	low	low	high	3	4	1	0.4	50000	2500	0.640
99	74	high	low	low	5	2	1	0.4	50000	2500	0.540
100	19	low	high	low	3	4	1	0.2	50000	20000	0.519
101	92	high	high	low	5	4	1	0.4	50000	20000	0.428
102	23	low	high	high	3	4	1	0.2	200000	2500	0.950
103	104	high	high	high	3	2	3	0.4	200000	20000	0.459
104	30	high	low	high	5	4	1	0.2	50000	2500	0.532
105	72	high	high	high	3	2	1	0.4	200000	2500	0.826
106	112	high	high	high	5	2	3	0.4	50000	20000	0.388
107	107	low	high	low	5	2	3	0.4	50000	20000	0.489
108	78	high	low	high	5	2	1	0.4	200000	20000	0.527
109	28	high	high	low	5	4	1	0.2	50000	2500	0.550
110	82	high	low	low	3	4	1	0.4	50000	2500	0.536
111	86	high	low	high	3	4	1	0.4	200000	20000	0.474
112	117	low	low	high	3	4	3	0.4	50000	20000	0.513
113	26	high	low	low	5	4	1	0.2	200000	20000	0.533
114	99	low	high	low	3	2	3	0.4	200000	20000	0.535
115	95	low	high	high	5	4	1	0.4	50000	20000	0.465
116	12	high	high	low	5	2	1	0.2	200000	2500	0.986
117	124	high	high	low	5	4	3	0.4	50000	2500	0.488
118	2	high	low	low	3	2	1	0.2	200000	20000	0.567
119	25	low	low	low	5	4	1	0.2	50000	2500	0.561
120	31	low	high	high	5	4	1	0.2	50000	2500	0.608
121	34	high	low	low	3	2	3	0.2	200000	2500	0.938
122	16	high	high	high	5	2	1	0.2	50000	20000	0.405
123	71	low	high	high	3	2	1	0.4	50000	20000	0.499
124	101	low	low	high	3	2	3	0.4	200000	20000	0.515
125	50	high	low	low	3	4	3	0.2	50000	2500	0.546
126	122	high	low	low	5	4	3	0.4	200000	20000	0.485
127	62	high	low	high	5	4	3	0.2	50000	20000	0.431
128	68	high	high	low	3	2	1	0.4	50000	20000	0.431

After all inputs and responses needed are completed, DOE software will evaluate all significant parameters and interactions. The ANOVA Table and regression information of significant parameters and significant interactions can be shown in tables 4.14-4.15.

Table 4.14 ANOVA Table of reduced model

ANOVA Table					
Source of Variation	Degrees of Freedom	Sum of Squares [Partial]	Mean Squares [Partial]	F Ratio	P Value
Model	32	4.168	0.1303	233.1642	4.67E-77
Main Effects	9	3.3457	0.3717	665.4542	1.10E-81
2-Way Interaction	13	0.7616	0.0586	104.873	2.63E-50
3-Way Interaction	10	0.0608	0.0061	10.8818	4.07E-12
Residual	95	0.0531	0.0006		
Lack of Fit	95	0.0531	0.0006		
Total	127	4.2211			

S = 0.0236
R-sq = 98.74%
R-sq(adj) = 98.32%

Table 4.15 Regression information of significant factors and interactions

Regression Information							
Term	Effect	Coefficient	Standard Error	Low CI	High CI	T Value	P Value
Intercept		0.6182	0.0021	0.6148	0.6217	295.9393	0
A:Purchase cost/unit for plant 1	-0.0708	-0.0354	0.0021	-0.0389	-0.0319	-16.945	0
B:Purchase cost/unit for plant 2	-0.0281	-0.014	0.0021	-0.0175	-0.0106	-6.7179	1.35E-09
C:Purchase cost/unit for plant 3	-0.0447	-0.0223	0.0021	-0.0258	-0.0189	-10.6895	0
D:Production cost/unit for plant 1	-0.022	-0.011	0.0021	-0.0145	-0.0075	-5.259	8.91E-07
E:Production cost/unit for plant 2	-0.0075	-0.0037	0.0021	-0.0072	-0.0003	-1.7939	0.076
F:Production cost/unit for plant 3	-0.0045	-0.0022	0.0021	-0.0057	0.0012	-1.0661	0.2891
G:Disassembly cost/unit	-0.036	-0.018	0.0021	-0.0215	-0.0145	-8.6196	1.47E-13
H:Demand Volume	0.185	0.0925	0.0021	0.0891	0.096	44.2876	0
J:Return Volume	-0.2463	-0.1231	0.0021	-0.1266	-0.1197	-58.9479	0
AC	0.0153	0.0077	0.0021	0.0042	0.0111	3.6675	0.0004
AD	0.0199	0.0099	0.0021	0.0065	0.0134	4.7616	6.87E-06
AF	-0.023	-0.0115	0.0021	-0.015	-0.008	-5.5045	3.14E-07
AH	0.0311	0.0156	0.0021	0.0121	0.019	7.4531	4.20E-11
BD	0.0125	0.0063	0.0021	0.0028	0.0097	3.0035	0.0034
BE	0.0139	0.007	0.0021	0.0035	0.0104	3.3316	0.0012
BH	0.0114	0.0057	0.0021	0.0022	0.0092	2.7259	0.0076
DE	0.0123	0.0062	0.0021	0.0027	0.0096	2.9483	0.004
DH	0.018	0.009	0.0021	0.0055	0.0125	4.3044	4.07E-05
FH	-0.0165	-0.0083	0.0021	-0.0117	-0.0048	-3.9566	0.0001
GH	-0.0131	-0.0065	0.0021	-0.01	-0.0031	-3.1282	0.0023
GJ	0.0278	0.0139	0.0021	0.0104	0.0173	6.6419	1.92E-09
HJ	-0.1396	-0.0698	0.0021	-0.0733	-0.0664	-33.4223	0
ABC	-0.0101	-0.0051	0.0021	-0.0085	-0.0016	-2.4182	0.0175
ABD	-0.0145	-0.0073	0.0021	-0.0107	-0.0038	-3.4729	0.0008
ACE	-0.0108	-0.0054	0.0021	-0.0089	-0.002	-2.5953	0.011
ACF	0.0151	0.0075	0.0021	0.0041	0.011	3.6066	0.0005
ADE	-0.0123	-0.0062	0.0021	-0.0096	-0.0027	-2.9444	0.0041
ADF	-0.012	-0.006	0.0021	-0.0095	-0.0025	-2.8766	0.005
ADH	-0.0172	-0.0086	0.0021	-0.0121	-0.0051	-4.1215	8.05E-05
AHJ	-0.0105	-0.0053	0.0021	-0.0087	-0.0018	-2.5188	0.0134
CDF	-0.0112	-0.0056	0.0021	-0.0091	-0.0021	-2.6819	0.0086
DEF	0.0203	0.0102	0.0021	0.0067	0.0136	4.8681	4.48E-06

From tables 4.14-4.15, eight factors, thirteen 2-way interactions and ten 3-way interactions are found to have a significant effect on the response. These factors are purchase cost/unit for plant 1 (A), purchase cost/unit for plant 2 (B), purchase cost/unit for plant 3 (C), production cost/unit for plant 1 (D), production cost/unit for plant 2 (E), disassembly cost/unit (G), demand volume (H), and return volume (J). The thirteen 2-way interactions are AC, AD, AF, AH, BD, BE, BH, DE, DH, FH, GH, GJ, and HJ. The ten 3-way interactions are ABC, ABD, ACE, ACF, ADE, ADF, ADH, AHJ, CDF, and DEF. The regression table provides very useful information. It helps analysts to better understand the effects of each significant parameter and interactions. For instance, if disassembly cost is varied from high ($0.4/unit) to low ($0.2/unit) the efficiency of this CLSC will be increased by an average 7.59% (effect of G+GH+GJ) if the rest of parameters remain the same. In this case study, the efficiency of the CLSC model can be predicted by a linear regression model (no transformation needed) from the information in the regression table. The predicted model is:

$$\begin{aligned}\text{Efficiency} = {} & 0.6182 - (0.0354*A) - (0.014*B) - (0.0223*C) - (0.011*D) - (0.0037*E) \\ & - (0.0022*F) - (0.018*G) + (0.0925*H) - (0.1231*J) + (0.0077*AC) + \\ & (0.0099*AD) -(0.0115*AF) + (0.0156*AH) + (0.0063*BD) + (0.007*BE) + \\ & (0.0057*BH) + (0.0062*DE) + (0.009*DH) - (0.0083*FH) - (0.0065*GH) \\ & + (0.0139*GJ) - (0.0698*HJ) - (0.0051*ABC) - (0.0073*ABD) - \\ & (0.0054*ACE) + (0.0075*ACF) - (0.0062*ADE) - (0.006*ADF) - \\ & (0.0086*ADH) - (0.0053*AHJ) - (0.0056*CDF) + (0.0102*DEF)\end{aligned}$$

All of the variables in this regression model are ranged between -1 (low) and +1 (high). Even though the production cost/unit from plant 3 (F) itself is not significant from statistical results, this factor must be included in the predicted model because the interactions between this factor and other factors significantly affect the response.

The model that uses the real data can be obtained by interpolation which is:

Efficiency = 0.4695 – (0.2687*A) – (0.0695*B) – (0.0672*C) + (0.0166*D) + (0.053*E) + (0.1336*F) - (0.2496*G) + (2.4328E-6*H) – (5.5318E-6*J) + (0.0089*AC) + (0.0548*AD) + (0.0125*AF) + (7.5702E-7*AH) + (0.0063*BD) + (0.007*BE) + (7.9527E-8*BH) - (0.0142*DE) + (1.199E-7*DH) – (1.1021E-7*FH) - (8.7134E-7*GH) + (1.5858E-5*GJ) – (1.064E-10*HJ) – (0.0051*ABC) – (0.0073*ABD) – (0.0054*ACE) + (0.0075*ACF) – (0.0062*ADE) – (0.006*ADF) – (1.148E-7*ADH) – (8.0184E-12*AHJ) – (0.0056*CDF) + (0.0102*DEF)

Both models will provide the same results but the second model can put the real data in directly. The predicted model is very useful in improving the efficiency of the CLSC by just varying the setup parameters. Figure 4.5 shows the comparison between predicted data and actual value.

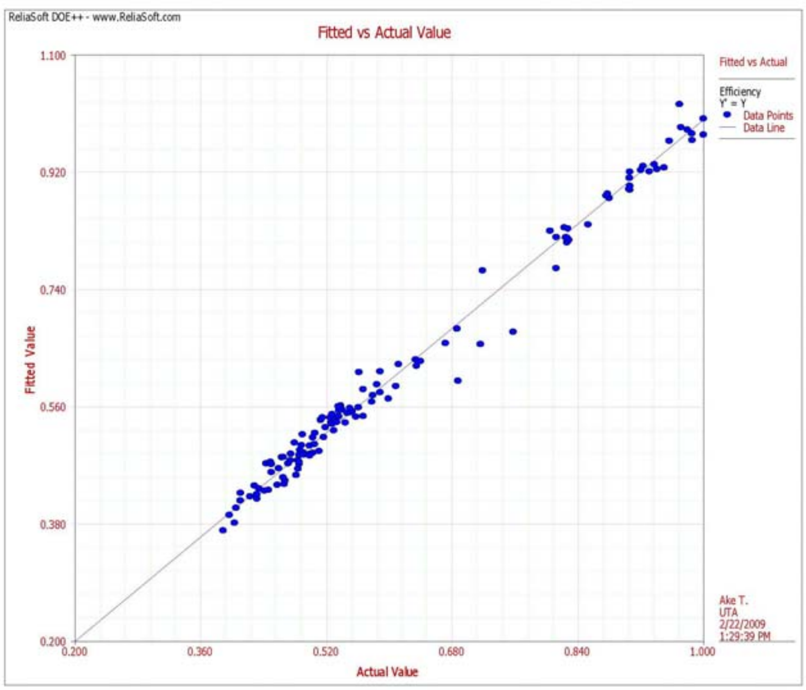

Fig 4.5 Fitted values versus actual values

From figure 4.5, the predicted model fits the actual values from the experiment very well.

CHAPTER 5

CONCLUSION AND DISCUSSION

5.1 Summary

Design of the optimized reverse supply chain model is a very important task to help companies save costs and benefit from their supply chains. In this study, reverse logistics is considered as a part of the Closed Loop Supply Chain (CLSC). CLSC combines forward and reverse flow together in the supply chain. Each component in a forward and reverse supply chain results in the efficiency of CLSC. Therefore, considering forward and reverse supply chain together as a CLSC will result in more benefits in improving efficiency of the supply chain than considering it separately. In theory, minimizing all costs will provide the highest profit, but in real life, firms cannot do that. For example, reduced production costs or material costs may result in more returns due to decreasing quality of the products. So, the companies need to smartly optimize costs or other parameters to gain the most benefit from their supply chains. This research proposes a methodology to design a good reverse supply chain by using the specified parameters. The statistical experiments with Data Envelopment Analysis (DEA) were applied to obtain an optimized model. This model is used to evaluate efficiency of the reverse logistics model and also provides the opportunity to improve efficiency by varying the significant parameters. Two case studies were provided as the examples to show how to apply this methodology.

5.1.1 Methodology

5.1.1.1 Simulation model

Since most data in the reverse supply chain are very difficult to obtain and many companies do not want to provide their reverse supply chain data due to business reasons, the data is secretly kept. Due to these reasons, there is a need to create a simulation model of CLSC to get reasonable data that can be used in this study. The created model will employ some reasonable parameters closed to real data from many sources, such as literature, the internet, as well as input data to generate the completed reverse supply chain data that are sufficient to be used to design and evaluate performance of CLSC. The CLSC model is composed of five main components which are supplier, manufacturing plant, distribution center/warehouse, retailers/customers and recovery facility. The objective of this model is to minimize the total cost of CLSC subjected to constraints at each component. The details of this simulation model are provided in chapter 3.

5.1.1.2 Data Envelopment Analysis (DEA)

DEA was first proposed by Charnes, Cooper and Rhodes in 1978. DEA is a linear programming-based technique that converts multiple input and output measures into a single comprehensive measure of productivity efficiency. DEA is used to evaluate the efficiency of decision making units (DMUs). In this study, each CLSC will be considered as a DMU. DEA can identify the "best" performing or the most efficient

DMU and measures the efficiency of other units based on the deviation from the efficient DMU. The DEA model employs input and output elements in terms of non-parametric linear programming and evaluates efficiency from the ratio between output and input. Efficiency values stay between 0 and 1. In this study, CLSC will be considered as a DMU. Each DMU consists of four main components which are Manufacturing Plants, Distribution Centers/Warehouses, Retailers/Customers and Recovery Facility. Performance of each component in each DMU needs to be considered because each component has its own strategy to reach 100% efficiency and to reach 100% for the overall system. It does not require all components to have 100% efficiency. Sometimes, there are conflicts of efficiency between components in the same DMU. The efficiency of one component may cause the inefficiency of the other components. For instance, the Recovery Facility can increase the efficiency by processing more reusable parts to plants to be remanufactured. Increasing returns may reduce the efficiency of Manufacturing Plants because the cause of return may come from unsatisfied products from customers that may reduce the demand volumes in the next period. To consider the performance of CLSC, inputs and outputs of each member need to be considered. In this case, inputs and outputs are classified in two categories, direct inputs/outputs and intermediate inputs/outputs. Direct inputs/outputs are independent variables while intermediate inputs/outputs are dependent variables. For example, intermediate outputs of Manufacturing Plants can be considered as intermediate inputs of Distribution Centers/Warehouses. Properly specified inputs/outputs for each member in the reverse supply chain are very important and will affect the performance evaluation of CLSC. The details of inputs and outputs of each component in this study are shown in chapter 3. Efficiency of each DMU is calculated from the average of the summation of efficiency of each component in each DMU subjected to the constraints of each component. The mathematical model for the DEA model for in this study is also available in chapter 3.

5.1.1.3 Design of experiment (DOE)

Design of experiment (DOE) is a statistical technique used to investigate a system. DOE creates the experimentation strategy used to test the significant parameters that result in the responses. DOE only applies a few resources but can provide a clear picture of the system in statistical aspects. It helps analysts in planning and testing the process in cost-effective ways and also helps in predicting the response from the inputs specified. In this study, 2 level factorial designs technique will be used. The 2 level factorial design is generally good enough to test all possible interactions of factors at each level and also point out parameters that significantly affect the responses. Design of experiment software (DOE++) will be used to help perform the 2 level factorial designs in this study. To do the experiment, parameters will be divided into two levels, low and high. Any interaction among significant parameters will be tested and the final model will be obtained related to significant parameters and interactions. In summary, the process to design and optimize the CLSC model in this study will follow the Flow chart in figure 5.1 (same as flow chart in chapter 3).

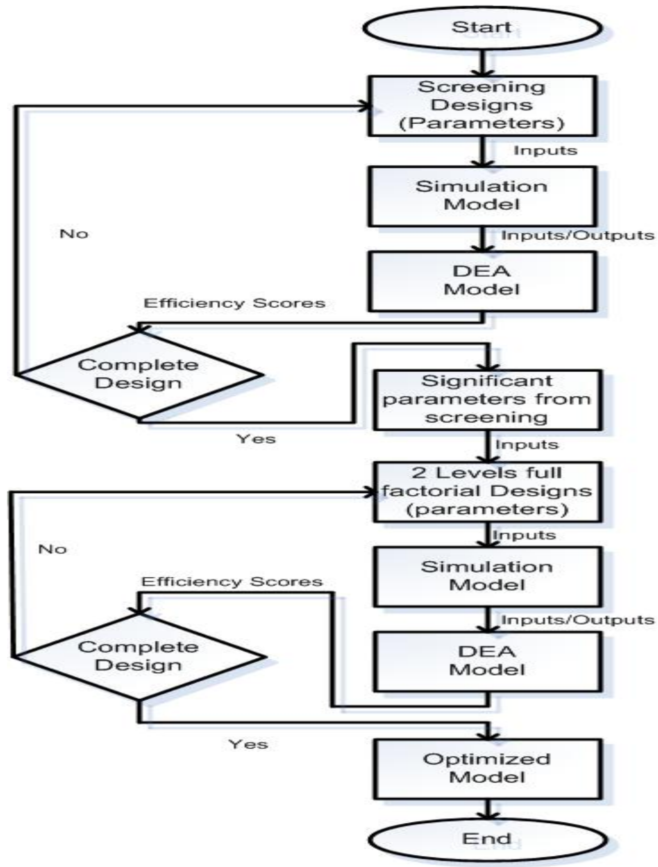

Fig 5.1 Flow chart of the methodology to design and optimize the CLSC model

5.1.2 Process of the flow chart

5.1.2.1 Design the parameters with screening test

Due to the many parameters involved in the models, to test all of them with 2 level full factorial design not only consumes a lot of time but also is costly in real-life scenarios. Screening tests are needed to help roughly eliminate non-significant parameters. In this study, fractional factorial design is used for screening the parameters. This design is not only good enough to identify the significant parameters among many, but also provides many options of a number of experiments which can be decided by the experimenter. The process of screening design starts from choosing the parameters to be tested, then putting these parameters in the simulation model to get all the optimized inputs/outputs for each scenario. In the next step, these inputs/outputs will be put into the DEA model to get the relative efficiency scores. After that these scores will be put back into the screening test models as the responses for each scenario, and then the screening test will be completed to obtain the significant parameters.

5.1.2.2 Do the experiments with significant parameters from step 1 by 2 level full factorial designs or 2 level fractional factorial designs with high resolution

After receiving significant parameters from screening designs, these parameters will be tested in 2 level full factorial design experiments or be tested with 2 level factional factorial design resolution V or above in the case that the number of significant factors from step 1 are too many. The number of experiments is equal to 2^K where K is the number of tested parameters for 2 level full factorial design or equal to 2^{K-P} for 2 level fractional factorial design where P is the small number in case of high resolution design (V and above). The process of the experiments is similar to the screening tests. The same simulation model and the same DEA model will be used to get inputs/outputs and relative efficiency scores, respectively. After obtaining all the responses (efficiency scores) for all scenarios, the experiments will be completed to get the optimized model and statistical information.

5.1.3 Case Study

Most reverse supply chains can be considered as CLSC. In this study, the example of a carpet manufacturing CLSC will be provided to illustrate how to apply this methodology. Two case studies of carpet manufacturing CLSC are proposed to show how to apply the methodology. Case study 1 consists of few parameters and the

CLSC is not complicated, while case study 2 has more components and a higher number of parameters. All the methodology applied with both case studies can be adapted and used with other CLSCs for other industries.

5.2 Discussion

Statistical experiments with DEA provide valuable information for designing CLSC. For example, the Pareto chart helps analysts understand the significant characteristics of the current system. The Pareto chart shows significant parameters in order. Figure 5.1 shows the Pareto chart of significant parameters and interactions from case study 1. Table 5.1 shows parameters and responses of each experiment from case study 1. From table 5.1, there are three experiments (highlighted, having highest demand volume, and lowest return volume) that have the highest efficiency (1). All of them have the same demand and return volume, but differences in other parameters. That can be explained by the Pareto chart. The first two parameters which have the most significant effects to the efficiency of CLSC are demand and return volume respectively. Therefore, when designing the CLSC, if we could control the most significant parameters, the efficiency could be improved substantially. The Regression table also provides the same information about the significant factors and interactions.

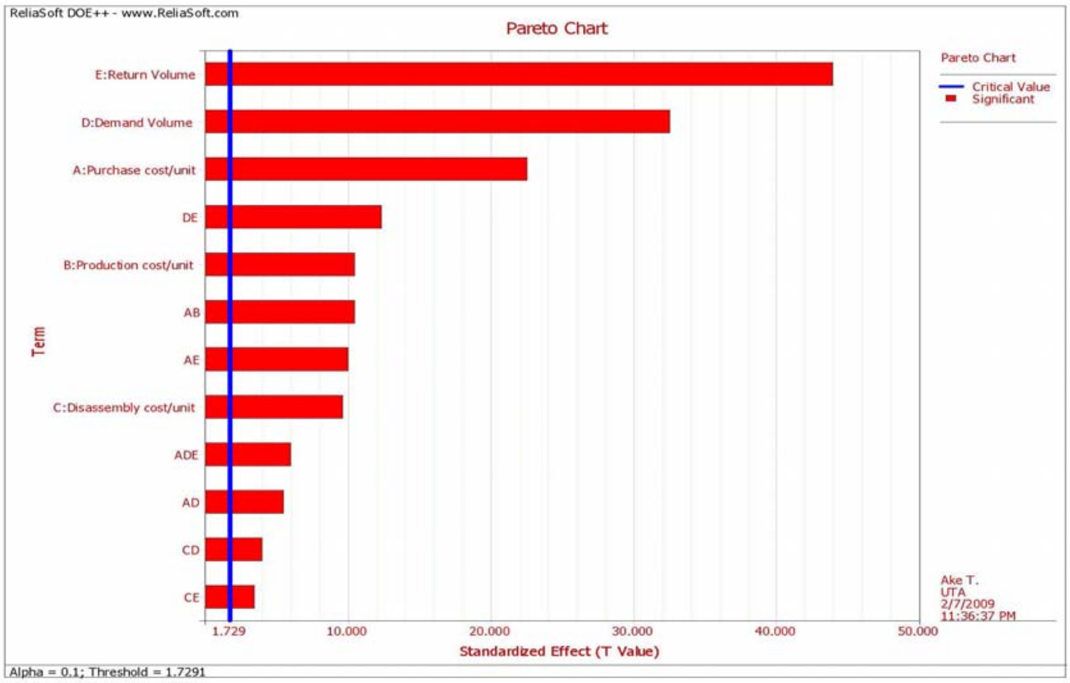

Fig 5.1 Pareto Chart of significant parameters and interactions from case study 1

Table 5.1 Parameters and responses of each experiment from case study 1

Run Order	Standard Order	Purchase cost/unit ($)	Production cost/unit ($)	Disassembly cost/unit ($)	Demand Volume (unit)	Return Volume (unit)	Efficiency
1	21	low	1	0.4	50000	20000	0.550
2	13	low	1	0.4	100000	2500	0.905
3	8	high	3	0.4	50000	2500	0.564
4	4	high	3	0.2	50000	2500	0.612
5	26	high	1	0.2	100000	20000	0.562
6	23	low	3	0.4	50000	20000	0.550
7	1	low	1	0.2	50000	2500	0.735
8	30	high	1	0.4	100000	20000	0.551
9	22	high	1	0.4	50000	20000	0.491
10	3	low	3	0.2	50000	2500	0.735
11	17	low	1	0.2	50000	20000	0.572
12	32	high	3	0.4	100000	20000	0.424
13	27	low	3	0.2	100000	20000	0.781
14	11	low	3	0.2	100000	2500	1.000
15	29	low	1	0.4	100000	20000	0.686
16	25	low	1	0.2	100000	20000	0.781
17	20	high	3	0.2	50000	20000	0.402
18	5	low	1	0.4	50000	2500	0.687
19	14	high	1	0.4	100000	2500	0.905
20	12	high	3	0.2	100000	2500	0.869
21	7	low	3	0.4	50000	2500	0.687
22	6	high	1	0.4	50000	2500	0.668
23	10	high	1	0.2	100000	2500	1.000
24	15	low	3	0.4	100000	2500	0.905
25	19	low	3	0.2	50000	20000	0.572
26	9	low	1	0.2	100000	2500	1.000
27	18	high	1	0.2	50000	20000	0.497
28	24	high	3	0.4	50000	20000	0.396
29	28	high	3	0.2	100000	20000	0.436
30	31	low	3	0.4	100000	20000	0.686
31	2	high	1	0.2	50000	2500	0.716
32	16	high	3	0.4	100000	2500	0.774

The rank of significant parameters can be observed from T-value while the coefficient column provides the predicted model. From case study 1 and 2, CLSC efficiency can be predicted by a linear regression model without transformation. After receiving the predicted model, it is much easier to improve efficiency just by varying the parameters without doing more experiments or collecting more inputs/outputs. It will be very useful for analysts or logistics experts to figure out the best way to improve the efficiency with many alternatives. Although there are many advantages from this methodology, there are some limits from using this, which are:

- The predicted model can give reliable results within the specified range of parameters. Also, the parameters can be varied within the range that is specified before doing the experiment.

- If the system is composed of many parameters (more than fifteen). The screening test by the 2 level fractional factorial design technique may not be appropriate to use. Other screening test techniques may be applied such as Plackett-Burman design, even though the results might not be as good as the 2 level fractional factorial designs provide. As well as the technique used to test significant parameters and interactions in the final step, if the significant parameters are more than seven, 2 level full factorial design may not be appropriate to use because too many experiments need to be conducted. The 2 level fractional factorial designs with resolution above V is a better option.

- For interpretation of the results from regression table, if there are significant interactions among factors. Interpretation will be more complicated.

- Analysts or people who do this methodology need to understand CLSC pretty well because they need to choose the parameters to do the experiments. If they choose too many non-significant parameters to be tested, this not only consumes a lot of time and money but also affects the quality of the model.

5.3 Contribution

This research provides many contributions to the body of knowledge in the area of supply chain design and management and also provides the opportunity to improve the current logistics operations.

The first contribution is a comprehensive methodology to simulate the CLSC model and consider all cost elements incurring in each component of CLSC. This model provides the ideal of how the CLSC operates. This model is optimized by minimizing the total cost of CLSC.

The second contribution proposes a new DEA model that can be applied to evaluate the relative efficiency of CLSC by considering inputs and outputs of each component in CLSC. This method not only provides the overall efficiency of CLSC but also shows the efficiency of each component, which is valuable information for analysts to consider in improving the system.

Finally, the third contribution of this study provides the opportunity to improve the efficiency of CLSC by using statistical experiments together with the DEA model. The logistics experts or analysts can use the optimized model to improve the efficiency of the supply chain by just varying the significant parameters in the model.

5.4 Future Research

Performance evaluation of the reverse supply chain with DEA technique and statistical experiments can help analysts, managers, or executives better understand their current operations and also provide a good opportunity for improving their current supply chain with many alternative options by doing the experiments. This methodology can be applied in many areas not only for reverse supply chain. Extending and adapting this methodology to the more complicated network supply chain would be interesting but may consume more time and effort. Another interesting future research is to use a more complicated DEA model in evaluating the relative efficiency and comparing it with this current model or employing a different statistical experiment technique.

APPENDIX A

SETUP PARAMETERS AND RESULTS FROM CASE STUDY 1

1. Case Study 1: Simple scenario

1.1 Screening test

Table A.1 illustrates setup parameters for screening test of Case Study 1.

Table A.1 Setup parameters for the experiments

Name	Units	Type	Low Level	High Level
Purchase cost/unit	$	Qualitative	low	high
Production cost/unit	$	Quantitative	1	3
Disassembly cost/unit	$	Quantitative	0.2	0.4
Demand Volume	unit	Quantitative	50000	100000
Return Volume	unit	Quantitative	2500	20000
Holding cost of product at plant	$	Quantitative	0.1	0.4
Holding Cost/unit of Materials at plant	$	Qualitative	low	high
Transportation cost/unit from plant to warehouse	$	Quantitative	0.05	0.1
Transportation cost/unit from recovery facility to plant	$	Quantitative	0.05	0.1

After putting these parameters in DOE software (DOE++), 32 experiments were generated to do a screening test (2 level fractional factorial design, Resolution IV). Table A.2 provides the parameters input of each experiment. All inputs from every experiment will be put in the simulation model (Model 3.1) in chapter 3 to get the sets of outputs. Then, all inputs and outputs of each experiment will be put in the DEA model in chapter 3 to obtain a relative efficiency score for each experiment. Table A.3 illustrates parameters and a response (relative efficiency) of each experiment for the screening test. After all input parameters and responses that need to be used are completed, DOE software can analyze the results to obtain the significant parameters from this screening test.

Table A.2 Parameters input for each designed experiment

Run Order	Standard Order	Purchase cost/unit ($)	Production cost/unit ($)	Disassembly cost/unit ($)	Demand Volume (unit)	Return Volume (unit)	Holding cost (product)/ unit @plant ($)	Holding cost (material)/ unit @plant ($)	Transportation cost/unit from plant to WH ($)	Transportation cost/unit from recovery to plant ($)
1	30	high	1	0.4	100000	20000	0.1	low	0.05	0.1
2	19	low	3	0.2	50000	20000	0.1	high	0.1	0.05
3	32	high	3	0.4	100000	20000	0.4	high	0.1	0.1
4	3	low	3	0.2	50000	2500	0.1	low	0.05	0.1
5	14	high	1	0.4	100000	2500	0.1	high	0.1	0.05
6	7	low	3	0.4	50000	2500	0.4	high	0.05	0.05
7	17	low	1	0.2	50000	20000	0.4	low	0.05	0.05
8	15	low	3	0.4	100000	2500	0.1	high	0.1	0.1
9	31	low	3	0.4	100000	20000	0.1	low	0.05	0.05
10	12	high	3	0.2	100000	2500	0.1	high	0.05	0.1
11	25	low	1	0.2	100000	20000	0.1	low	0.1	0.1
12	1	low	1	0.2	50000	2500	0.4	high	0.1	0.1
13	6	high	1	0.4	50000	2500	0.4	high	0.05	0.1
14	16	high	3	0.4	100000	2500	0.4	low	0.05	0.05
15	9	low	1	0.2	100000	2500	0.1	high	0.05	0.05
16	21	low	1	0.4	50000	20000	0.1	high	0.05	0.1
17	28	high	3	0.2	100000	20000	0.1	low	0.1	0.05
18	24	high	3	0.4	50000	20000	0.1	high	0.05	0.05
19	18	high	1	0.2	50000	20000	0.1	high	0.1	0.1
20	10	high	1	0.2	100000	2500	0.4	low	0.1	0.1
21	26	high	1	0.2	100000	20000	0.4	high	0.05	0.05
22	4	high	3	0.2	50000	2500	0.4	high	0.1	0.05
23	29	low	1	0.4	100000	20000	0.4	high	0.1	0.05
24	13	low	1	0.4	100000	2500	0.4	low	0.05	0.1
25	5	low	1	0.4	50000	2500	0.1	low	0.1	0.05
26	2	high	1	0.2	50000	2500	0.1	low	0.05	0.05
27	27	low	3	0.2	100000	20000	0.4	high	0.05	0.1
28	11	low	3	0.2	100000	2500	0.4	low	0.1	0.05
29	22	high	1	0.4	50000	20000	0.4	low	0.1	0.05
30	20	high	3	0.2	50000	20000	0.4	low	0.05	0.1
31	8	high	3	0.4	50000	2500	0.1	low	0.1	0.1
32	23	low	3	0.4	50000	20000	0.4	low	0.1	0.1

Table A.3 Parameters and a response for each experiment for screening test

Run Order	Standard Order	Purchase cost/unit ($)	Production cost/unit ($)	Disassembly cost/unit ($)	Demand Volume (unit)	Return Volume (unit)	Holding cost (product)/ unit @plant ($)	Holding cost (material)/ unit @plant ($)	Transportation cost/unit from plant to WH ($)	Transportation cost/unit from recovery to plant ($)	Efficiency
1	30	high	1	0.4	100000	20000	0.1	low	0.05	0.1	0.668
2	19	low	3	0.2	50000	20000	0.1	high	0.1	0.05	0.572
3	32	high	3	0.4	100000	20000	0.4	high	0.1	0.1	0.422
4	3	low	3	0.2	50000	2500	0.1	low	0.05	0.1	0.72
5	14	high	1	0.4	100000	2500	0.1	high	0.1	0.05	0.873
6	7	low	3	0.4	50000	2500	0.4	high	0.05	0.05	0.684
7	17	low	1	0.2	50000	20000	0.4	low	0.05	0.05	0.572
8	15	low	3	0.4	100000	2500	0.1	high	0.1	0.1	0.887
9	31	low	3	0.4	100000	20000	0.1	low	0.05	0.05	0.679
10	12	high	3	0.2	100000	2500	0.1	high	0.05	0.1	0.84
11	25	low	1	0.2	100000	20000	0.1	low	0.1	0.1	0.752
12	1	low	1	0.2	50000	2500	0.4	high	0.1	0.1	0.72
13	6	high	1	0.4	50000	2500	0.4	high	0.05	0.1	0.626
14	16	high	3	0.4	100000	2500	0.4	low	0.05	0.05	0.767
15	9	low	1	0.2	100000	2500	0.1	high	0.05	0.05	1
16	21	low	1	0.4	50000	20000	0.1	high	0.05	0.1	0.546
17	28	high	3	0.2	100000	20000	0.1	low	0.1	0.05	0.436
18	24	high	3	0.4	50000	20000	0.1	high	0.05	0.05	0.395
19	18	high	1	0.2	50000	20000	0.1	high	0.1	0.1	0.47
20	10	high	1	0.2	100000	2500	0.4	low	0.1	0.1	0.961
21	26	high	1	0.2	100000	20000	0.4	high	0.05	0.05	0.537
22	4	high	3	0.2	50000	2500	0.4	high	0.1	0.05	0.612
23	29	low	1	0.4	100000	20000	0.4	high	0.1	0.05	0.679
24	13	low	1	0.4	100000	2500	0.4	low	0.05	0.1	0.887
25	5	low	1	0.4	50000	2500	0.1	low	0.1	0.05	0.684
26	2	high	1	0.2	50000	2500	0.1	low	0.05	0.05	0.741
27	27	low	3	0.2	100000	20000	0.4	high	0.05	0.1	0.752
28	11	low	3	0.2	100000	2500	0.4	low	0.1	0.05	1
29	22	high	1	0.4	50000	20000	0.4	low	0.1	0.05	0.487
30	20	high	3	0.2	50000	20000	0.4	low	0.05	0.1	0.4
31	8	high	3	0.4	50000	2500	0.1	low	0.1	0.1	0.555
32	23	low	3	0.4	50000	20000	0.4	low	0.1	0.1	0.546

DOE software will evaluate all effects of all parameters (nine factors) first; the results from the initial analysis are shown below in table A.4 – table A.5 and figure A.1 – figure A.2. Table A.4 provides design setting, factor properties and ANOVA Table of all factors in an initial design. Table A.5 shows regression information of all factors in the initial design. Figure A.1 illustrates normal probability plot of effect of all initial parameters of screening test. Figure A.2 shows Pareto chart of all initial parameters of screening test.

Table A.4 Design setting, factor properties and ANOVA Table of all factors in initial design

Current Design Settings

Factors:	9
Total Blocks:	1
Total Center Points:	0
Observations:	32
Responses:	1

Factor Properties

Factor	Name	Units	Type	Low Level	High Level
A	Purchase cost/unit	$	Qualitative	low	high
B	Production cost/unit	$	Quantitative	1	3
C	Disassembly cost/unit	$	Quantitative	0.2	0.4
D	Demand Volume	unit	Quantitative	5.00E+04	1.00E+05
E	Return Volume	unit	Quantitative	2500	2.00E+04
F	Holding cost of product at plant	$	Quantitative	0.1	0.4
G	Holding Cost/unit of Materials at plant	$	Qualitative	low	high
H	Transportation cost/unit from P to W	$	Quantitative	0.05	0.1
J	Transportation cost/unit from R to P	$	Quantitative	0.05	0.1

ANOVA Table

Source of Variation	Degrees of Freedom	Sum of Squares [Partial]	Mean Squares [Partial]	F Ratio	P Value
Model	31	0.9246	0.0298	-	-
Main Effects	9	0.8195	0.0911	-	-
2-Way Interaction	21	0.1049	0.005	-	-
3-Way Interaction	1	0.0002	0.0002	-	-
Residual	0				
Total	31	0.9246			

Table A.5 Regression information of all factors in initial design

Regression Information							
Term	Effect	Coefficient	Standard Error	Low CI	High CI	T Value	P Value
Intercept		0.6709	-	-	-	-	-
A:Purchase cost/unit*	-0.1181	-0.0591	-	-	-	-	-
B:Production cost/unit*	-0.0585	-0.0293	-	-	-	-	-
C:Disassembly cost/unit*	-0.0437	-0.0219	-	-	-	-	-
D:Demand Volume*	0.1756	0.0878	-	-	-	-	-
E:Return Volume*	-0.2278	-0.1139	-	-	-	-	-
F:Holding cost of product at plant	-0.0104	-0.0052	-	-	-	-	-
G:Holding Cost/unit of Materials at plant	-0.015	-0.0075	-	-	-	-	-
H:Transportation cost/unit from P to W	-0.0099	-0.0049	-	-	-	-	-
J:Transportation cost/unit from R to P	0.0021	0.0011	-	-	-	-	-
AB*	-0.0585	-0.0293	-	-	-	-	-
AC	0.0182	0.0091	-	-	-	-	-
AD	-0.0234	-0.0117	-	-	-	-	-
AE*	-0.0422	-0.0211	-	-	-	-	-
AF	-0.0104	-0.0052	-	-	-	-	-
AG	-0.015	-0.0075	-	-	-	-	-
AH	-0.0099	-0.0049	-	-	-	-	-
AJ	0.0096	0.0048	-	-	-	-	-
BC	-0.0059	-0.0029	-	-	-	-	-
BD	-0.0133	-0.0066	-	-	-	-	-
BE	-0.0051	-0.0026	-	-	-	-	-
BF	0.0228	0.0114	-	-	-	-	-
BG	0.0226	0.0113	-	-	-	-	-
BH	-0.016	-0.008	-	-	-	-	-
BJ	-0.005	-0.0025	-	-	-	-	-
CD	-0.0082	-0.0041	-	-	-	-	-
CE*	0.0351	0.0176	-	-	-	-	-
CF	-0.0133	-0.0066	-	-	-	-	-
CG	-0.0051	-0.0026	-	-	-	-	-
DE*	-0.0585	-0.0292	-	-	-	-	-
DF	-0.0059	-0.0029	-	-	-	-	-
ABJ	-0.005	-0.0025	-	-	-	-	-

*: Significant effects according to Lenth's method.

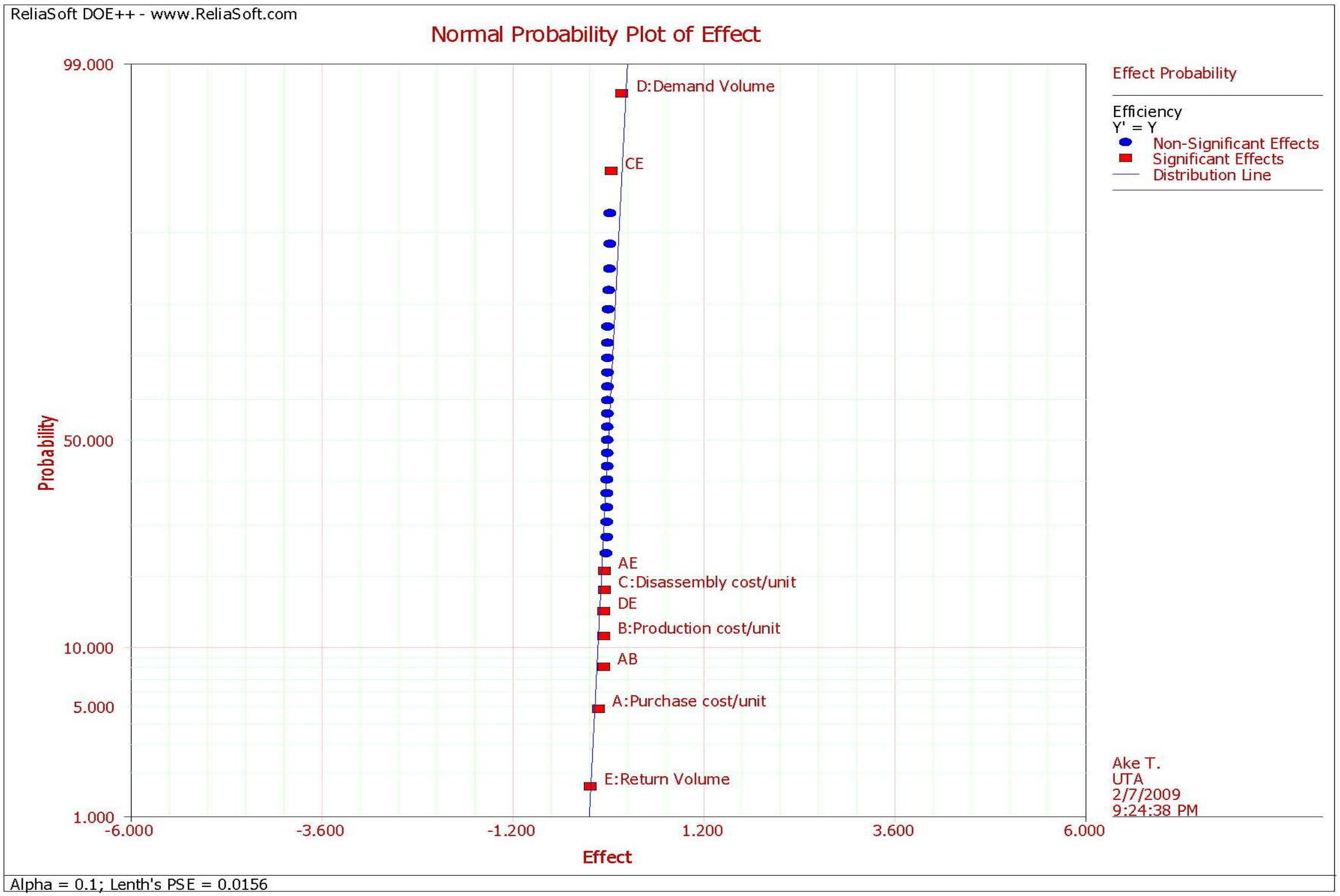

Fig A.1 Normal Probability Plot of Effect of all initial parameters of screening test

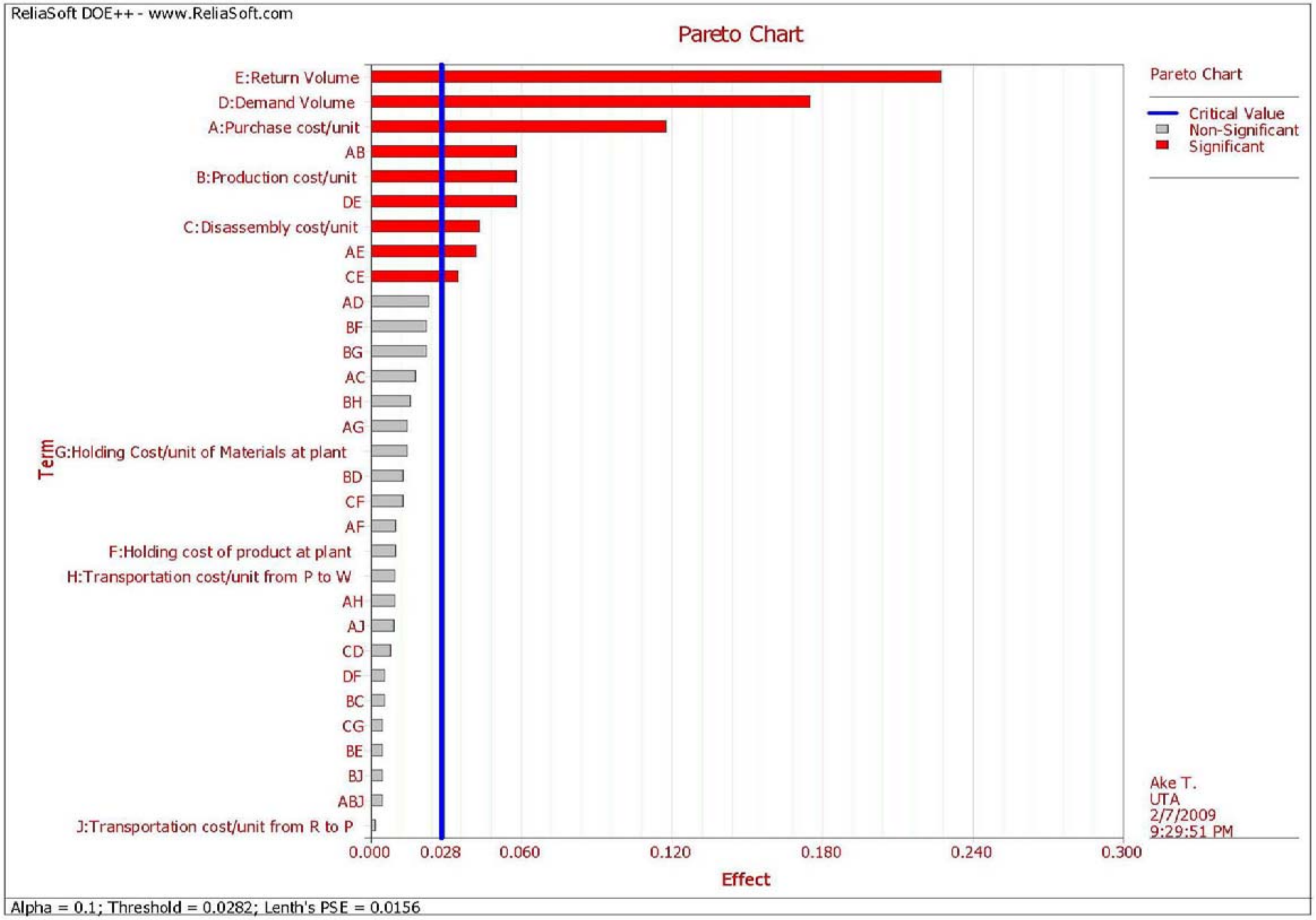

Fig A.2 Pareto Chart of all initial parameters of screening test

In the next step, DOE software will be used to eliminate non-significant parameters from the initial test.

Table A.6 Design setting, factor properties and ANOVA Table of reduced model in screening design

Current Design Settings

Factors:	9
Total Blocks:	1
Total Center Points:	0
Observations:	32
Responses:	1

Factor Properties

Factor	Name	Units	Type	Low Level	High Level
A	Purchase cost/unit	$	Qualitative	low	high
B	Production cost/unit	$	Quantitative	1	3
C	Disassembly cost/unit	$	Quantitative	0.2	0.4
D	Demand Volume	unit	Quantitative	5.00E+04	1.00E+05
E	Return Volume	unit	Quantitative	2500	2.00E+04
F	Holding cost of product at plant	$	Quantitative	0.1	0.4
G	Holding Cost/unit of Materials at plant	$	Qualitative	low	high
H	Transportation cost/unit from P to W	$	Quantitative	0.05	0.1
J	Transportation cost/unit from R to P	$	Quantitative	0.05	0.1

ANOVA Table

Source of Variation	Degrees of Freedom	Sum of Squares [Partial]	Mean Squares [Partial]	F Ratio	P Value
Model	9	0.8949	0.0994	73.6451	2.44E-14
Main Effects	5	0.816	0.1632	120.8733	3.08E-15
2-Way Interaction	4	0.0789	0.0197	14.6099	5.76E-06
Residual	22	0.0297	0.0014		
Lack of Fit	22	0.0297	0.0014		
Total	31	0.9246			

S = 0.0367
R-sq = 96.79%
R-sq(adj) = 95.47%

Table A.7 Regression information of significant factors from screening design

Regression Information

Term	Effect	Coefficient	Standard Error	Low CI	High CI	T Value	P Value
Intercept		0.6709	0.0065	0.6598	0.6821	103.2889	0
A:Purchase cost/unit	-0.1181	-0.0591	0.0065	-0.0702	-0.0479	-9.0925	6.62E-09
B:Production cost/unit	-0.0585	-0.0293	0.0065	-0.0404	-0.0181	-4.503	0.0002
C:Disassembly cost/unit	-0.0437	-0.0219	0.0065	-0.033	-0.0107	-3.3676	0.0028
D:Demand Volume	0.1756	0.0878	0.0065	0.0767	0.099	13.5185	3.90E-12
E:Return Volume	-0.2278	-0.1139	0.0065	-0.125	-0.1027	-17.5307	2.05E-14
AB	-0.0585	-0.0293	0.0065	-0.0404	-0.0181	-4.503	0.0002
AE	-0.0422	-0.0211	0.0065	-0.0323	-0.01	-3.2521	0.0037
CE	0.0351	0.0176	0.0065	0.0064	0.0287	2.7037	0.013
DE	-0.0585	-0.0292	0.0065	-0.0404	-0.0181	-4.503	0.0002

Figure A.3 shows normal probability plot of significant parameters of reduced model in screening test. Figure A.4 illustrates a Pareto chart of significant parameters of reduced model.

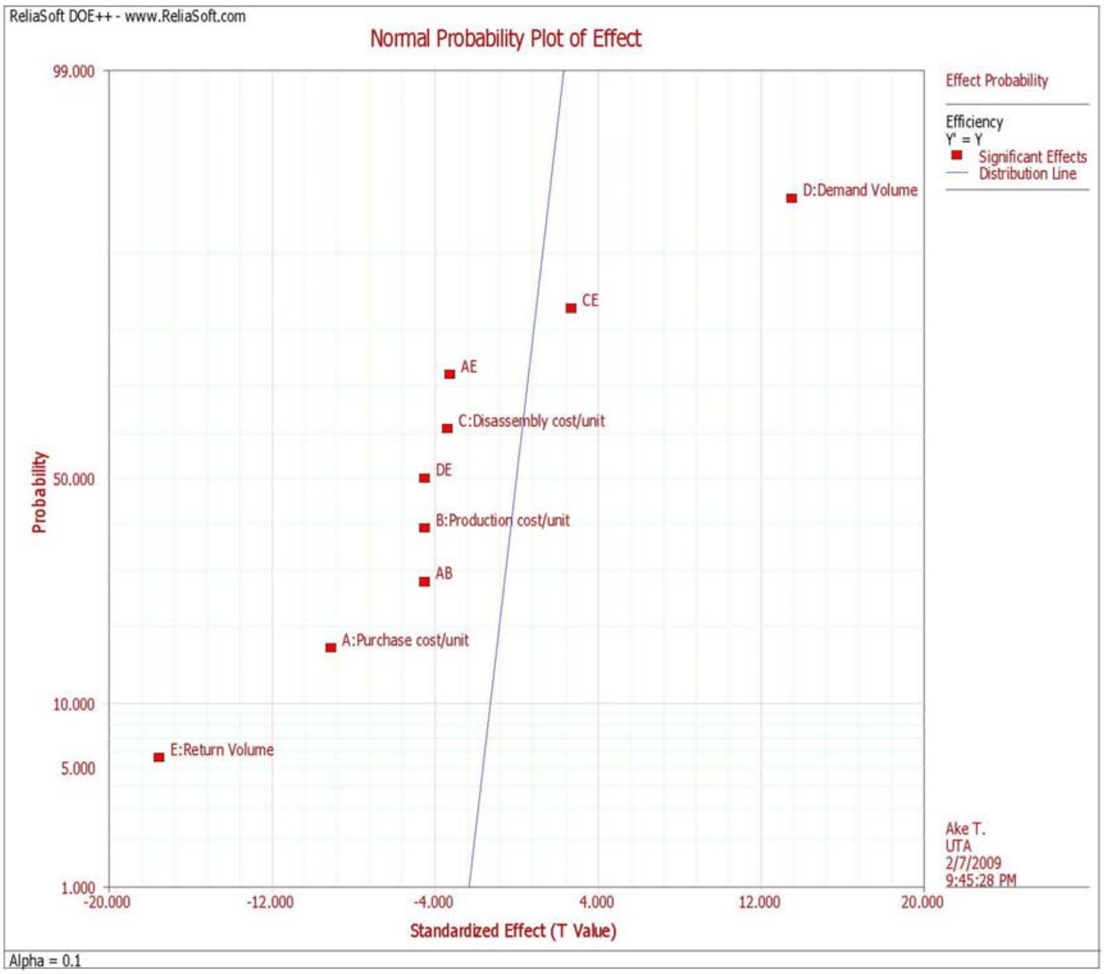

Fig A.3 Normal probability plot of Effect of reduced model

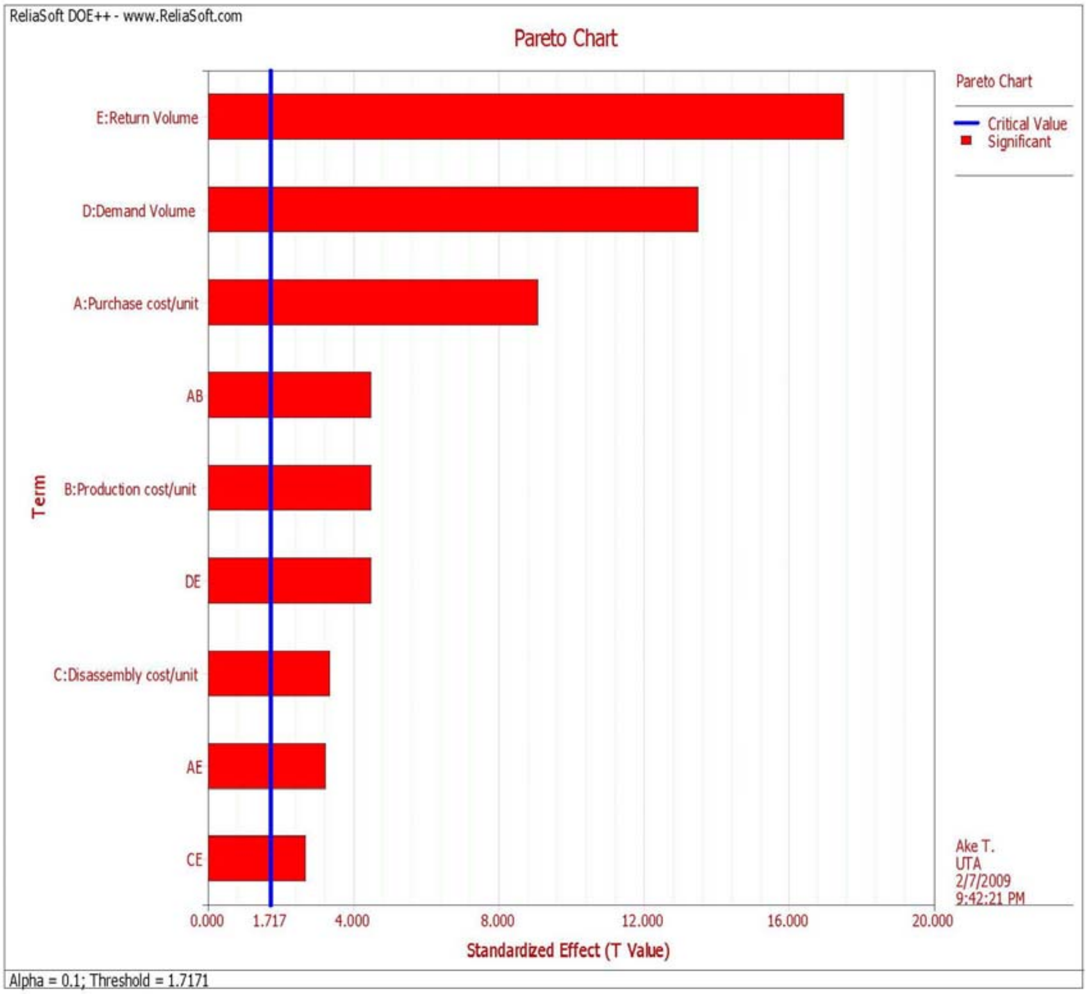

Fig A.4 Pareto chart of significant parameters of reduced model

From the results, five out of nine factors and four two-way interactions among these five factors have significant effects to the response. These five factors will be brought to be tested again by the 2 level full factorial technique. These five factors are Return volume, Demand volume, Purchase cost, Production cost, and Disassembly cost.

1.2 2 level full factorial design

After receiving the significant parameters from the screening test, these factors will be tested again by the 2 level full factorial design technique to obtain reliable results. Table

A.8 shows setup parameters for 2 level full factorial tests for case study 1. For five factors, DOE software will generate 32 experiments. Table A.9 provides parameters input for each experiment.

Table A.8 Setup parameters for 2 levels full factorial tests for case study 1

Name	Units	Type	Low Level	High Level
Purchase cost/unit	$	Qualitative	low	high
Production cost/unit	$	Quantitative	1	3
Disassembly cost/unit	$	Quantitative	0.2	0.4
Demand Volume	unit	Quantitative	50000	100000
Return Volume	unit	Quantitative	2500	20000

Table A.9 Parameters input for each experiment for 2 level full factorial design

Run Order	Standard Order	Purchase cost/unit ($)	Production cost/unit ($)	Disassembly cost/unit ($)	Demand Volume (unit)	Return Volume (unit)
1	21	low	1	0.4	50000	20000
2	13	low	1	0.4	100000	2500
3	8	high	3	0.4	50000	2500
4	4	high	3	0.2	50000	2500
5	26	high	1	0.2	100000	20000
6	23	low	3	0.4	50000	20000
7	1	low	1	0.2	50000	2500
8	30	high	1	0.4	100000	20000
9	22	high	1	0.4	50000	20000
10	3	low	3	0.2	50000	2500
11	17	low	1	0.2	50000	20000
12	32	high	3	0.4	100000	20000
13	27	low	3	0.2	100000	20000
14	11	low	3	0.2	100000	2500
15	29	low	1	0.4	100000	20000
16	25	low	1	0.2	100000	20000
17	20	high	3	0.2	50000	20000
18	5	low	1	0.4	50000	2500
19	14	high	1	0.4	100000	2500
20	12	high	3	0.2	100000	2500
21	7	low	3	0.4	50000	2500
22	6	high	1	0.4	50000	2500
23	10	high	1	0.2	100000	2500
24	15	low	3	0.4	100000	2500
25	19	low	3	0.2	50000	20000
26	9	low	1	0.2	100000	2500
27	18	high	1	0.2	50000	20000
28	24	high	3	0.4	50000	20000
29	28	high	3	0.2	100000	20000
30	31	low	3	0.4	100000	20000
31	2	high	1	0.2	50000	2500
32	16	high	3	0.4	100000	2500

All inputs from every experiment will be put in the simulation model (Model 3.1) again to obtain the sets of outputs. Then, all inputs and outputs of each experiment will be put in the DEA model in chapter 3 to obtain a relative efficiency score for each experiment. Table A.10 illustrates parameters and a response (relative efficiency) of each experiment.

Table A.10 Parameters and a response (relative efficiency) of each experiment

Run Order	Standard Order	Purchase cost/unit ($)	Production cost/unit ($)	Disassembly cost/unit ($)	Demand Volume (unit)	Return Volume (unit)	Efficiency
1	21	low	1	0.4	50000	20000	0.550
2	13	low	1	0.4	100000	2500	0.905
3	8	high	3	0.4	50000	2500	0.564
4	4	high	3	0.2	50000	2500	0.612
5	26	high	1	0.2	100000	20000	0.562
6	23	low	3	0.4	50000	20000	0.550
7	1	low	1	0.2	50000	2500	0.735
8	30	high	1	0.4	100000	20000	0.551
9	22	high	1	0.4	50000	20000	0.491
10	3	low	3	0.2	50000	2500	0.735
11	17	low	1	0.2	50000	20000	0.572
12	32	high	3	0.4	100000	20000	0.424
13	27	low	3	0.2	100000	20000	0.781
14	11	low	3	0.2	100000	2500	1.000
15	29	low	1	0.4	100000	20000	0.686
16	25	low	1	0.2	100000	20000	0.781
17	20	high	3	0.2	50000	20000	0.402
18	5	low	1	0.4	50000	2500	0.687
19	14	high	1	0.4	100000	2500	0.905
20	12	high	3	0.2	100000	2500	0.869
21	7	low	3	0.4	50000	2500	0.687
22	6	high	1	0.4	50000	2500	0.668
23	10	high	1	0.2	100000	2500	1.000
24	15	low	3	0.4	100000	2500	0.905
25	19	low	3	0.2	50000	20000	0.572
26	9	low	1	0.2	100000	2500	1.000
27	18	high	1	0.2	50000	20000	0.497
28	24	high	3	0.4	50000	20000	0.396
29	28	high	3	0.2	100000	20000	0.436
30	31	low	3	0.4	100000	20000	0.686
31	2	high	1	0.2	50000	2500	0.716
32	16	high	3	0.4	100000	2500	0.774

After all inputs and responses needed are completed, DOE software will evaluate the initial results that include all non-significant interactions. The results from the initial analysis can be shown below in table A.11 – table A.12 and figure A.5 – figure A.6.

Table A.11 provides the design setting, factor properties and ANOVA Table of all factors in an initial design. Table A.12 shows regression information of all factors and interactions in initial design.

Table A.11 Design setting, factor properties and ANOVA Table of all factors in the initial design

Current Design Settings

Factors:	5
Total Blocks:	1
Total Center Points:	0
Observations:	32
Responses:	1

Factor Properties

Factor	Name	Units	Type	Low Level	High Level
A	Purchase cost/unit	$	Qualitative	low	high
B	Production cost/unit	$	Quantitative	1	3
C	Disassembly cost/unit	$	Quantitative	0.2	0.4
D	Demand Volume	unit	Quantitative	5.00E+04	1.00E+05
E	Return Volume	unit	Quantitative	2500	2.00E+04

ANOVA Table

Source of Variation	Degrees of Freedom	Sum of Squares [Partial]	Mean Squares [Partial]	F Ratio	P Value
Model	31	0.9896	0.0319	-	-
Main Effects	5	0.8765	0.1753	-	-
2-Way Interaction	10	0.1016	0.0102	-	-
3-Way Interaction	10	0.0109	0.0011	-	-
4-Way Interaction	5	0.0006	0.0001	-	-
5-Way Interaction	1	3.13E-08	3.13E-08	-	-
Residual	0				
Total	31	0.9896			

Table A.12 Regression information of all factors and interactions in initial design

Regression Information							
Term	**Effect**	**Coefficient**	**Standard Error**	**Low CI**	**High CI**	**T Value**	**P Value**
Intercept		0.6781	-	-	-	-	-
A:Purchase cost/unit*	-0.1228	-0.0614	-	-	-	-	-
B:Production cost/unit*	-0.0571	-0.0285	-	-	-	-	-
C:Disassembly cost/unit*	-0.0526	-0.0263	-	-	-	-	-
D:Demand Volume*	0.1769	0.0885	-	-	-	-	-
E:Return Volume*	-0.2391	-0.1195	-	-	-	-	-
AB*	-0.0571	-0.0285	-	-	-	-	-
AC	0.0124	0.0062	-	-	-	-	-
AD*	-0.0301	-0.015	-	-	-	-	-
AE*	-0.0546	-0.0273	-	-	-	-	-
BC	-6.25E-05	-3.13E-05	-	-	-	-	-
BD	-0.0073	-0.0037	-	-	-	-	-
BE	0.0017	0.0008	-	-	-	-	-
CD*	-0.0216	-0.0108	-	-	-	-	-
CE*	0.0189	0.0095	-	-	-	-	-
DE*	-0.0673	-0.0337	-	-	-	-	-
ABC	-6.25E-05	-3.13E-05	-	-	-	-	-
ABD	-0.0073	-0.0037	-	-	-	-	-
ABE	0.0017	0.0008	-	-	-	-	-
ACD	0.0084	0.0042	-	-	-	-	-
ACE	0.0124	0.0062	-	-	-	-	-
ADE*	-0.0328	-0.0164	-	-	-	-	-
BCD	-6.25E-05	-3.13E-05	-	-	-	-	-
BCE	-6.25E-05	-3.13E-05	-	-	-	-	-
BDE	-0.0006	-0.0003	-	-	-	-	-
CDE	0.0019	0.001	-	-	-	-	-
ABCD	-6.25E-05	-3.13E-05	-	-	-	-	-
ABCE	-6.25E-05	-3.13E-05	-	-	-	-	-
ABDE	-0.0006	-0.0003	-	-	-	-	-
ACDE	0.0084	0.0042	-	-	-	-	-
BCDE	-6.25E-05	-3.13E-05	-	-	-	-	-
ABCDE	-6.25E-05	-3.13E-05	-	-	-	-	-

*: Significant effects according to Lenth's method.

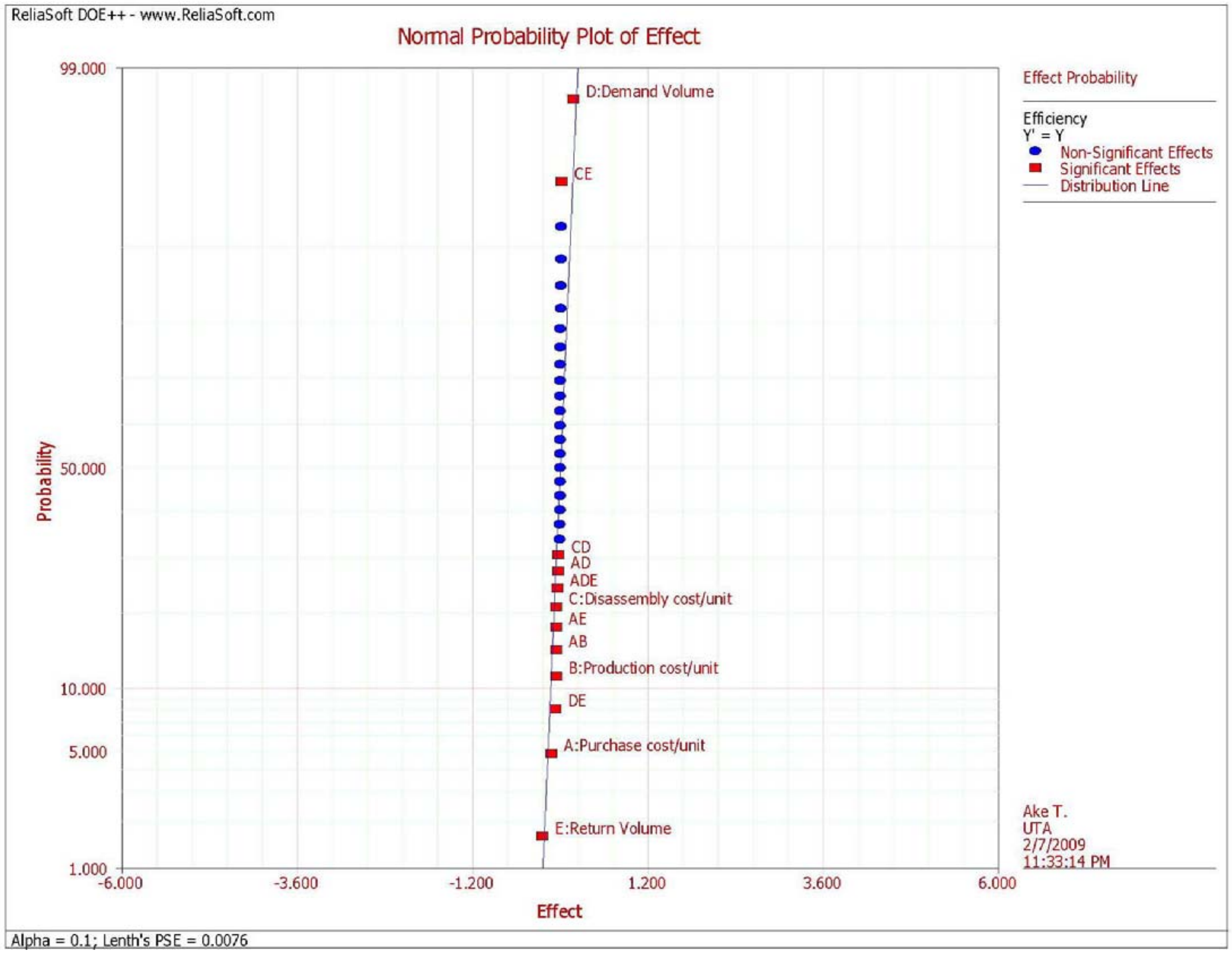

Fig A.5 Normal Probability Plot of Effect of all initial parameters of screening test

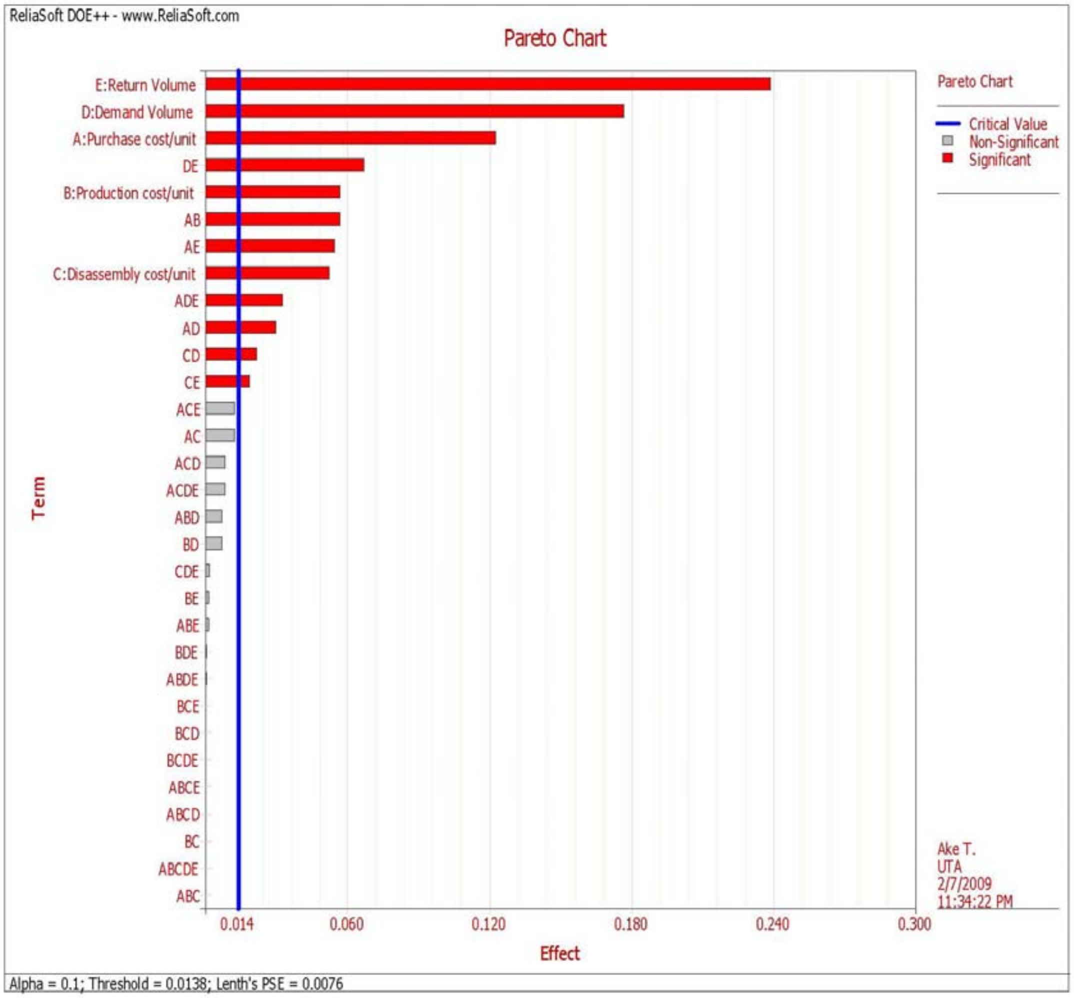

Fig A.6 Pareto chart of all parameters and interactions

In the next step, DOE software will be used to eliminate non-significant parameters and non-significant interactions from the initial test. Table A.13 provides the design setting, factor properties and ANOVA Table of reduced model in 2 level full factorial designs. Table A.12 shows regression information of significant factors and interactions.

Table A.13 Design setting, factor properties and ANOVA Table of reduced model in 2 level full factorial design

Current Design Settings

Factors:	5
Total Blocks:	1
Total Center Points:	0
Observations:	32
Responses:	1

Factor Properties

Factor	Name	Units	Type	Low Level	High Level
A	Purchase cost/unit	$	Qualitative	low	high
B	Production cost/unit	$	Quantitative	1	3
C	Disassembly cost/unit	$	Quantitative	0.2	0.4
D	Demand Volume	unit	Quantitative	5.00E+04	1.00E+05
E	Return Volume	unit	Quantitative	2500	2.00E+04

ANOVA Table

Source of Variation	Degrees of Freedom	Sum of Squares [Partial]	Mean Squares [Partial]	F Ratio	P Value
Model	12	0.985	0.0821	342.7285	1.50E-19
Main Effects	5	0.8765	0.1753	731.9072	4.95E-21
2-Way Interaction	6	0.0999	0.0167	69.5406	6.56E-12
3-Way Interaction	1	0.0086	0.0086	35.9629	9.04E-06
Residual	19	0.0046	0.0002		
Lack of Fit	19	0.0046	0.0002		
Total	31	0.9896			

S = 0.0155
R-sq = 99.54%
R-sq(adj) = 99.25%

Table A.14 Regression information of significant factors and interactions

Regression Information

Term	Effect	Coefficient	Standard Error	Low CI	High CI	T Value	P Value
Intercept		0.6781	0.0027	0.6734	0.6828	247.8606	0
A:Purchase cost/unit	-0.1228	-0.0614	0.0027	-0.0661	-0.0567	-22.4456	3.89E-15
B:Production cost/unit	-0.0571	-0.0285	0.0027	-0.0333	-0.0238	-10.4289	2.66E-09
C:Disassembly cost/unit	-0.0526	-0.0263	0.0027	-0.031	-0.0216	-9.6065	1.00E-08
D:Demand Volume	0.1769	0.0885	0.0027	0.0837	0.0932	32.3376	0
E:Return Volume	-0.2391	-0.1195	0.0027	-0.1243	-0.1148	-43.6917	0
AB	-0.0571	-0.0285	0.0027	-0.0333	-0.0238	-10.4289	2.66E-09
AD	-0.0301	-0.015	0.0027	-0.0198	-0.0103	-5.4943	2.67E-05
AE	-0.0546	-0.0273	0.0027	-0.032	-0.0226	-9.972	5.51E-09
CD	-0.0216	-0.0108	0.0027	-0.0155	-0.0061	-3.9408	0.0009
CE	0.0189	0.0095	0.0027	0.0047	0.0142	3.4611	0.0026
DE	-0.0673	-0.0337	0.0027	-0.0384	-0.0289	-12.3022	1.70E-10
ADE	-0.0328	-0.0164	0.0027	-0.0211	-0.0117	-5.9969	9.04E-06

Figure A.7 shows normal probability plot of significant parameters and interactions.

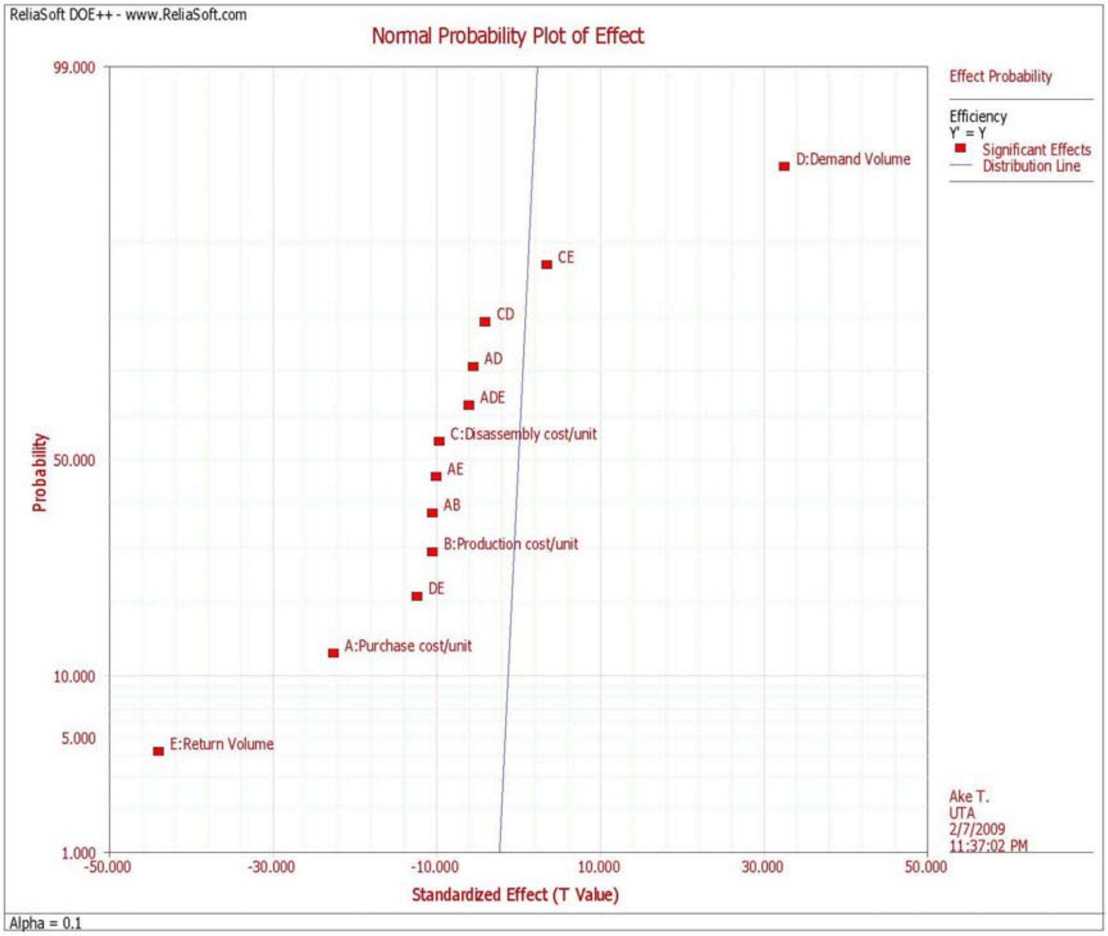

Fig A.7 Normal probability plot of significant parameters and interactions

Figure A.8 shows the Pareto chart of all significant parameters and interactions. Figure A.9 provides the main effects plot of significant parameters while figure A.10 shows the interaction matrix plot between significant parameters.

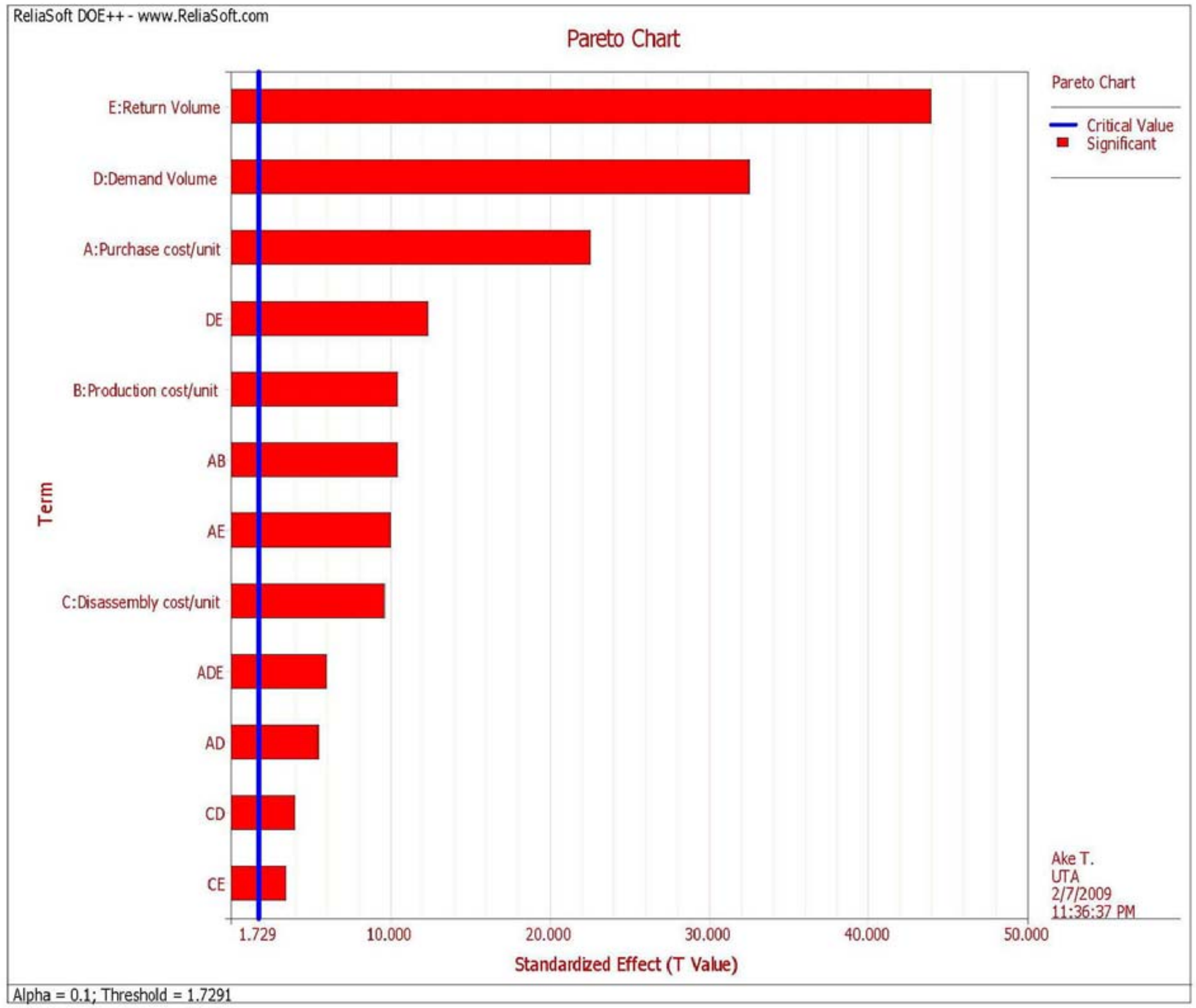

Fig A.8 Pareto chart of all significant parameters and interactions

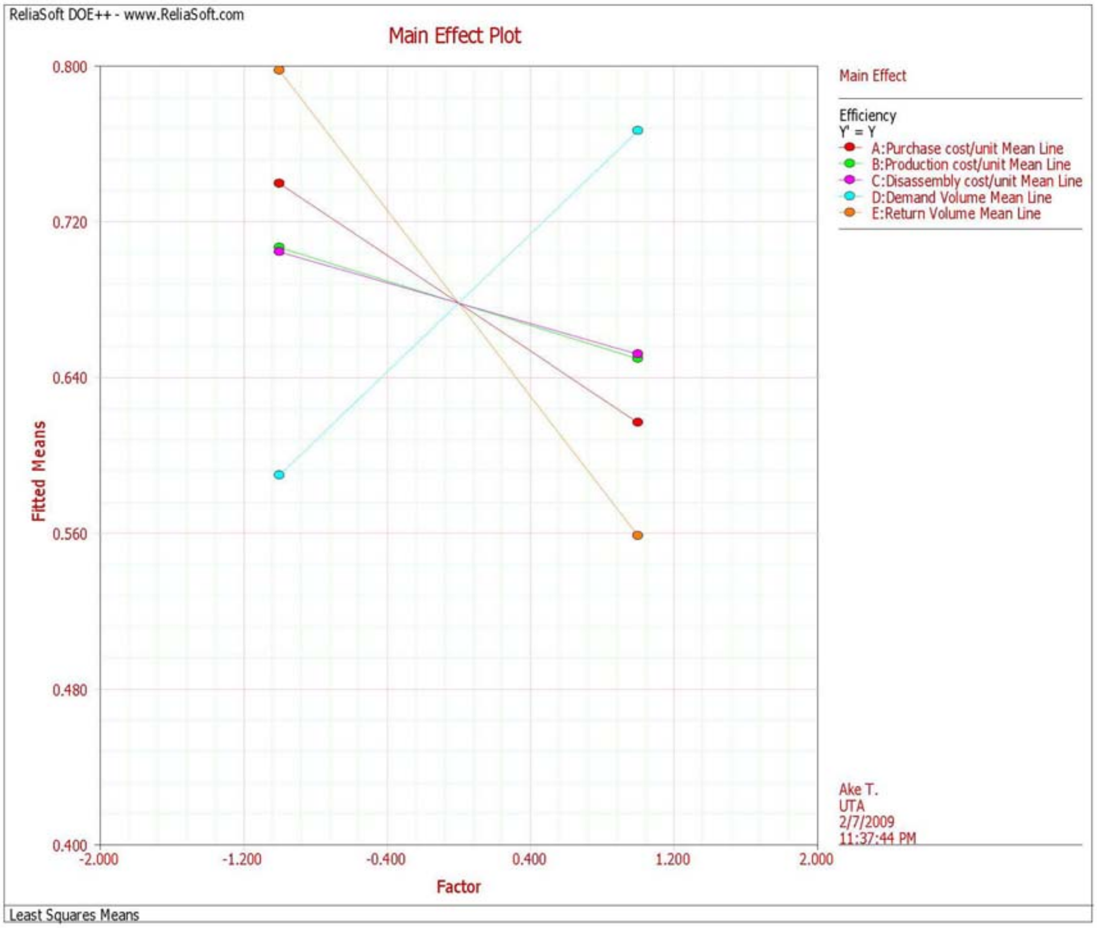

Fig A.9 Main effects plot of significant parameters

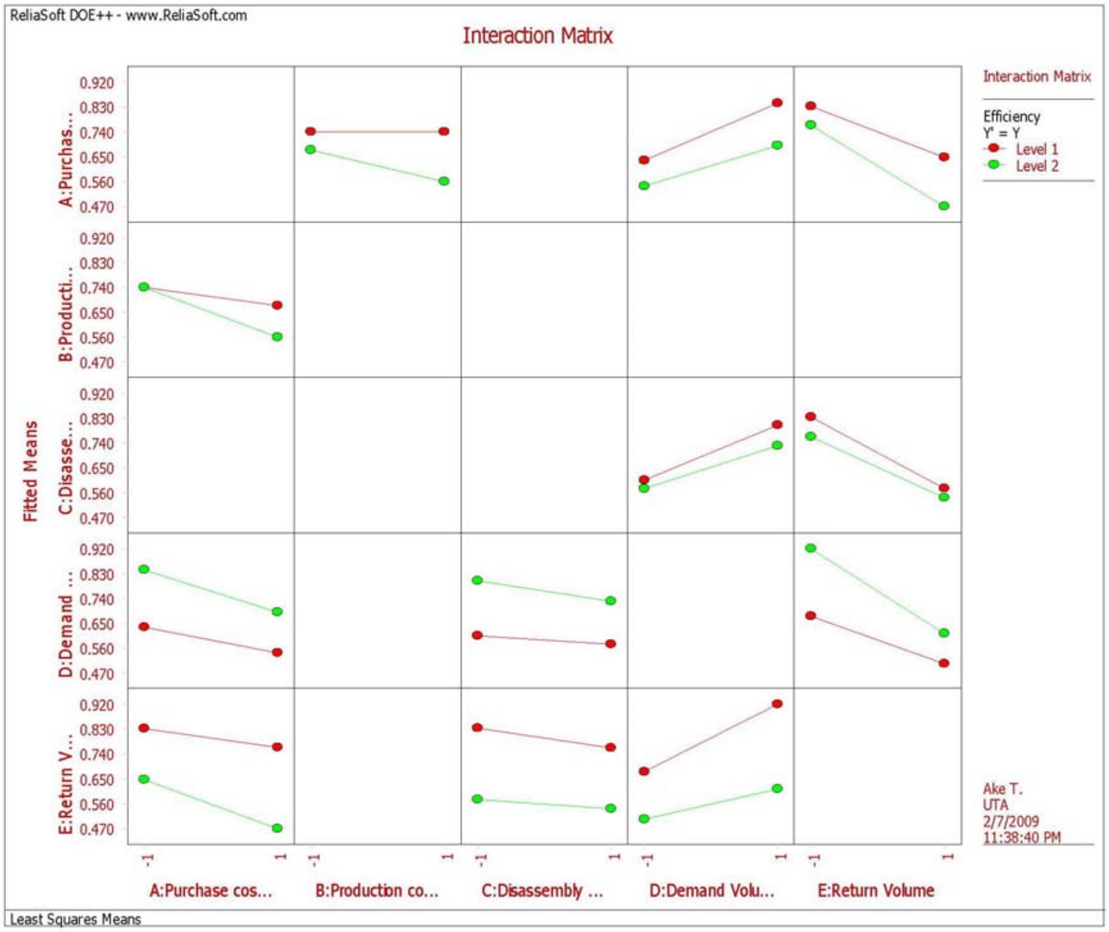

Fig A.10 Interaction matrix plot between significant parameters

Figure A.11 shows the plot between effects and fitted mean. Figure A.12 shows the plot between predicted value (fitted model) and the actual value.

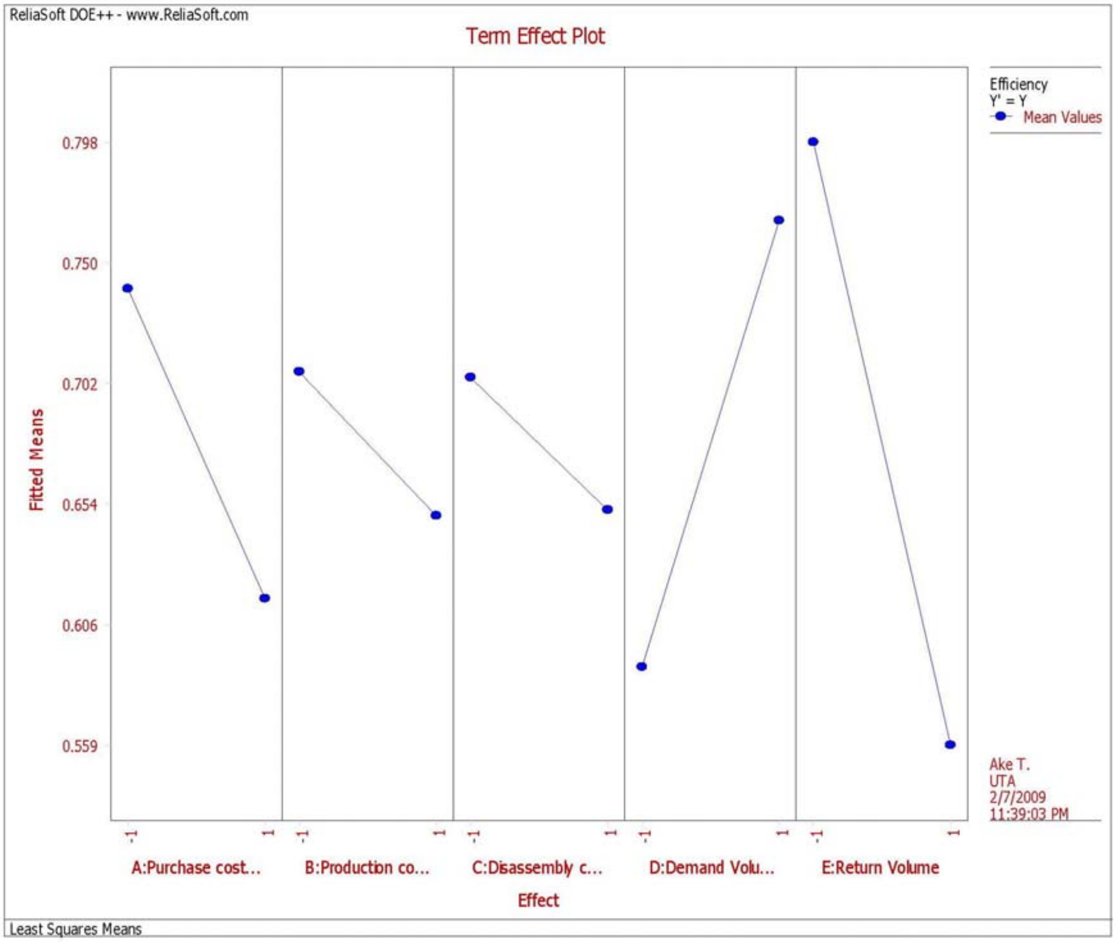

Fig A.11 Plot between effects and fitted mean

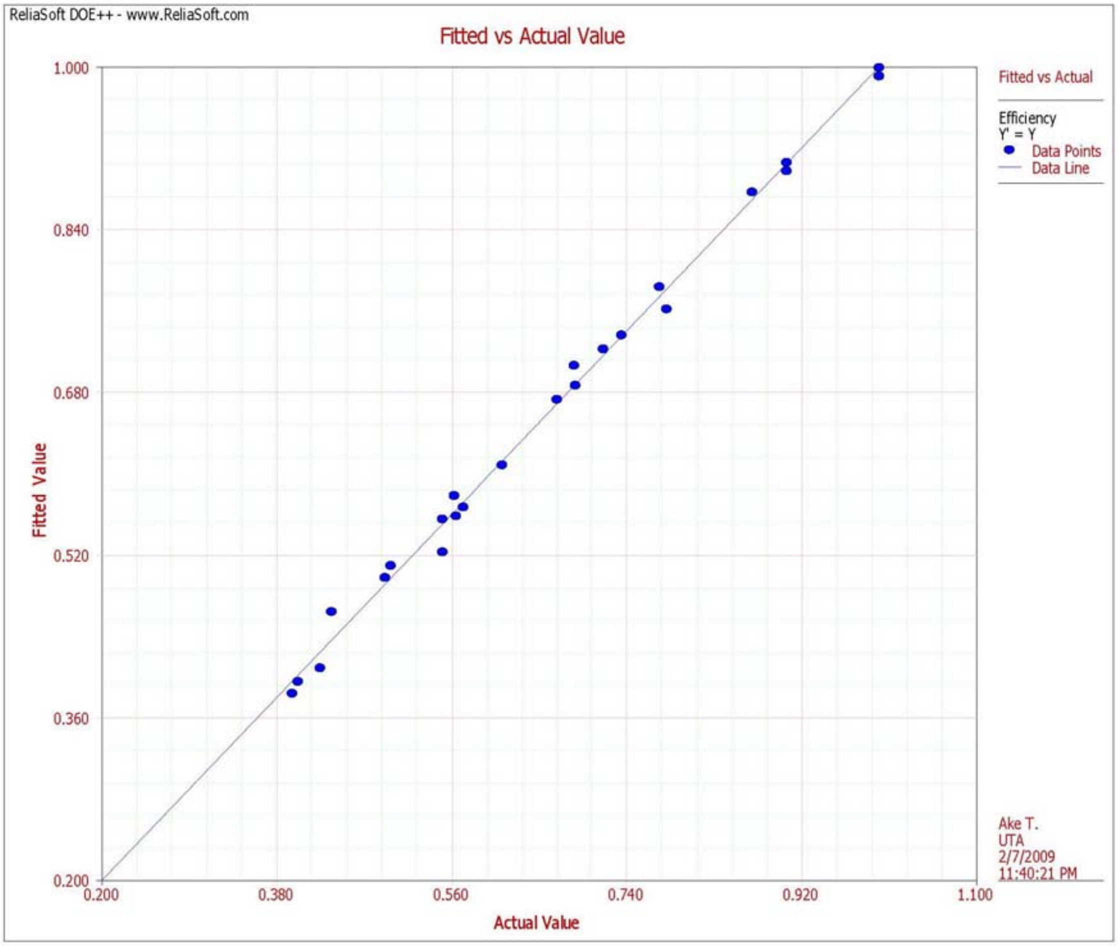

Fig A.12 Plot between predicted value (fitted model) and the actual value

APPENDIX B

SETUP PARAMETERS AND RESULTS FROM CASE STUDY 2

1. Case Study 2: Complex scenario

1.1 Screening test

Table B.1 illustrates setup parameters for screening test of Case Study 2.

Table B.1 Setup parameters for the experiments

Name	Units	Type	Low Level	High Level
Purchase cost/unit for plant 1	$	Qualitative	low	high
Purchase cost/unit for plant 2	$	Qualitative	low	high
Purchase cost/unit for plant 3	$	Qualitative	low	high
Production cost/unit for plant 1	$	Quantitative	3	5
Production cost/unit for plant 2	$	Quantitative	2	4
Production cost/unit for plant 3	$	Quantitative	1	3
Disassembly cost/unit	$	Quantitative	0.2	0.4
Demand Volume	unit	Quantitative	50000	200000
Return Volume	unit	Quantitative	2500	20000
Transportation cost/unit from plant 1 to warehouses	$	Quantitative	0.075	0.125
Transportation cost/unit from plant 2 to warehouses	$	Quantitative	0.025	0.075
Transportation cost/unit from plant 3 to warehouses	$	Quantitative	0.05	0.1

After putting these parameters in DOE software (DOE++), 64 experiments were generated to do a screening test (2 level fractional factorial design, Resolution IV). Table B.2 provides the parameters input of each experiment. All inputs from every experiment will be put in the simulation model (Model 3.1) in chapter 3 to get the sets of outputs. Then, all inputs and outputs of each experiment will be put in the DEA model in chapter 3 to obtain a relative efficiency score for each experiment. Table B.3 illustrates parameters and a response (relative efficiency) of each experiment for the screening test. After all input parameters and responses that need to be used are completed, DOE software can analyze the results to obtain the significant parameters from this screening test.

Table B.2 Parameters input for each designed experiment

Run Order	Standard Order	Purchase cost/unit ($), plant 1	Purchase cost/unit ($), plant 2	Purchase cost/unit ($), plant 3	Production cost/unit ($), plant 1	Production cost/unit ($), plant 2	Production cost/unit ($), plant 3	Disassembly cost/unit ($)	Demand Volume (unit)	Return Volume (unit)	Transportation cost/unit from plant 1 to WH ($)	Transportation cost/unit from plant 2 to WH ($)	Transportation cost/unit from plant 3 to WH ($)
1	58	high	low	low	5	4	3	0.4	50000	2500	0.075	0.025	0.1
2	16	high	high	high	5	2	1	0.4	200000	2500	0.075	0.075	0.1
3	31	low	high	high	5	4	1	0.2	50000	2500	0.125	0.075	0.05
4	50	high	low	low	3	4	3	0.4	200000	20000	0.125	0.025	0.05
5	2	high	low	low	3	2	1	0.4	200000	2500	0.075	0.025	0.05
6	26	high	low	low	5	4	1	0.4	50000	2500	0.125	0.075	0.05
7	38	high	low	high	3	2	3	0.2	200000	20000	0.075	0.075	0.05
8	51	low	high	low	3	4	3	0.4	200000	2500	0.075	0.025	0.1
9	6	high	low	high	3	2	1	0.2	200000	20000	0.125	0.025	0.1
10	29	low	low	high	5	4	1	0.4	200000	2500	0.125	0.025	0.1
11	10	high	low	low	5	2	1	0.4	50000	20000	0.125	0.025	0.1
12	34	high	low	low	3	2	3	0.4	200000	2500	0.125	0.075	0.1
13	28	high	high	low	5	4	1	0.2	200000	2500	0.125	0.025	0.1
14	15	low	high	high	5	2	1	0.2	50000	20000	0.125	0.025	0.1
15	27	low	high	low	5	4	1	0.4	50000	20000	0.075	0.075	0.1
16	25	low	low	low	5	4	1	0.2	200000	20000	0.075	0.025	0.05
17	14	high	low	high	5	2	1	0.2	50000	2500	0.075	0.025	0.05
18	3	low	high	low	3	2	1	0.4	200000	20000	0.125	0.025	0.1
19	62	high	low	high	5	4	3	0.2	50000	20000	0.125	0.025	0.05
20	17	low	low	low	3	4	1	0.2	50000	2500	0.125	0.025	0.1
21	9	low	low	low	5	2	1	0.2	200000	2500	0.075	0.075	0.1
22	35	low	high	low	3	2	3	0.4	200000	20000	0.075	0.075	0.05
23	4	high	high	low	3	2	1	0.2	50000	2500	0.075	0.075	0.1
24	43	low	high	low	5	2	3	0.4	50000	2500	0.125	0.075	0.1
25	19	low	high	low	3	4	1	0.4	200000	2500	0.125	0.075	0.05
26	21	low	low	high	3	4	1	0.4	50000	20000	0.075	0.025	0.05
27	11	low	high	low	5	2	1	0.4	50000	2500	0.075	0.025	0.05
28	57	low	low	low	5	4	3	0.2	200000	20000	0.125	0.075	0.1
29	20	high	high	low	3	4	1	0.2	50000	20000	0.075	0.025	0.05
30	59	low	high	low	5	4	3	0.4	50000	20000	0.125	0.025	0.05
31	8	high	high	high	3	2	1	0.4	50000	20000	0.125	0.075	0.05
32	1	low	low	low	3	2	1	0.2	50000	20000	0.125	0.075	0.05
33	52	high	high	low	3	4	3	0.2	50000	20000	0.125	0.075	0.1
34	24	high	high	high	3	4	1	0.4	50000	2500	0.125	0.025	0.1
35	45	low	low	high	5	2	3	0.4	200000	20000	0.075	0.025	0.1
36	44	high	high	low	5	2	3	0.2	200000	20000	0.075	0.025	0.1
37	32	high	high	high	5	4	1	0.4	200000	20000	0.075	0.025	0.05
38	13	low	low	high	5	2	1	0.4	200000	20000	0.125	0.075	0.05
39	5	low	low	high	3	2	1	0.4	50000	2500	0.075	0.075	0.1
40	55	low	high	high	3	4	3	0.2	200000	20000	0.125	0.025	0.05
41	60	high	high	low	5	4	3	0.2	200000	2500	0.075	0.075	0.05
42	40	high	high	high	3	2	3	0.4	50000	20000	0.075	0.025	0.1
43	18	high	low	low	3	4	1	0.4	200000	20000	0.075	0.075	0.1
44	41	low	low	low	5	2	3	0.2	200000	2500	0.125	0.025	0.05
45	37	low	low	high	3	2	3	0.4	50000	2500	0.125	0.025	0.05
46	22	high	low	high	3	4	1	0.2	200000	2500	0.125	0.075	0.05
47	12	high	high	low	5	2	1	0.2	200000	20000	0.125	0.075	0.05
48	47	low	high	high	5	2	3	0.2	50000	20000	0.075	0.075	0.05
49	63	low	high	high	5	4	3	0.2	50000	2500	0.075	0.025	0.1
50	53	low	low	high	3	4	3	0.4	50000	20000	0.125	0.075	0.1
51	46	high	low	high	5	2	3	0.2	50000	2500	0.125	0.075	0.1
52	23	low	high	high	3	4	1	0.2	200000	20000	0.075	0.075	0.1
53	33	low	low	low	3	2	3	0.2	50000	20000	0.075	0.025	0.1
54	61	low	low	high	5	4	3	0.4	200000	2500	0.075	0.075	0.05
55	49	low	low	low	3	4	3	0.2	50000	2500	0.075	0.075	0.05
56	30	high	low	high	5	4	1	0.2	50000	20000	0.075	0.075	0.1
57	7	low	high	high	3	2	1	0.2	200000	2500	0.075	0.025	0.05
58	39	low	high	high	3	2	3	0.2	200000	2500	0.125	0.075	0.1
59	56	high	high	high	3	4	3	0.4	50000	2500	0.075	0.075	0.05
60	48	high	high	high	5	2	3	0.4	200000	2500	0.125	0.025	0.05
61	42	high	low	low	5	2	3	0.4	50000	20000	0.075	0.075	0.05
62	36	high	high	low	3	2	3	0.2	50000	2500	0.125	0.025	0.05
63	54	high	low	high	3	4	3	0.2	200000	2500	0.075	0.025	0.1
64	64	high	high	high	5	4	3	0.4	200000	20000	0.125	0.075	0.1

Table B.3 Parameters and a response for each experiment for screening test

Run Order	Standard Order	Purchase cost/unit ($), plant 1	Purchase cost/unit ($), plant 2	Purchase cost/unit ($), plant 3	Production cost/unit ($), plant 1	Production cost/unit ($), plant 2	Production cost/unit ($), plant 3	Disassembly cost/unit ($)	Demand Volume (unit)	Return Volume (unit)	Transportation cost/unit from plant 1 to WH ($)	Transportation cost/unit from plant 2 to WH ($)	Transportation cost/unit from plant 3 to WH ($)	Efficiency
1	58	high	low	low	5	4	3	0.4	50000	2500	0.075	0.025	0.1	0.526
2	16	high	high	high	5	2	1	0.4	200000	2500	0.075	0.075	0.1	0.885
3	31	low	high	high	5	4	1	0.2	50000	2500	0.125	0.075	0.05	0.608
4	50	high	low	low	3	4	3	0.4	200000	20000	0.125	0.025	0.05	0.491
5	2	high	low	low	3	2	1	0.4	200000	2500	0.075	0.025	0.05	0.906
6	26	high	low	low	5	4	1	0.4	50000	2500	0.125	0.075	0.05	0.533
7	38	high	low	high	3	2	3	0.2	200000	20000	0.075	0.075	0.05	0.485
8	51	low	high	low	3	4	3	0.4	200000	2500	0.075	0.025	0.1	0.892
9	6	high	low	high	3	2	1	0.2	200000	20000	0.125	0.025	0.1	0.500
10	29	low	low	high	5	4	1	0.4	200000	2500	0.125	0.025	0.1	0.858
11	10	high	low	low	5	2	1	0.4	50000	20000	0.125	0.025	0.1	0.464
12	34	high	low	low	3	2	3	0.4	200000	2500	0.125	0.075	0.1	0.846
13	28	high	high	low	5	4	1	0.2	200000	2500	0.125	0.025	0.1	0.949
14	15	low	high	high	5	2	1	0.2	50000	20000	0.125	0.025	0.1	0.478
15	27	low	high	low	5	4	1	0.4	50000	20000	0.075	0.075	0.1	0.451
16	25	low	low	low	5	4	1	0.2	200000	20000	0.075	0.025	0.05	0.541
17	14	high	low	high	5	2	1	0.2	50000	2500	0.075	0.025	0.05	0.550
18	3	low	high	low	3	2	1	0.4	200000	20000	0.125	0.025	0.1	0.688
19	62	high	low	high	5	4	3	0.2	50000	20000	0.125	0.025	0.05	0.435
20	17	low	low	low	3	4	1	0.2	50000	2500	0.125	0.025	0.1	0.813
21	9	low	low	low	5	2	1	0.2	200000	2500	0.075	0.075	0.1	0.999
22	35	low	high	low	3	2	3	0.4	200000	20000	0.075	0.075	0.05	0.542
23	4	high	high	low	3	2	1	0.2	50000	2500	0.075	0.075	0.1	0.556
24	43	low	high	low	5	2	3	0.4	50000	2500	0.125	0.075	0.1	0.630
25	19	low	high	low	3	4	1	0.4	200000	2500	0.125	0.075	0.05	0.906
26	21	low	low	high	3	4	1	0.4	50000	20000	0.075	0.025	0.05	0.518
27	11	low	high	low	5	2	1	0.4	50000	2500	0.075	0.025	0.05	0.537
28	57	low	low	low	5	4	3	0.2	200000	20000	0.125	0.075	0.1	0.584
29	20	high	high	low	3	4	1	0.2	50000	20000	0.075	0.025	0.05	0.453
30	59	low	high	low	5	4	3	0.4	50000	20000	0.125	0.025	0.05	0.498
31	8	high	high	high	3	2	1	0.4	50000	20000	0.125	0.075	0.05	0.403
32	1	low	low	low	3	2	1	0.2	50000	20000	0.125	0.075	0.05	0.758
33	52	high	high	low	3	4	3	0.2	50000	20000	0.125	0.075	0.1	0.414
34	24	high	high	high	3	4	1	0.4	50000	2500	0.125	0.025	0.1	0.482
35	45	low	low	high	5	2	3	0.4	200000	20000	0.075	0.025	0.1	0.509
36	44	high	high	low	5	2	3	0.2	200000	20000	0.075	0.025	0.1	0.485
37	32	high	high	high	5	4	1	0.4	200000	20000	0.075	0.025	0.05	0.462
38	13	low	low	high	5	2	1	0.4	200000	20000	0.125	0.075	0.05	0.515
39	5	low	low	high	3	2	1	0.4	50000	2500	0.075	0.075	0.1	0.637
40	55	low	high	high	3	4	3	0.2	200000	20000	0.125	0.025	0.05	0.494
41	60	high	high	low	5	4	3	0.2	200000	2500	0.075	0.075	0.05	0.919
42	40	high	high	high	3	2	3	0.4	50000	20000	0.075	0.025	0.1	0.400
43	18	high	low	low	3	4	1	0.4	200000	20000	0.075	0.075	0.1	0.527
44	41	low	low	low	5	2	3	0.2	200000	2500	0.125	0.025	0.05	1.000
45	37	low	low	high	3	2	3	0.4	50000	2500	0.125	0.025	0.05	0.637
46	22	high	low	high	3	4	1	0.2	200000	2500	0.125	0.075	0.05	0.921
47	12	high	high	low	5	2	1	0.2	200000	20000	0.125	0.075	0.05	0.539
48	47	low	high	high	5	2	3	0.2	50000	20000	0.075	0.075	0.05	0.480
49	63	low	high	high	5	4	3	0.2	50000	2500	0.075	0.025	0.1	0.612
50	53	low	low	high	3	4	3	0.4	50000	20000	0.125	0.075	0.1	0.515
51	46	high	low	high	5	2	3	0.2	50000	2500	0.125	0.075	0.1	0.552
52	23	low	high	high	3	4	1	0.2	200000	20000	0.075	0.075	0.1	0.517
53	33	low	low	low	3	2	3	0.2	50000	20000	0.075	0.025	0.1	0.758
54	61	low	low	high	5	4	3	0.4	200000	2500	0.075	0.075	0.05	0.853
55	49	low	low	low	3	4	3	0.2	50000	2500	0.075	0.075	0.05	0.813
56	30	high	low	high	5	4	1	0.2	50000	20000	0.075	0.075	0.1	0.430
57	7	low	high	high	3	2	1	0.2	200000	2500	0.075	0.025	0.05	0.953
58	39	low	high	high	3	2	3	0.2	200000	2500	0.125	0.075	0.1	0.933
59	56	high	high	high	3	4	3	0.4	50000	2500	0.075	0.075	0.05	0.481
60	48	high	high	high	5	2	3	0.4	200000	2500	0.125	0.025	0.05	0.795
61	42	high	low	low	5	2	3	0.4	50000	20000	0.075	0.075	0.05	0.461
62	36	high	high	low	3	2	3	0.2	50000	2500	0.125	0.025	0.05	0.516
63	54	high	low	high	3	4	3	0.2	200000	2500	0.075	0.025	0.1	0.908
64	64	high	high	high	5	4	3	0.4	200000	20000	0.125	0.075	0.1	0.437

DOE software will evaluate all effects of all parameters (twelve factors) first; the results from the initial analysis are shown below in table B.4 – table B.5 and figure B.1. Table B.4 provides the design setting, factor properties and ANOVA Table of all factors in an initial design. Table B.5 shows regression information of all factors in the initial design. Figure B.1 illustrates normal probability plot of the effect of all initial parameters of screening test.

Table B.4 Design setting, factor properties and ANOVA Table of all factors in initial design

Current Design Settings

Factors:	12
Total Blocks:	1
Total Center Points:	0
Observations:	64
Responses:	1

Factor Properties

Factor	Name	Units	Type	Low Level	High Level
A	Purchase cost/unit for plant 1	$	Qualitative	low	high
B	Purchase cost/unit for plant 2	$	Qualitative	low	high
C	Purchase cost/unit for plant 3	$	Qualitative	low	high
D	Production cost/unit for plant 1	$	Quantitative	3	5
E	Production cost/unit for plant 2	$	Quantitative	2	4
F	Production cost/unit for plant 3	$	Quantitative	1	3
G	Disassembly cost/unit	$	Quantitative	0.2	0.4
H	Demand Volume	unit	Quantitative	5.00E+04	2.00E+05
J	Return Volume	unit	Quantitative	2500	2.00E+04
K	Transportation cost/unit from P1 to W	$	Quantitative	0.075	0.125
L	Transportation cost/unit from P2 to W	$	Quantitative	0.025	0.075
M	Transportation cost/unit from P3 to W	$	Quantitative	0.05	0.1

ANOVA Table

Source of Variation	Degrees of Freedom	Sum of Squares [Partial]	Mean Squares [Partial]	F Ratio	P Value
Model	63	2.1614	0.0343	-	-
Main Effects	12	1.6813	0.1401	-	-
2-Way Interaction	50	0.4783	0.0096	-	-
3-Way Interaction	1	0.0017	0.0017	-	-
Residual	0				
Total	63	2.1614			

Table B.5 Regression information of all factors in initial design

Regression Information							
Term	Effect	Coefficient	Standard Error	Low CI	High CI	T Value	P Value
Intercept		0.6287	-	-	-	-	-
A:Purchase cost/unit for plant 1*	-0.0878	-0.0439	-	-	-	-	-
B:Purchase cost/unit for plant 2*	-0.0452	-0.0226	-	-	-	-	-
C:Purchase cost/unit for plant 3*	-0.0547	-0.0274	-	-	-	-	-
D:Production cost/unit for plant 1*	-0.0339	-0.017	-	-	-	-	-
E:Production cost/unit for plant 2*	-0.0174	-0.0087	-	-	-	-	-
F:Production cost/unit for plant 3	-0.0138	-0.0069	-	-	-	-	-
G:Disassembly cost/unit*	-0.0521	-0.0261	-	-	-	-	-
H:Demand Volume*	0.17	0.085	-	-	-	-	-
J:Return Volume*	-0.2429	-0.1215	-	-	-	-	-
K:Transportation cost/unit from P1 to W	0.0046	0.0023	-	-	-	-	-
L:Transportation cost/unit from P2 to W	0.0007	0.0003	-	-	-	-	-
M:Transportation cost/unit from P3 to W	0.0073	0.0036	-	-	-	-	-
AB*	0.0227	0.0114	-	-	-	-	-
AC*	0.026	0.013	-	-	-	-	-
AD*	0.0421	0.0211	-	-	-	-	-
AE*	0.0189	0.0094	-	-	-	-	-
AF	-0.012	-0.006	-	-	-	-	-
AG*	0.02	0.01	-	-	-	-	-
AH*	0.0423	0.0212	-	-	-	-	-
AJ	-0.0033	-0.0017	-	-	-	-	-
AK	-0.0144	-0.0072	-	-	-	-	-
AL	0.0034	0.0017	-	-	-	-	-
AM	-0.0064	-0.0032	-	-	-	-	-
BE	0.0022	0.0011	-	-	-	-	-
BF	-0.0076	-0.0038	-	-	-	-	-
BJ	-0.0016	-0.0008	-	-	-	-	-
BK	0.0045	0.0023	-	-	-	-	-
BL	-0.0001	-5.50E-05	-	-	-	-	-
BM	0.0067	0.0034	-	-	-	-	-
CD	0.0137	0.0069	-	-	-	-	-
CE	0.0061	0.003	-	-	-	-	-
CF	0.0017	0.0008	-	-	-	-	-
CH	0.0055	0.0027	-	-	-	-	-
CJ	-0.0124	-0.0062	-	-	-	-	-
CK	-0.0119	-0.0059	-	-	-	-	-
CL	0.003	0.0015	-	-	-	-	-
CM	-0.0034	-0.0017	-	-	-	-	-
DE	0.0059	0.0029	-	-	-	-	-
DF	0.0122	0.0061	-	-	-	-	-
DJ	-0.0094	-0.0047	-	-	-	-	-
DK	0.0063	0.0032	-	-	-	-	-
DL	0.0103	0.0051	-	-	-	-	-
DM	0.0004	0.0002	-	-	-	-	-
EF	0.0075	0.0038	-	-	-	-	-
EG	-0.0092	-0.0046	-	-	-	-	-
EH	-0.0027	-0.0014	-	-	-	-	-
EJ*	-0.0263	-0.0131	-	-	-	-	-
EK	-0.0023	-0.0011	-	-	-	-	-
EL	-0.0022	-0.0011	-	-	-	-	-
EM	-0.008	-0.004	-	-	-	-	-
FG	-0.0026	-0.0013	-	-	-	-	-
FH*	-0.0172	-0.0086	-	-	-	-	-
FL	-0.0015	-0.0007	-	-	-	-	-
FM	-0.0008	-0.0004	-	-	-	-	-
GJ*	0.0227	0.0113	-	-	-	-	-
GK	0.0024	0.0012	-	-	-	-	-
GL	-0.0032	-0.0016	-	-	-	-	-
GM	0.0058	0.0029	-	-	-	-	-
HJ*	-0.145	-0.0725	-	-	-	-	-
HK	-9.49E-06	-4.74E-06	-	-	-	-	-
HL	-0.0022	-0.0011	-	-	-	-	-
HM	0.0049	0.0025	-	-	-	-	-
ACH	-0.0105	-0.0052	-	-	-	-	-

*: Significant effects according to Lenth's method.

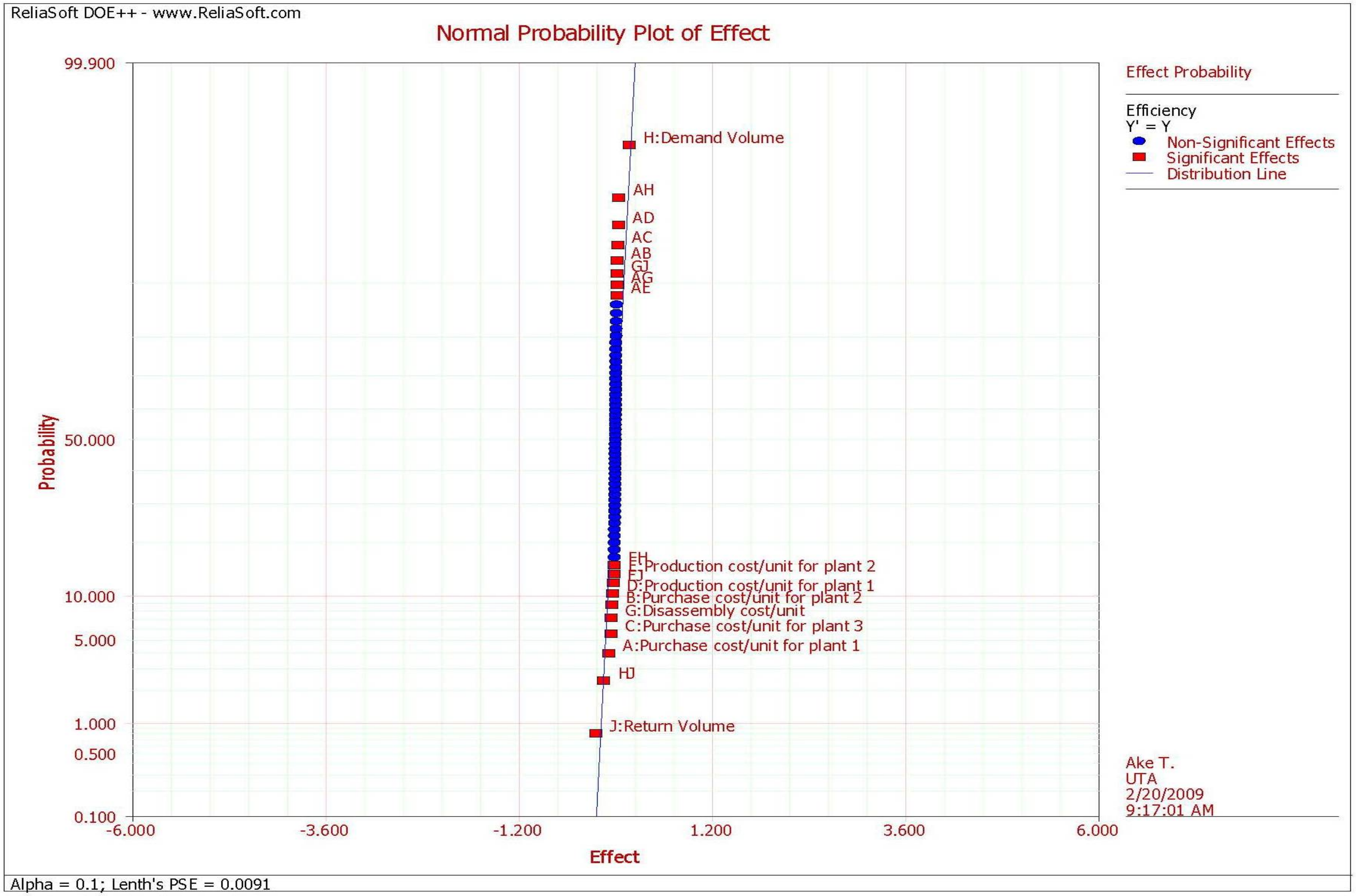

Fig B.1 Normal Probability Plot Effect of all initial parameters of screening test

In the next step, DOE software will be used to eliminate non-significant parameters from the initial test.

Table B.6 Design setting, factor properties and ANOVA Table of reduced model in screening design

Current Design Settings

Factors:	12
Total Blocks:	1
Total Center Points:	0
Observations:	64
Responses:	1

Factor Properties

Factor	Name	Units	Type	Low Level	High Level
A	Purchase cost/unit for plant 1	$	Qualitative	low	high
B	Purchase cost/unit for plant 2	$	Qualitative	low	high
C	Purchase cost/unit for plant 3	$	Qualitative	low	high
D	Production cost/unit for plant 1	$	Quantitative	3	5
E	Production cost/unit for plant 2	$	Quantitative	2	4
F	Production cost/unit for plant 3	$	Quantitative	1	3
G	Disassembly cost/unit	$	Quantitative	0.2	0.4
H	Demand Volume	unit	Quantitative	5.00E+04	2.00E+05
J	Return Volume	unit	Quantitative	2500	2.00E+04
K	Transportation cost/unit from P1 to W	$	Quantitative	0.075	0.125
L	Transportation cost/unit from P2 to W	$	Quantitative	0.025	0.075
M	Transportation cost/unit from P3 to W	$	Quantitative	0.05	0.1

ANOVA Table

Source of Variation	Degrees of Freedom	Sum of Squares [Partial]	Mean Squares [Partial]	F Ratio	P Value
Model	19	2.1288	0.112	151.6295	7.73E-34
Main Effects	9	1.6801	0.1867	252.6331	7.52E-35
2-Way Interaction	10	0.4487	0.0449	60.7262	2.05E-22
Residual	44	0.0325	0.0007		
Lack of Fit	44	0.0325	0.0007		
Total	63	2.1614			

S = 0.0272
R-sq = 98.50%
R-sq(adj) = 97.85%

Table B.7 Regression information of significant factors from screening design

Regression Information							
Term	Effect	Coefficient	Standard Error	Low CI	High CI	T Value	P Value
Intercept		0.6287	0.0034	0.623	0.6344	185.0208	0
A:Purchase cost/unit for plant 1	-0.0878	-0.0439	0.0034	-0.0496	-0.0382	-12.9199	1.11E-16
B:Purchase cost/unit for plant 2	-0.0452	-0.0226	0.0034	-0.0283	-0.0169	-6.6576	3.64E-08
C:Purchase cost/unit for plant 3	-0.0547	-0.0274	0.0034	-0.0331	-0.0216	-8.051	3.41E-10
D:Production cost/unit for plant 1	-0.0339	-0.017	0.0034	-0.0227	-0.0112	-4.989	1.00E-05
E:Production cost/unit for plant 2	-0.0174	-0.0087	0.0034	-0.0144	-0.003	-2.5572	0.0141
F:Production cost/unit for plant 3	-0.0138	-0.0069	0.0034	-0.0126	-0.0012	-2.0281	0.0486
G:Disassembly cost/unit	-0.0521	-0.0261	0.0034	-0.0318	-0.0204	-7.6724	1.20E-09
H:Demand Volume	0.17	0.085	0.0034	0.0793	0.0907	25.0127	0
J:Return Volume	-0.2429	-0.1215	0.0034	-0.1272	-0.1157	-35.7434	0
AB	0.0227	0.0114	0.0034	0.0057	0.0171	3.3472	0.0017
AC	0.026	0.013	0.0034	0.0073	0.0187	3.826	0.0004
AD	0.0421	0.0211	0.0034	0.0153	0.0268	6.1966	1.73E-07
AE	0.0189	0.0094	0.0034	0.0037	0.0151	2.7762	0.008
AG	0.02	0.01	0.0034	0.0043	0.0157	2.9443	0.0052
AH	0.0423	0.0212	0.0034	0.0155	0.0269	6.2288	1.56E-07
EJ	-0.0263	-0.0131	0.0034	-0.0189	-0.0074	-3.8684	0.0004
FH	-0.0172	-0.0086	0.0034	-0.0143	-0.0029	-2.5374	0.0148
GJ	0.0227	0.0113	0.0034	0.0056	0.017	3.337	0.0017
HJ	-0.145	-0.0725	0.0034	-0.0782	-0.0668	-21.338	0

Figure B.2 shows normal probability plot of significant parameters of reduced model in screening test. Figure B.3 illustrates a Pareto chart of significant parameters of reduced model.

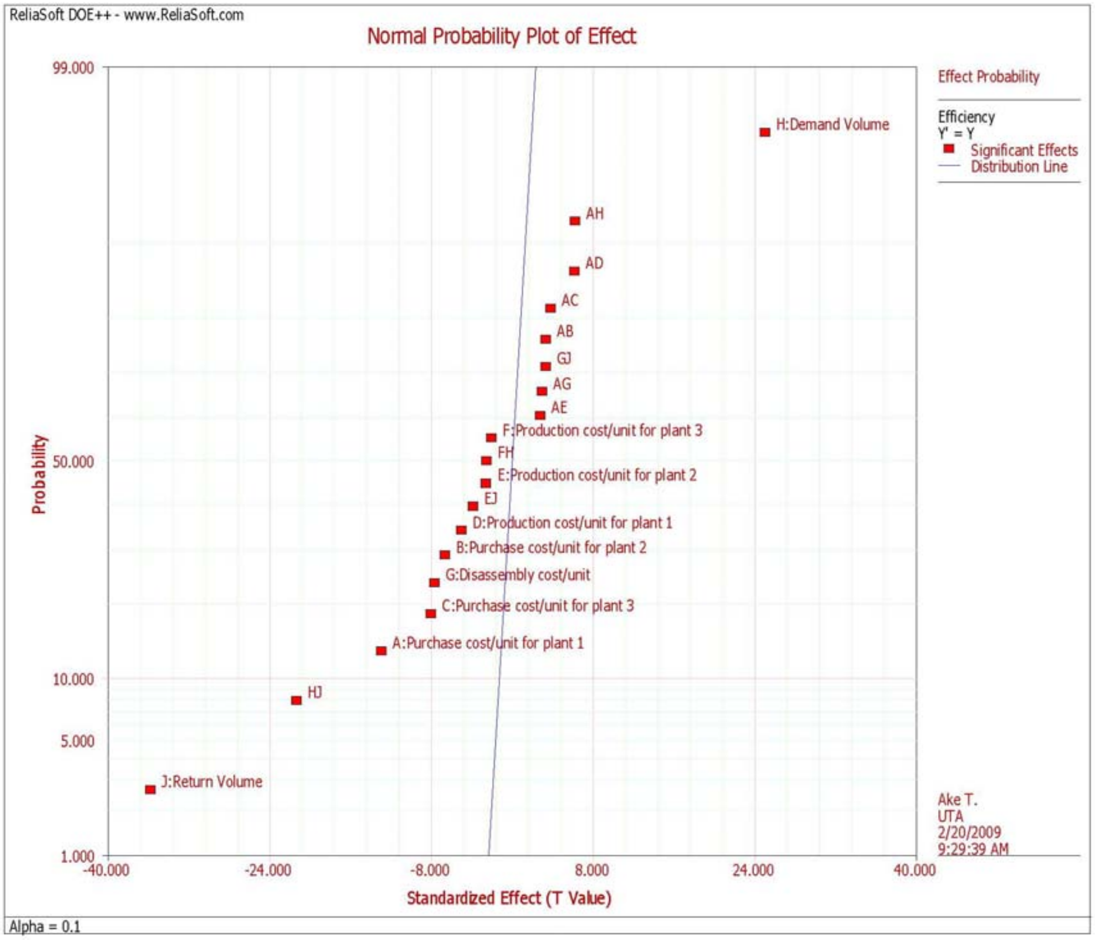

Fig B.2 Normal probability plot of effect of reduced model

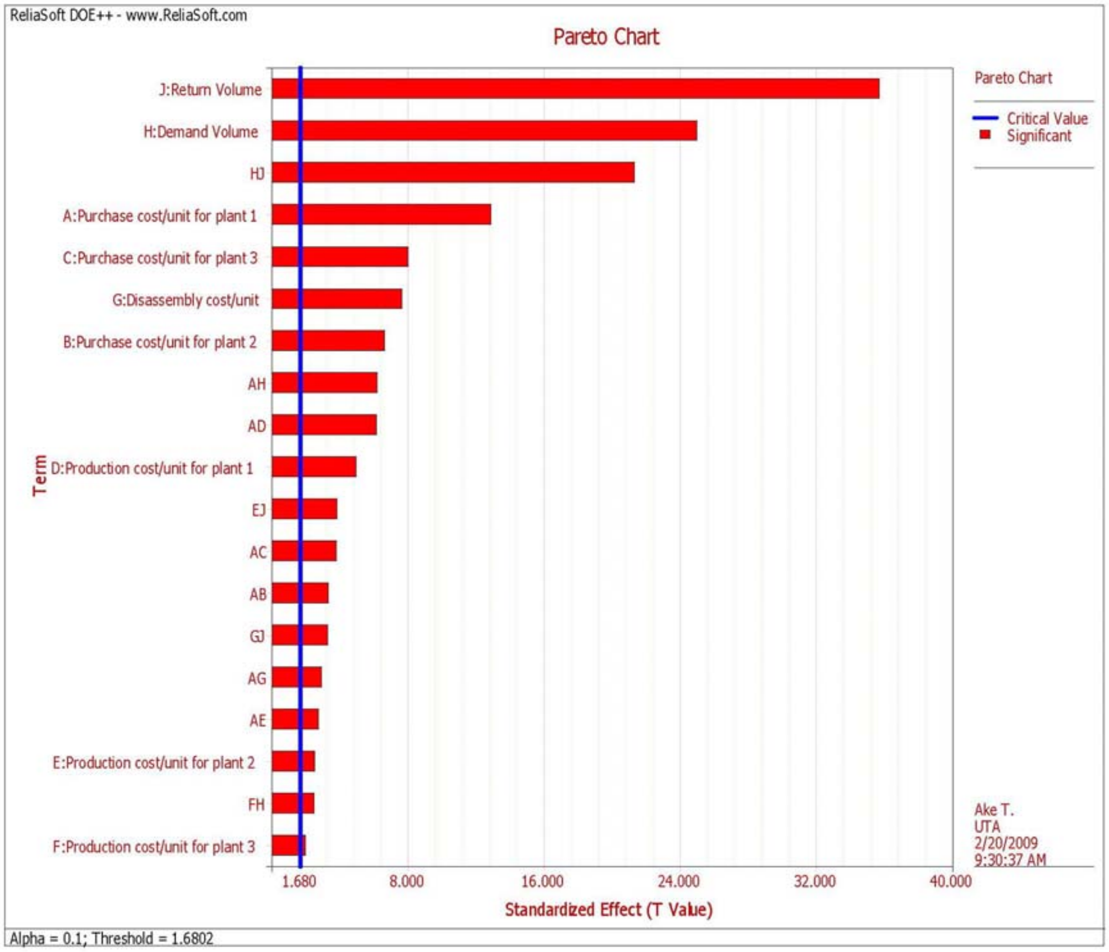

Fig B.3 Pareto chart of significant parameters of reduced model

From the results, nine out of twelve factors and ten two-way interactions among these nine factors have significant effects to the response. Normally, these nine parameters should be analyzed again with the 2 level full factorial designs but if we did the 2 level full factorial test, the number of experiments will be equal to 2^9 or 512 experiments which consumes a lot of time to do and it is not practical in real life to do too many experiments (wastes both time and money). In this case, 2 level fractional factorial design with higher resolution (V or above) can be employed again to thoroughly evaluate the model. Even though this method is not as good as 2 level full factorial design, it saves a lot of time and the results are still reasonable to use. Therefore, all nine significant parameters will be analyzed again with 2 level fractional factorial design using resolution VI with $1/2^2$ fraction. For nine factors, 128 experiments ($2^9 *1/2^2$) will be conducted. These nine factors are purchase cost/unit for plant 1, purchase cost/unit for plant 2, purchase cost/unit for plant 3, production cost/unit for plant 1, production cost/unit for plant 2, production cost/unit for plant 3, disassembly cost/unit, demand volume, and return volume.

1.2 2 level fractional factorial design using resolution VI

After receiving the significant parameters from the screening test, these factors will be tested again by the 2 level fractional factorial design using resolution VI to obtain reliable results. Table B.8 shows setup parameters for level fractional factorial design using resolution VI tests for case study 2. For nine factors resolution VI, DOE software will generate 128 experiments. Table B.9 provides parameters input for each experiment.

Table B.8 Setup parameters for 2 level fractional factorial test resolution VI

Name	Units	Type	Low Level	High Level
Purchase cost/unit for plant 1	$	Qualitative	low	high
Purchase cost/unit for plant 2	$	Qualitative	low	high
Purchase cost/unit for plant 3	$	Qualitative	low	high
Production cost/unit for plant 1	$	Quantitative	3	5
Production cost/unit for plant 2	$	Quantitative	2	4
Production cost/unit for plant 3	$	Quantitative	1	3
Disassembly cost/unit	$	Quantitative	0.2	0.4
Demand Volume	unit	Quantitative	50000	200000
Return Volume	unit	Quantitative	2500	20000

Table B.9 Parameters input for each experiment for 2 level fractional factorial test resolution VI

Run Order	Standard Order	Purchase cost/unit ($), plant 1	Purchase cost/unit ($), plant 2	Purchase cost/unit ($), plant 3	Production cost/unit ($), plant 1	Production cost/unit ($), plant 2	Production cost/unit ($), plant 3	Disassembly cost/unit ($)	Demand Volume (unit)	Return Volume (unit)
1	84	high	high	low	3	4	1	0.4	200000	20000
2	93	low	low	high	5	4	1	0.4	200000	2500
3	113	low	low	low	3	4	3	0.4	200000	2500
4	57	low	low	low	5	4	3	0.2	50000	20000
5	97	low	low	low	3	2	3	0.4	50000	2500
6	5	low	low	high	3	2	1	0.2	200000	20000
7	125	low	low	high	5	4	3	0.4	200000	20000
8	41	low	low	low	5	2	3	0.2	200000	20000
9	36	high	high	low	3	2	3	0.2	50000	20000
10	121	low	low	low	5	4	3	0.4	50000	2500
11	127	low	high	high	5	4	3	0.4	50000	2500
12	20	high	high	low	3	4	1	0.2	200000	2500
13	59	low	high	low	5	4	3	0.2	200000	2500
14	4	high	high	low	3	2	1	0.2	50000	2500
15	73	low	low	low	5	2	1	0.4	200000	20000
16	111	low	high	high	5	2	3	0.4	200000	2500
17	21	low	low	high	3	4	1	0.2	50000	20000
18	103	low	high	high	3	2	3	0.4	50000	2500
19	126	high	low	high	5	4	3	0.4	50000	2500
20	64	high	high	high	5	4	3	0.2	200000	2500
21	88	high	high	high	3	4	1	0.4	50000	2500
22	96	high	high	high	5	4	1	0.4	200000	2500
23	56	high	high	high	3	4	3	0.2	50000	2500
24	69	low	low	high	3	2	1	0.4	200000	2500
25	77	low	low	high	5	2	1	0.4	50000	2500
26	58	high	low	low	5	4	3	0.2	200000	2500
27	53	low	low	high	3	4	3	0.2	50000	2500
28	87	low	high	high	3	4	1	0.4	200000	20000
29	13	low	low	high	5	2	1	0.2	50000	20000
30	6	high	low	high	3	2	1	0.2	50000	2500
31	108	high	high	low	5	2	3	0.4	200000	2500
32	90	high	low	low	5	4	1	0.4	200000	2500
33	105	low	low	low	5	2	3	0.4	200000	2500
34	89	low	low	low	5	4	1	0.4	50000	20000
35	123	low	high	low	5	4	3	0.4	200000	20000
36	15	low	high	high	5	2	1	0.2	200000	2500
37	70	high	low	high	3	2	1	0.4	50000	20000
38	128	high	high	high	5	4	3	0.4	200000	20000
39	22	high	low	high	3	4	1	0.2	200000	2500
40	44	high	high	low	5	2	3	0.2	200000	20000
41	66	high	low	low	3	2	1	0.4	200000	2500
42	32	high	high	high	5	4	1	0.2	200000	20000
43	106	high	low	low	5	2	3	0.4	50000	20000
44	47	low	high	high	5	2	3	0.2	200000	20000
45	43	low	high	low	5	2	3	0.2	50000	2500
46	29	low	low	high	5	4	1	0.2	200000	20000
47	63	low	high	high	5	4	3	0.2	50000	20000
48	102	high	low	high	3	2	3	0.4	50000	2500
49	45	low	low	high	5	2	3	0.2	50000	2500
50	118	high	low	high	3	4	3	0.4	200000	2500
51	8	high	high	high	3	2	1	0.2	200000	20000
52	109	low	low	high	5	2	3	0.4	50000	20000
53	27	low	high	low	5	4	1	0.2	200000	20000
54	33	low	low	low	3	2	3	0.2	50000	20000
55	42	high	low	low	5	2	3	0.2	50000	2500
56	100	high	high	low	3	2	3	0.4	50000	2500
57	119	low	high	high	3	4	3	0.4	200000	2500
58	10	high	low	low	5	2	1	0.2	50000	20000
59	91	low	high	low	5	4	1	0.4	200000	2500
60	3	low	high	low	3	2	1	0.2	200000	20000
61	65	low	low	low	3	2	1	0.4	50000	20000
62	46	high	low	high	5	2	3	0.2	200000	20000
63	76	high	high	low	5	2	1	0.4	200000	20000
64	35	low	high	low	3	2	3	0.2	200000	2500

Table B.9 - continued

Run Order	Standard Order	Purchase cost/unit ($), plant 1	Purchase cost/unit ($), plant 2	Purchase cost/unit ($), plant 3	Production cost/unit ($), plant 1	Production cost/unit ($), plant 2	Production cost/unit ($), plant 3	Disassembly cost/unit ($)	Demand Volume (unit)	Return Volume (unit)
65	60	high	high	low	5	4	3	0.2	50000	20000
66	37	low	low	high	3	2	3	0.2	200000	2500
67	120	high	high	high	3	4	3	0.4	50000	20000
68	52	high	high	low	3	4	3	0.2	200000	20000
69	116	high	high	low	3	4	3	0.4	200000	2500
70	40	high	high	high	3	2	3	0.2	200000	2500
71	17	low	low	low	3	4	1	0.2	200000	2500
72	54	high	low	high	3	4	3	0.2	200000	20000
73	110	high	low	high	5	2	3	0.4	200000	2500
74	49	low	low	low	3	4	3	0.2	200000	20000
75	80	high	high	high	5	2	1	0.4	50000	2500
76	51	low	high	low	3	4	3	0.2	50000	2500
77	67	low	high	low	3	2	1	0.4	200000	2500
78	61	low	low	high	5	4	3	0.2	200000	2500
79	81	low	low	low	3	4	1	0.4	200000	20000
80	55	low	high	high	3	4	3	0.2	200000	20000
81	11	low	high	low	5	2	1	0.2	50000	20000
82	75	low	high	low	5	2	1	0.4	50000	2500
83	114	high	low	low	3	4	3	0.4	50000	20000
84	115	low	high	low	3	4	3	0.4	50000	20000
85	38	high	low	high	3	2	3	0.2	50000	20000
86	94	high	low	high	5	4	1	0.4	50000	20000
87	79	low	high	high	5	2	1	0.4	200000	20000
88	39	low	high	high	3	2	3	0.2	50000	20000
89	18	high	low	low	3	4	1	0.2	50000	20000
90	9	low	low	low	5	2	1	0.2	200000	2500
91	7	low	high	high	3	2	1	0.2	50000	2500
92	14	high	low	high	5	2	1	0.2	200000	2500
93	48	high	high	high	5	2	3	0.2	50000	2500
94	24	high	high	high	3	4	1	0.2	50000	20000
95	98	high	low	low	3	2	3	0.4	200000	20000
96	1	low	low	low	3	2	1	0.2	50000	2500
97	83	low	high	low	3	4	1	0.4	50000	2500
98	85	low	low	high	3	4	1	0.4	50000	2500
99	74	high	low	low	5	2	1	0.4	50000	2500
100	19	low	high	low	3	4	1	0.2	50000	20000
101	92	high	high	low	5	4	1	0.4	50000	20000
102	23	low	high	high	3	4	1	0.2	200000	2500
103	104	high	high	high	3	2	3	0.4	200000	20000
104	30	high	low	high	5	4	1	0.2	50000	2500
105	72	high	high	high	3	2	1	0.4	200000	2500
106	112	high	high	high	5	2	3	0.4	50000	20000
107	107	low	high	low	5	2	3	0.4	50000	20000
108	78	high	low	high	5	2	1	0.4	200000	20000
109	28	high	high	low	5	4	1	0.2	50000	2500
110	82	high	low	low	3	4	1	0.4	50000	2500
111	86	high	low	high	3	4	1	0.4	200000	20000
112	117	low	low	high	3	4	3	0.4	50000	20000
113	26	high	low	low	5	4	1	0.2	200000	20000
114	99	low	high	low	3	2	3	0.4	200000	20000
115	95	low	high	high	5	4	1	0.4	50000	20000
116	12	high	high	low	5	2	1	0.2	200000	2500
117	124	high	high	low	5	4	3	0.4	50000	2500
118	2	high	low	low	3	2	1	0.2	200000	20000
119	25	low	low	low	5	4	1	0.2	50000	2500
120	31	low	high	high	5	4	1	0.2	50000	2500
121	34	high	low	low	3	2	3	0.2	200000	2500
122	16	high	high	high	5	2	1	0.2	50000	20000
123	71	low	high	high	3	2	1	0.4	50000	20000
124	101	low	low	high	3	2	3	0.4	200000	20000
125	50	high	low	low	3	4	3	0.2	50000	2500
126	122	high	low	low	5	4	3	0.4	200000	20000
127	62	high	low	high	5	4	3	0.2	50000	20000
128	68	high	high	low	3	2	1	0.4	50000	20000

All inputs from every experiment will be put in the simulation model (Model 3.1) again to obtain the sets of outputs. Then, all inputs and outputs of each experiment will be put in the DEA model in chapter 3 to obtain a relative efficiency score for each experiment. Table B.10 illustrates parameters and a response (relative efficiency) of each experiment.

Table B.10 Parameters and a response (relative efficiency) of each experiment

Run Order	Standard Order	Purchase cost/unit ($), plant 1	Purchase cost/unit ($), plant 2	Purchase cost/unit ($), plant 3	Production cost/unit ($), plant 1	Production cost/unit ($), plant 2	Production cost/unit ($), plant 3	Disassembly cost/unit ($)	Demand Volume (unit)	Return Volume (unit)	Efficiency
1	84	high	high	low	3	4	1	0.4	200000	20000	0.525
2	93	low	low	high	5	4	1	0.4	200000	2500	0.853
3	113	low	low	low	3	4	3	0.4	200000	2500	0.906
4	57	low	low	low	5	4	3	0.2	50000	20000	0.538
5	97	low	low	low	3	2	3	0.4	50000	2500	0.719
6	5	low	low	high	3	2	1	0.2	200000	20000	0.538
7	125	low	low	high	5	4	3	0.4	200000	20000	0.499
8	41	low	low	low	5	2	3	0.2	200000	20000	0.584
9	36	high	high	low	3	2	3	0.2	50000	20000	0.410
10	121	low	low	low	5	4	3	0.4	50000	2500	0.716
11	127	low	high	high	5	4	3	0.4	50000	2500	0.588
12	20	high	high	low	3	4	1	0.2	200000	2500	0.971
13	59	low	high	low	5	4	3	0.2	200000	2500	0.970
14	4	high	high	low	3	2	1	0.2	50000	2500	0.558
15	73	low	low	low	5	2	1	0.4	200000	20000	0.553
16	111	low	high	high	5	2	3	0.4	200000	2500	0.825
17	21	low	low	high	3	4	1	0.2	50000	20000	0.526
18	103	low	high	high	3	2	3	0.4	50000	2500	0.588
19	126	high	low	high	5	4	3	0.4	50000	2500	0.511
20	64	high	high	high	5	4	3	0.2	200000	2500	0.880
21	88	high	high	high	3	4	1	0.4	50000	2500	0.481
22	96	high	high	high	5	4	1	0.4	200000	2500	0.823
23	56	high	high	high	3	4	3	0.2	50000	2500	0.503
24	69	low	low	high	3	2	1	0.4	200000	2500	0.877
25	77	low	low	high	5	2	1	0.4	50000	2500	0.544
26	58	high	low	low	5	4	3	0.2	200000	2500	0.931
27	53	low	low	high	3	4	3	0.2	50000	2500	0.686
28	87	low	high	high	3	4	1	0.4	200000	20000	0.505
29	13	low	low	high	5	2	1	0.2	50000	20000	0.466
30	6	high	low	high	3	2	1	0.2	50000	2500	0.552
31	108	high	high	low	5	2	3	0.4	200000	2500	0.826
32	90	high	low	low	5	4	1	0.4	200000	2500	0.876
33	105	low	low	low	5	2	3	0.4	200000	2500	0.906
34	89	low	low	low	5	4	1	0.4	50000	20000	0.443
35	123	low	high	low	5	4	3	0.4	200000	20000	0.687
36	15	low	high	high	5	2	1	0.2	200000	2500	0.923
37	70	high	low	high	3	2	1	0.4	50000	20000	0.446
38	128	high	high	high	5	4	3	0.4	200000	20000	0.434
39	22	high	low	high	3	4	1	0.2	200000	2500	0.920
40	44	high	high	low	5	2	3	0.2	200000	20000	0.484
41	66	high	low	low	3	2	1	0.4	200000	2500	0.906
42	32	high	high	high	5	4	1	0.2	200000	20000	0.475
43	106	high	low	low	5	2	3	0.4	50000	20000	0.457
44	47	low	high	high	5	2	3	0.2	200000	20000	0.486
45	43	low	high	low	5	2	3	0.2	50000	2500	0.671
46	29	low	low	high	5	4	1	0.2	200000	20000	0.516
47	63	low	high	high	5	4	3	0.2	50000	20000	0.499
48	102	high	low	high	3	2	3	0.4	50000	2500	0.527
49	45	low	low	high	5	2	3	0.2	50000	2500	0.567
50	118	high	low	high	3	4	3	0.4	200000	2500	0.813
51	8	high	high	high	3	2	1	0.2	200000	20000	0.485
52	109	low	low	high	5	2	3	0.4	50000	20000	0.467
53	27	low	high	low	5	4	1	0.2	200000	20000	0.535
54	33	low	low	low	3	2	3	0.2	50000	20000	0.758
55	42	high	low	low	5	2	3	0.2	50000	2500	0.561
56	100	high	high	low	3	2	3	0.4	50000	2500	0.489
57	119	low	high	high	3	4	3	0.4	200000	2500	0.829
58	10	high	low	low	5	2	1	0.2	50000	20000	0.463
59	91	low	high	low	5	4	1	0.4	200000	2500	0.878
60	3	low	high	low	3	2	1	0.2	200000	20000	0.578
61	65	low	low	low	3	2	1	0.4	50000	20000	0.634
62	46	high	low	high	5	2	3	0.2	200000	20000	0.465
63	76	high	high	low	5	2	1	0.4	200000	20000	0.529
64	35	low	high	low	3	2	3	0.2	200000	2500	0.980

Table B.10 - continued

Run Order	Standard Order	Purchase cost/unit ($), plant 1	Purchase cost/unit ($), plant 2	Purchase cost/unit ($), plant 3	Production cost/unit ($), plant 1	Production cost/unit ($), plant 2	Production cost/unit ($), plant 3	Disassembly cost/unit ($)	Demand Volume (unit)	Return Volume (unit)	Efficiency
65	60	high	high	low	5	4	3	0.2	50000	20000	0.411
66	37	low	low	high	3	2	3	0.2	200000	2500	0.956
67	120	high	high	high	3	4	3	0.4	50000	20000	0.396
68	52	high	high	low	3	4	3	0.2	200000	20000	0.485
69	116	high	high	low	3	4	3	0.4	200000	2500	0.827
70	40	high	high	high	3	2	3	0.2	200000	2500	0.906
71	17	low	low	low	3	4	1	0.2	200000	2500	1.000
72	54	high	low	high	3	4	3	0.2	200000	20000	0.471
73	110	high	low	high	5	2	3	0.4	200000	2500	0.805
74	49	low	low	low	3	4	3	0.2	200000	20000	0.599
75	80	high	high	high	5	2	1	0.4	50000	2500	0.483
76	51	low	high	low	3	4	3	0.2	50000	2500	0.686
77	67	low	high	low	3	2	1	0.4	200000	2500	0.905
78	61	low	low	high	5	4	3	0.2	200000	2500	0.941
79	81	low	low	low	3	4	1	0.4	200000	20000	0.579
80	55	low	high	high	3	4	3	0.2	200000	20000	0.490
81	11	low	high	low	5	2	1	0.2	50000	20000	0.450
82	75	low	high	low	5	2	1	0.4	50000	2500	0.536
83	114	high	low	low	3	4	3	0.4	50000	20000	0.441
84	115	low	high	low	3	4	3	0.4	50000	20000	0.513
85	38	high	low	high	3	2	3	0.2	50000	20000	0.449
86	94	high	low	high	5	4	1	0.4	50000	20000	0.423
87	79	low	high	high	5	2	1	0.4	200000	20000	0.479
88	39	low	high	high	3	2	3	0.2	50000	20000	0.505
89	18	high	low	low	3	4	1	0.2	50000	20000	0.450
90	9	low	low	low	5	2	1	0.2	200000	2500	1.000
91	7	low	high	high	3	2	1	0.2	50000	2500	0.612
92	14	high	low	high	5	2	1	0.2	200000	2500	0.985
93	48	high	high	high	5	2	3	0.2	50000	2500	0.502
94	24	high	high	high	3	4	1	0.2	50000	20000	0.403
95	98	high	low	low	3	2	3	0.4	200000	20000	0.491
96	1	low	low	low	3	2	1	0.2	50000	2500	0.812
97	83	low	high	low	3	4	1	0.4	50000	2500	0.635
98	85	low	low	high	3	4	1	0.4	50000	2500	0.640
99	74	high	low	low	5	2	1	0.4	50000	2500	0.540
100	19	low	high	low	3	4	1	0.2	50000	20000	0.519
101	92	high	high	low	5	4	1	0.4	50000	20000	0.428
102	23	low	high	high	3	4	1	0.2	200000	2500	0.950
103	104	high	high	high	3	2	3	0.4	200000	20000	0.459
104	30	high	low	high	5	4	1	0.2	50000	2500	0.532
105	72	high	high	high	3	2	1	0.4	200000	2500	0.826
106	112	high	high	high	5	2	3	0.4	50000	20000	0.388
107	107	low	high	low	5	2	3	0.4	50000	20000	0.489
108	78	high	low	high	5	2	1	0.4	200000	20000	0.527
109	28	high	high	low	5	4	1	0.2	50000	2500	0.550
110	82	high	low	low	3	4	1	0.4	50000	2500	0.536
111	86	high	low	high	3	4	1	0.4	200000	20000	0.474
112	117	low	low	high	3	4	3	0.4	50000	20000	0.513
113	26	high	low	low	5	4	1	0.2	200000	20000	0.533
114	99	low	high	low	3	2	3	0.4	200000	20000	0.535
115	95	low	high	high	5	4	1	0.4	50000	20000	0.465
116	12	high	high	low	5	2	1	0.2	200000	2500	0.986
117	124	high	high	low	5	4	3	0.4	50000	2500	0.488
118	2	high	low	low	3	2	1	0.2	200000	20000	0.567
119	25	low	low	low	5	4	1	0.2	50000	2500	0.561
120	31	low	high	high	5	4	1	0.2	50000	2500	0.608
121	34	high	low	low	3	2	3	0.2	200000	2500	0.938
122	16	high	high	high	5	2	1	0.2	50000	20000	0.405
123	71	low	high	high	3	2	1	0.4	50000	20000	0.499
124	101	low	low	high	3	2	3	0.4	200000	20000	0.515
125	50	high	low	low	3	4	3	0.2	50000	2500	0.546
126	122	high	low	low	5	4	3	0.4	200000	20000	0.485
127	62	high	low	high	5	4	3	0.2	50000	20000	0.431
128	68	high	high	low	3	2	1	0.4	50000	20000	0.431

After all inputs and responses needed are completed, DOE software will evaluate the initial results that include all non-significant interactions. The results from the initial analysis can be shown below in table B.11 – table B.12 and figure B.4 – figure B.5. Table B.11 provides the design setting, factor properties and ANOVA Table of all factors in an initial design. Table B.12 shows regression information of all factors and interactions in initial design.

Table B.11 Design setting, factor properties and ANOVA Table of all factors in the initial design

Current Design Settings

Factors:	9
Total Blocks:	1
Total Center Points:	0
Observations:	128
Responses:	1

Factor Properties

Factor	Name	Units	Type	Low Level	High Level
A	Purchase cost/unit for plant 1	$	Qualitative	low	high
B	Purchase cost/unit for plant 2	$	Qualitative	low	high
C	Purchase cost/unit for plant 3	$	Qualitative	low	high
D	Production cost/unit for plant 1	$	Quantitative	3	5
E	Production cost/unit for plant 2	$	Quantitative	2	4
F	Production cost/unit for plant 3	$	Quantitative	1	3
G	Disassembly cost/unit	$	Quantitative	0.2	0.4
H	Demand Volume	unit	Quantitative	5.00E+04	2.00E+05
J	Return Volume	unit	Quantitative	2500	2.00E+04

ANOVA Table

Source of Variation	Degrees of Freedom	Sum of Squares [Partial]	Mean Squares [Partial]	F Ratio	P Value
Model	127	4.2211	0.0332	-	-
Main Effects	9	3.3457	0.3717	-	-
2-Way Interaction	36	0.7773	0.0216	-	-
3-Way Interaction	55	0.0854	0.0016	-	-
4-Way Interaction	27	0.0128	0.0005	-	-
Residual	0				
Total	127	4.2211			

Table B.12 Regression information of all factors and interactions in initial design

Regression Information

Term	Effect	Coefficient	Standard Error	Low CI	High CI	T Value	P Value
Intercept		0.6182	-	-	-	-	-
A:Purchase cost/unit for plant 1*	-0.0708	-0.0354	-	-	-	-	-
B:Purchase cost/unit for plant 2*	-0.0281	-0.014	-	-	-	-	-
C:Purchase cost/unit for plant 3*	-0.0447	-0.0223	-	-	-	-	-
D:Production cost/unit for plant 1*	-0.022	-0.011	-	-	-	-	-
E:Production cost/unit for plant 2	-0.0075	-0.0037	-	-	-	-	-
F:Production cost/unit for plant 3	-0.0045	-0.0022	-	-	-	-	-
G:Disassembly cost/unit*	-0.036	-0.018	-	-	-	-	-
H:Demand Volume*	0.185	0.0925	-	-	-	-	-
J:Return Volume*	-0.2463	-0.1231	-	-	-	-	-
AB	0.003	0.0015	-	-	-	-	-
AC*	0.0153	0.0077	-	-	-	-	-
AD*	0.0199	0.0099	-	-	-	-	-
AE	-0.0048	-0.0024	-	-	-	-	-
AF*	-0.023	-0.0115	-	-	-	-	-
AG	0.0012	0.0006	-	-	-	-	-
AH*	0.0311	0.0156	-	-	-	-	-
AJ	0.0008	0.0004	-	-	-	-	-
BC	0.0052	0.0026	-	-	-	-	-
BD*	0.0125	0.0063	-	-	-	-	-
BE*	0.0139	0.007	-	-	-	-	-
BF	-0.0019	-0.001	-	-	-	-	-
BG	0.0022	0.0011	-	-	-	-	-
BH*	0.0114	0.0057	-	-	-	-	-
BJ	-0.0006	-0.0003	-	-	-	-	-
CD	0.0049	0.0025	-	-	-	-	-
CE	0.008	0.004	-	-	-	-	-
CF	-0.0064	-0.0032	-	-	-	-	-
CG	0.0006	0.0003	-	-	-	-	-
CH	-0.0061	-0.0031	-	-	-	-	-
CJ	-0.0017	-0.0009	-	-	-	-	-
DE*	0.0123	0.0062	-	-	-	-	-
DF	0.0084	0.0042	-	-	-	-	-
DG	0.0061	0.0031	-	-	-	-	-
DH*	0.018	0.009	-	-	-	-	-
DJ	0.0004	0.0002	-	-	-	-	-
EF	0.0076	0.0038	-	-	-	-	-
EG	0.0076	0.0038	-	-	-	-	-
EH	0.0023	0.0012	-	-	-	-	-
EJ	-0.002	-0.001	-	-	-	-	-
FG	-0.0001	-5.75E-05	-	-	-	-	-
FH*	-0.0165	-0.0083	-	-	-	-	-
FJ	0.0041	0.002	-	-	-	-	-
GH*	-0.0131	-0.0065	-	-	-	-	-
GJ*	0.0278	0.0139	-	-	-	-	-
HJ*	-0.1396	-0.0698	-	-	-	-	-
ABC*	-0.0101	-0.0051	-	-	-	-	-
ABD*	-0.0145	-0.0073	-	-	-	-	-
ABE	-0.0072	-0.0036	-	-	-	-	-
ABF	-3.48E-05	-1.74E-05	-	-	-	-	-
ABG	-0.0034	-0.0017	-	-	-	-	-
ABH	-0.0029	-0.0015	-	-	-	-	-
ABJ	-0.0009	-0.0004	-	-	-	-	-
ACD	-0.0056	-0.0028	-	-	-	-	-
ACE*	-0.0108	-0.0054	-	-	-	-	-
ACF*	0.0151	0.0075	-	-	-	-	-
ACG	-2.66E-05	-1.33E-05	-	-	-	-	-
ACH	-0.0028	-0.0014	-	-	-	-	-
ACJ	0.0024	0.0012	-	-	-	-	-
ADE*	-0.0123	-0.0062	-	-	-	-	-
ADF*	-0.012	-0.006	-	-	-	-	-
ADG	-0.0069	-0.0035	-	-	-	-	-
ADH*	-0.0172	-0.0086	-	-	-	-	-
ADJ	-0.0011	-0.0006	-	-	-	-	-
AEF	-0.0018	-0.0009	-	-	-	-	-
AEG	-0.006	-0.003	-	-	-	-	-
AEH	-0.0063	-0.0032	-	-	-	-	-
AEJ	0.0023	0.0011	-	-	-	-	-
AFG	0.0015	0.0007	-	-	-	-	-
AFH	-0.0003	-0.0002	-	-	-	-	-
AFJ	-0.002	-0.001	-	-	-	-	-
AGH	-0.0056	-0.0028	-	-	-	-	-
AGJ	0.0038	0.0019	-	-	-	-	-
AHJ*	-0.0105	-0.0053	-	-	-	-	-
BDF	0.0028	0.0014	-	-	-	-	-
BDG	-0.0027	-0.0013	-	-	-	-	-
BDJ	0.0032	0.0016	-	-	-	-	-
BEF	-0.0052	-0.0026	-	-	-	-	-
BEG	-0.0008	-0.0004	-	-	-	-	-
BEJ	0.0053	0.0026	-	-	-	-	-
BFH	0.006	0.003	-	-	-	-	-
BGH	0.0038	0.0019	-	-	-	-	-
BHJ	0.0033	0.0016	-	-	-	-	-
CDF*	-0.0112	-0.0056	-	-	-	-	-
CDG	-0.0063	-0.0031	-	-	-	-	-
CDJ	0.0011	0.0006	-	-	-	-	-
CEF	-0.0036	-0.0018	-	-	-	-	-
CEG	-0.0089	-0.0044	-	-	-	-	-
CEJ	-0.0024	-0.0012	-	-	-	-	-
CFH	0.0033	0.0017	-	-	-	-	-
CGH	-0.0045	-0.0023	-	-	-	-	-
CHJ	-0.0057	-0.0028	-	-	-	-	-
DEF*	0.0203	0.0102	-	-	-	-	-
DEG	0.0026	0.0013	-	-	-	-	-
DEJ	0.004	0.002	-	-	-	-	-
DFG	0.0082	0.0041	-	-	-	-	-
DFH	-0.0039	-0.0019	-	-	-	-	-
DFJ	-0.0008	-0.0004	-	-	-	-	-
DGH	-0.0013	-0.0007	-	-	-	-	-
DGJ	0.003	0.0015	-	-	-	-	-
DHJ	0.0021	0.001	-	-	-	-	-
ABDF	-0.0029	-0.0014	-	-	-	-	-
ABDG	0.0031	0.0016	-	-	-	-	-
ABDJ	-0.0036	-0.0018	-	-	-	-	-
ABEF	-0.0002	-8.15E-05	-	-	-	-	-
ABEG	0.001	0.0005	-	-	-	-	-
ABEJ	-0.0045	-0.0022	-	-	-	-	-
ABFH	0.0004	0.0002	-	-	-	-	-
ABGH	-0.0018	-0.0009	-	-	-	-	-
ABHJ	-0.0023	-0.0012	-	-	-	-	-
ACDF	0.0042	0.0021	-	-	-	-	-
ACDG	0.006	0.003	-	-	-	-	-
ACDJ	-0.0022	-0.0011	-	-	-	-	-
ACEF	0.0051	0.0026	-	-	-	-	-
ACEG	0.009	0.0045	-	-	-	-	-
ACEJ	0.0026	0.0013	-	-	-	-	-
ACFH	-0.0031	-0.0015	-	-	-	-	-
ACGH	0.004	0.002	-	-	-	-	-
ACHJ	0.0047	0.0023	-	-	-	-	-
ADEF	-0.0036	-0.0018	-	-	-	-	-
ADEG	-0.0029	-0.0015	-	-	-	-	-
ADEJ	-0.0043	-0.0022	-	-	-	-	-
ADFG	-0.0078	-0.0039	-	-	-	-	-
ADFH	-0.0011	-0.0006	-	-	-	-	-
ADFJ	0.0014	0.0007	-	-	-	-	-
ADGH	0.0014	0.0007	-	-	-	-	-
ADGJ	0.0017	0.0008	-	-	-	-	-
ADHJ	-0.0032	-0.0016	-	-	-	-	-

*: Significant effects according to Lenth's method.

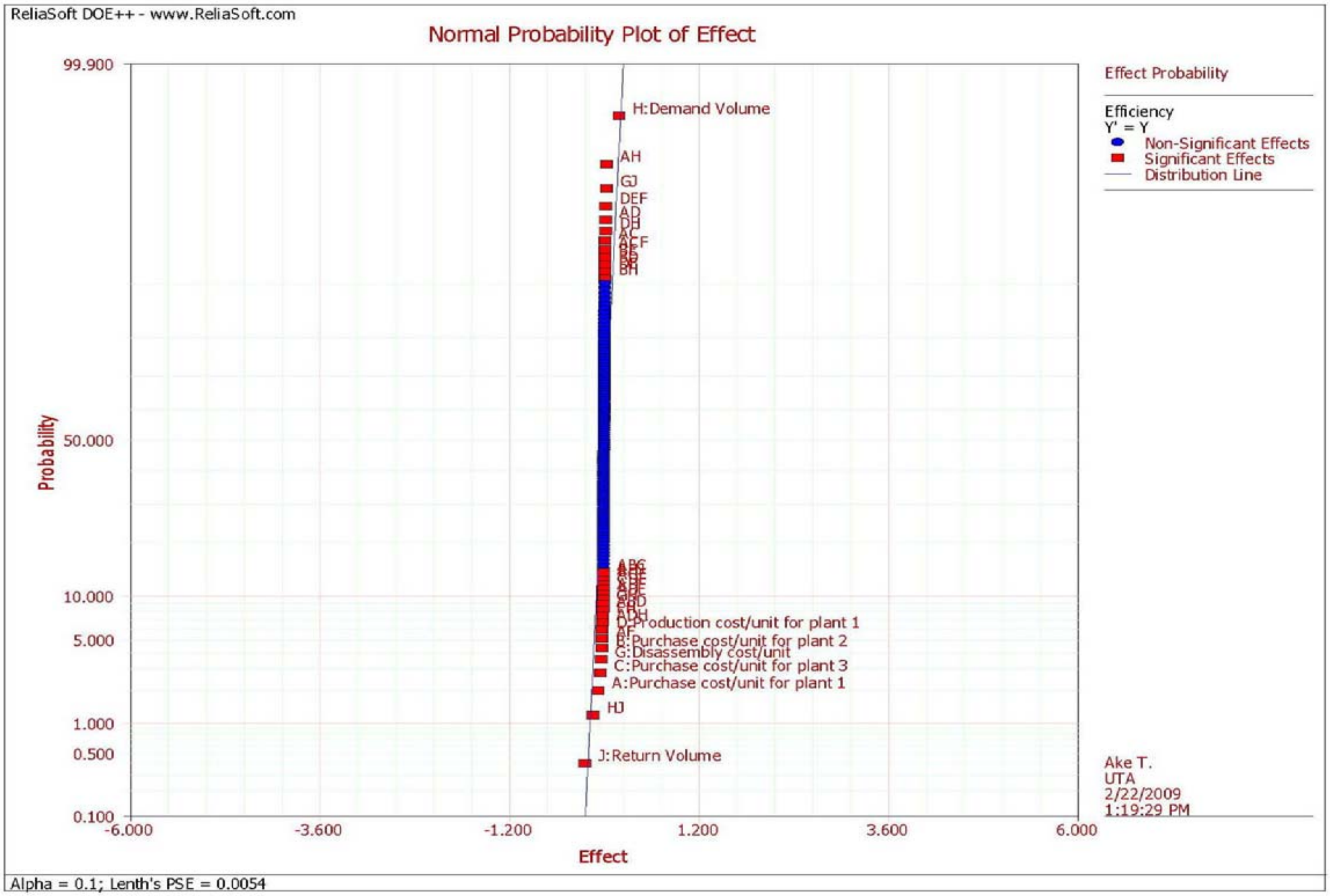

Fig B.4 Normal Probability Plot of Effect of all initial parameters of screening test

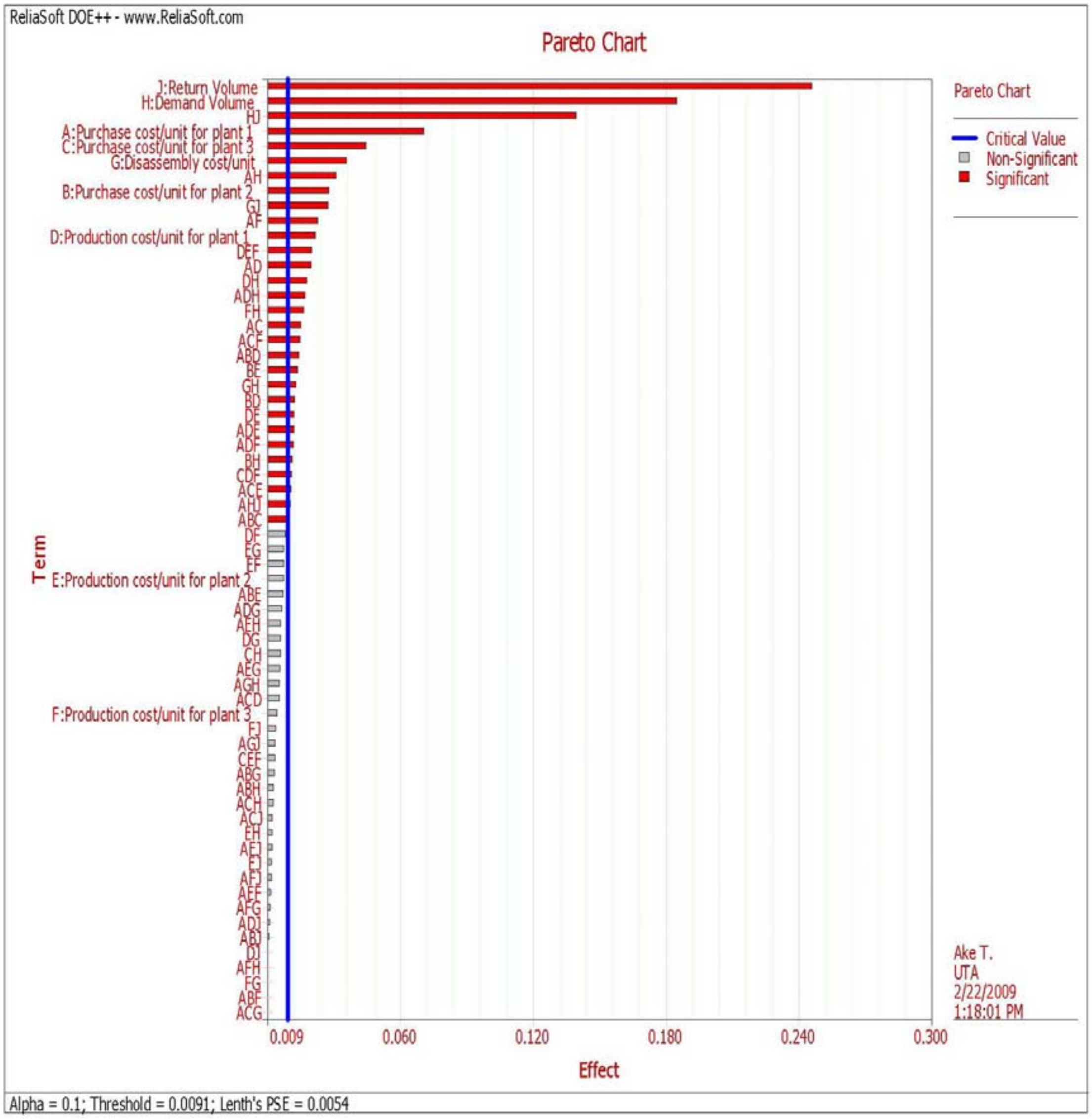

Fig B.5 Pareto chart of all parameters and interactions

In the next step, DOE software will be used to eliminate non-significant parameters and non-significant interactions from the initial test. Table B.13 provides the design setting, factor properties and ANOVA Table of the reduced model (eliminated non-significant factors and interactions). Table B.14 shows regression information of all significant factors and interactions.

Table B.13 Design setting, factor properties and ANOVA Table of reduced model

Current Design Settings

Factors:	9
Total Blocks:	1
Total Center Points:	0
Observations:	128
Responses:	1

Factor Properties

Factor	Name	Units	Type	Low Level	High Level
A	Purchase cost/unit for plant 1	$	Qualitative	low	high
B	Purchase cost/unit for plant 2	$	Qualitative	low	high
C	Purchase cost/unit for plant 3	$	Qualitative	low	high
D	Production cost/unit for plant 1	$	Quantitative	3	5
E	Production cost/unit for plant 2	$	Quantitative	2	4
F	Production cost/unit for plant 3	$	Quantitative	1	3
G	Disassembly cost/unit	$	Quantitative	0.2	0.4
H	Demand Volume	unit	Quantitative	5.00E+04	2.00E+05
J	Return Volume	unit	Quantitative	2500	2.00E+04

ANOVA Table

Source of Variation	Degrees of Freedom	Sum of Squares [Partial]	Mean Squares [Partial]	F Ratio	P Value
Model	32	4.168	0.1303	233.1642	4.67E-77
Main Effects	9	3.3457	0.3717	665.4542	1.10E-81
2-Way Interaction	13	0.7616	0.0586	104.873	2.63E-50
3-Way Interaction	10	0.0608	0.0061	10.8818	4.07E-12
Residual	95	0.0531	0.0006		
Lack of Fit	95	0.0531	0.0006		
Total	127	4.2211			

S = 0.0236
R-sq = 98.74%
R-sq(adj) = 98.32%

Table B.14 Regression information of significant factors and interactions

Term	Effect	Coefficient	Standard Error	Low CI	High CI	T Value	P Value
Intercept		0.6182	0.0021	0.6148	0.6217	295.9393	0
A:Purchase cost/unit for plant 1	-0.0708	-0.0354	0.0021	-0.0389	-0.0319	-16.945	0
B:Purchase cost/unit for plant 2	-0.0281	-0.014	0.0021	-0.0175	-0.0106	-6.7179	1.35E-09
C:Purchase cost/unit for plant 3	-0.0447	-0.0223	0.0021	-0.0258	-0.0189	-10.6895	0
D:Production cost/unit for plant 1	-0.022	-0.011	0.0021	-0.0145	-0.0075	-5.259	8.91E-07
E:Production cost/unit for plant 2	-0.0075	-0.0037	0.0021	-0.0072	-0.0003	-1.7939	0.076
F:Production cost/unit for plant 3	-0.0045	-0.0022	0.0021	-0.0057	0.0012	-1.0661	0.2891
G:Disassembly cost/unit	-0.036	-0.018	0.0021	-0.0215	-0.0145	-8.6196	1.47E-13
H:Demand Volume	0.185	0.0925	0.0021	0.0891	0.096	44.2876	0
J:Return Volume	-0.2463	-0.1231	0.0021	-0.1266	-0.1197	-58.9479	0
AC	0.0153	0.0077	0.0021	0.0042	0.0111	3.6675	0.0004
AD	0.0199	0.0099	0.0021	0.0065	0.0134	4.7616	6.87E-06
AF	-0.023	-0.0115	0.0021	-0.015	-0.008	-5.5045	3.14E-07
AH	0.0311	0.0156	0.0021	0.0121	0.019	7.4531	4.20E-11
BD	0.0125	0.0063	0.0021	0.0028	0.0097	3.0035	0.0034
BE	0.0139	0.007	0.0021	0.0035	0.0104	3.3316	0.0012
BH	0.0114	0.0057	0.0021	0.0022	0.0092	2.7259	0.0076
DE	0.0123	0.0062	0.0021	0.0027	0.0096	2.9483	0.004
DH	0.018	0.009	0.0021	0.0055	0.0125	4.3044	4.07E-05
FH	-0.0165	-0.0083	0.0021	-0.0117	-0.0048	-3.9566	0.0001
GH	-0.0131	-0.0065	0.0021	-0.01	-0.0031	-3.1282	0.0023
GJ	0.0278	0.0139	0.0021	0.0104	0.0173	6.6419	1.92E-09
HJ	-0.1396	-0.0698	0.0021	-0.0733	-0.0664	-33.4223	0
ABC	-0.0101	-0.0051	0.0021	-0.0085	-0.0016	-2.4182	0.0175
ABD	-0.0145	-0.0073	0.0021	-0.0107	-0.0038	-3.4729	0.0008
ACE	-0.0108	-0.0054	0.0021	-0.0089	-0.002	-2.5953	0.011
ACF	0.0151	0.0075	0.0021	0.0041	0.011	3.6066	0.0005
ADE	-0.0123	-0.0062	0.0021	-0.0096	-0.0027	-2.9444	0.0041
ADF	-0.012	-0.006	0.0021	-0.0095	-0.0025	-2.8766	0.005
ADH	-0.0172	-0.0086	0.0021	-0.0121	-0.0051	-4.1215	8.05E-05
AHJ	-0.0105	-0.0053	0.0021	-0.0087	-0.0018	-2.5188	0.0134
CDF	-0.0112	-0.0056	0.0021	-0.0091	-0.0021	-2.6819	0.0086
DEF	0.0203	0.0102	0.0021	0.0067	0.0136	4.8681	4.48E-06

Figure B.6 shows normal probability plot of significant parameters and interactions.

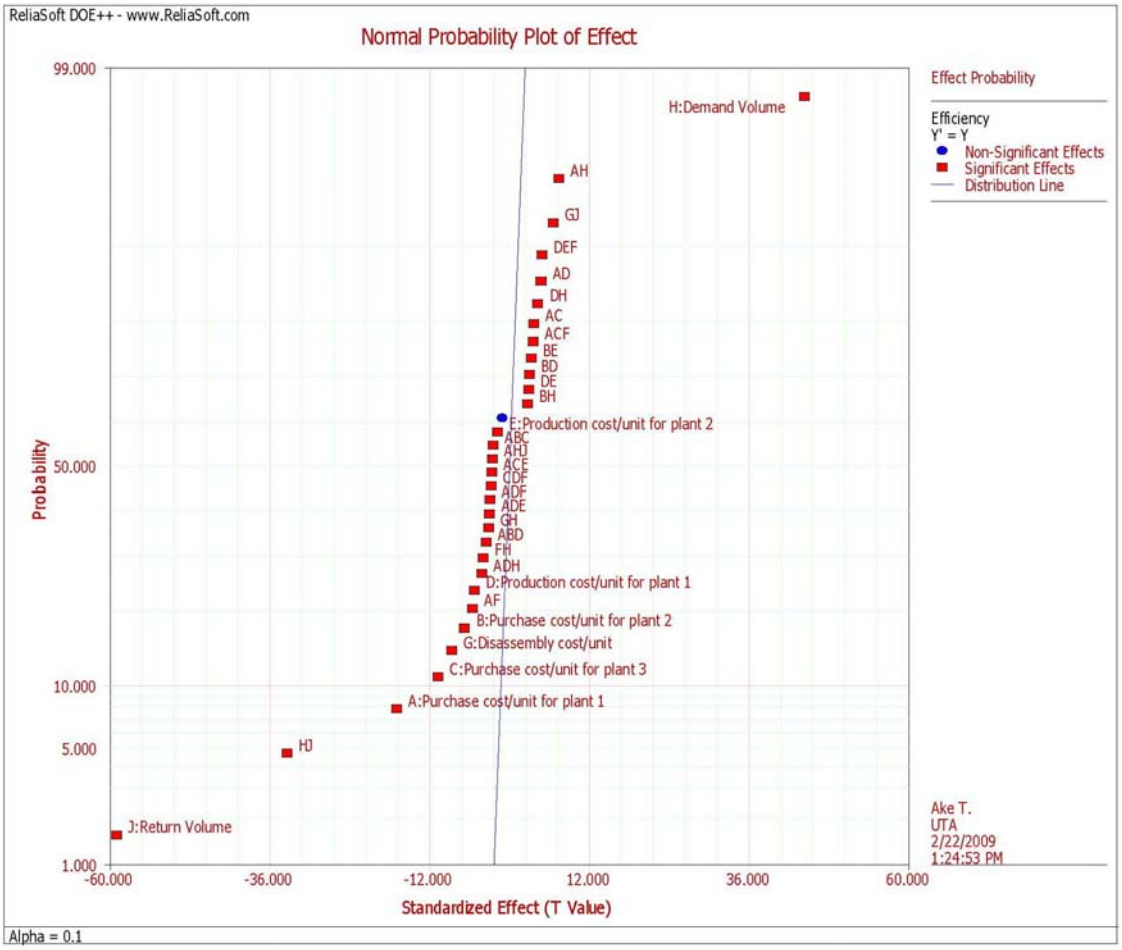

Fig B.6 Normal probability plot of significant parameters and interactions

Figure B.7 shows the Pareto chart of all significant parameters and interactions. Figure B.8 provides the main effects plot of significant parameters while figure B.9 shows the interaction matrix plot between significant parameters.

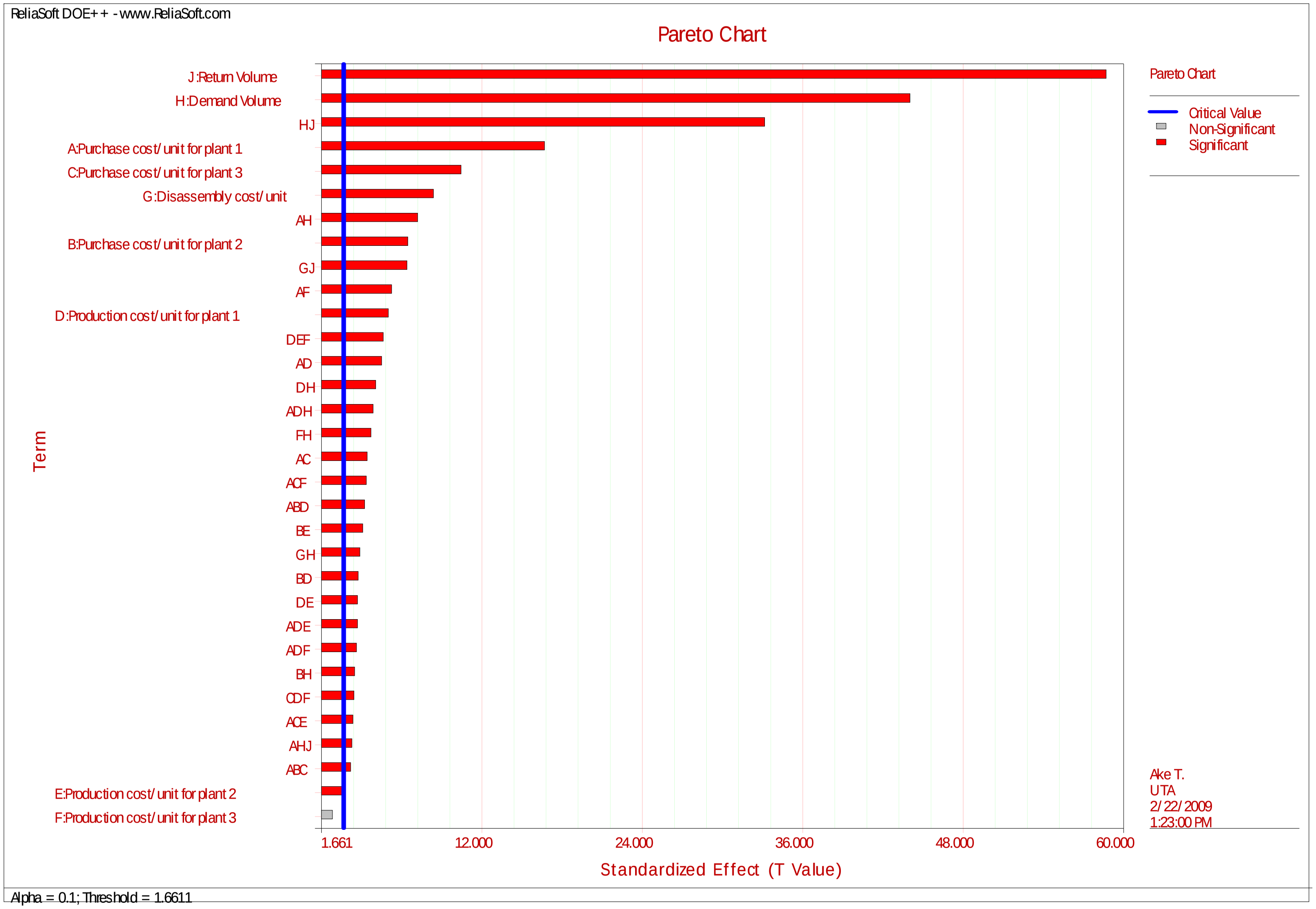

Fig B.7 Pareto chart of all significant parameters and interactions

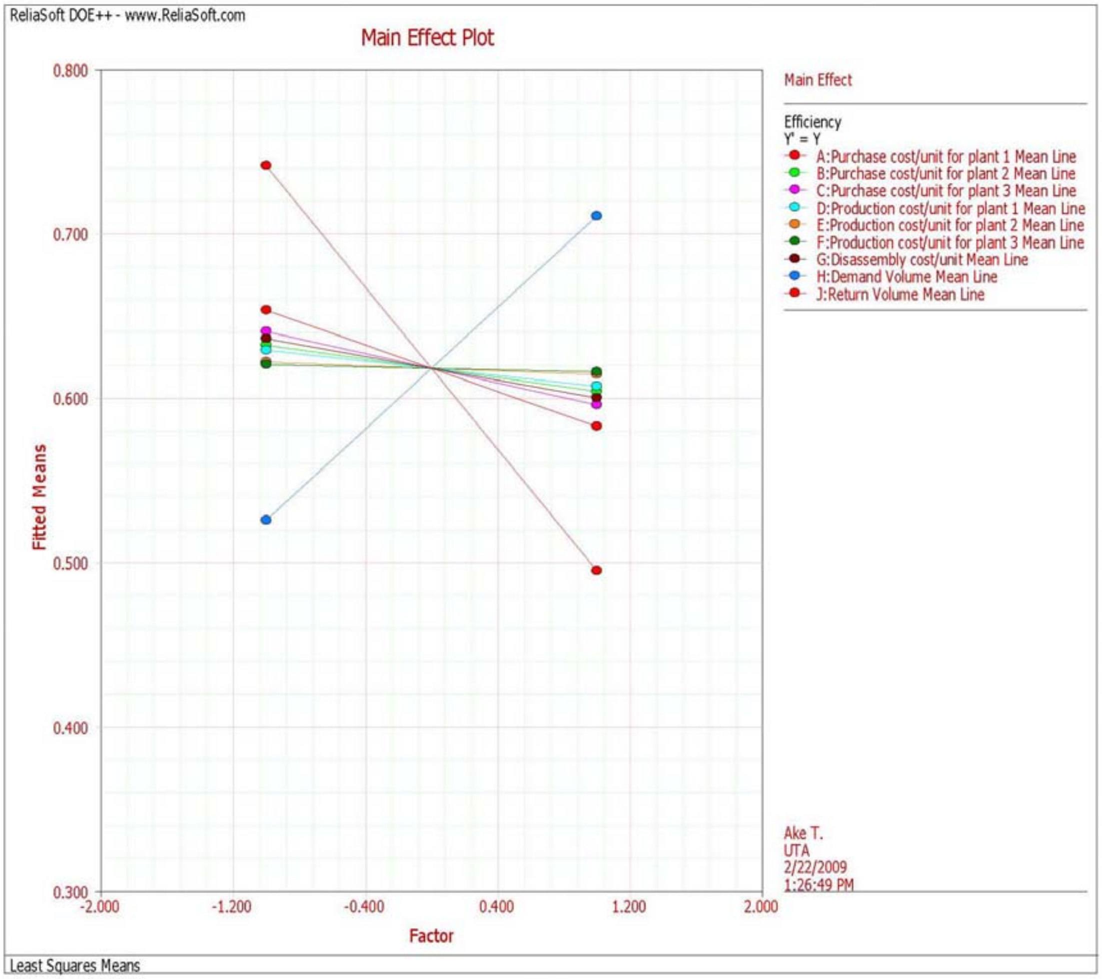

Fig B.8 Main effects plot of significant parameters

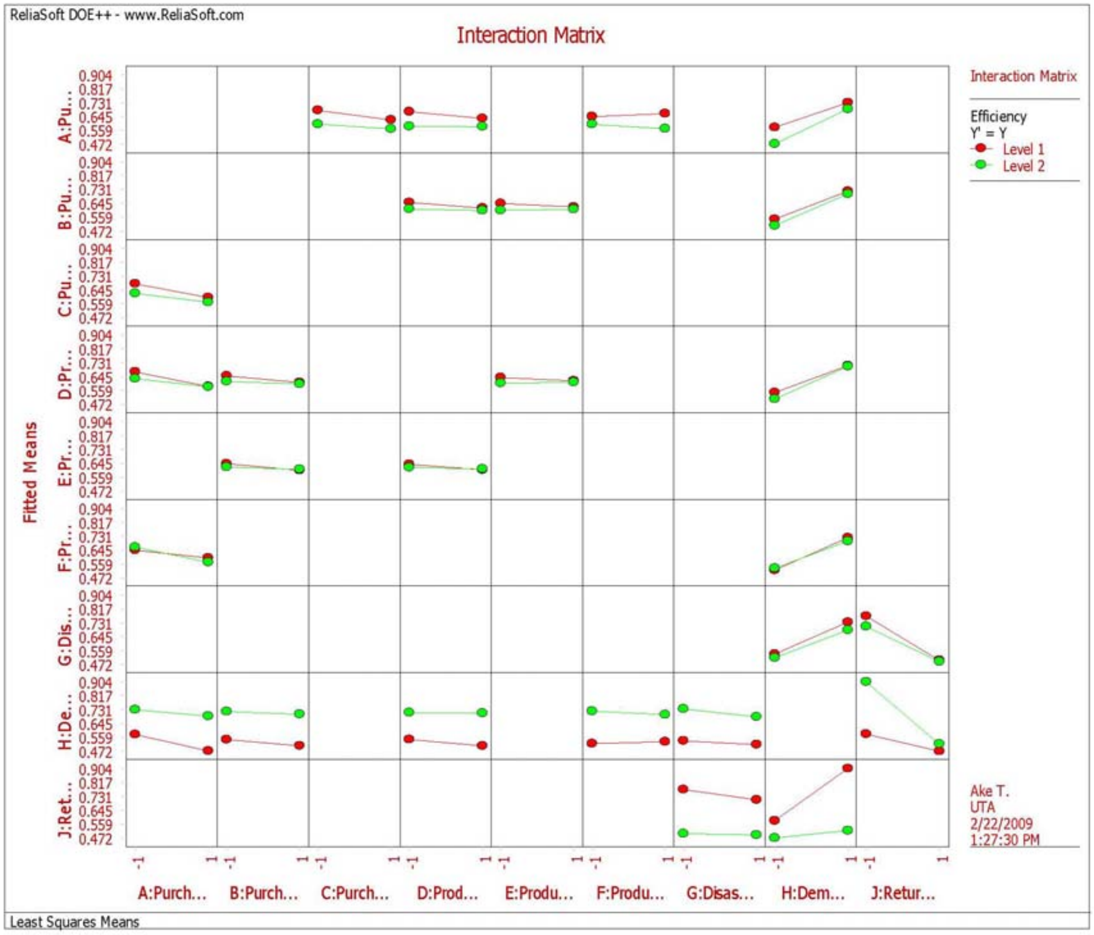

Fig B.9 Interaction matrix plot between significant parameters

Figure B.10 shows the plot between effects and fitted mean. Figure B.11 shows the plot between predicted value (fitted model) and the actual value.

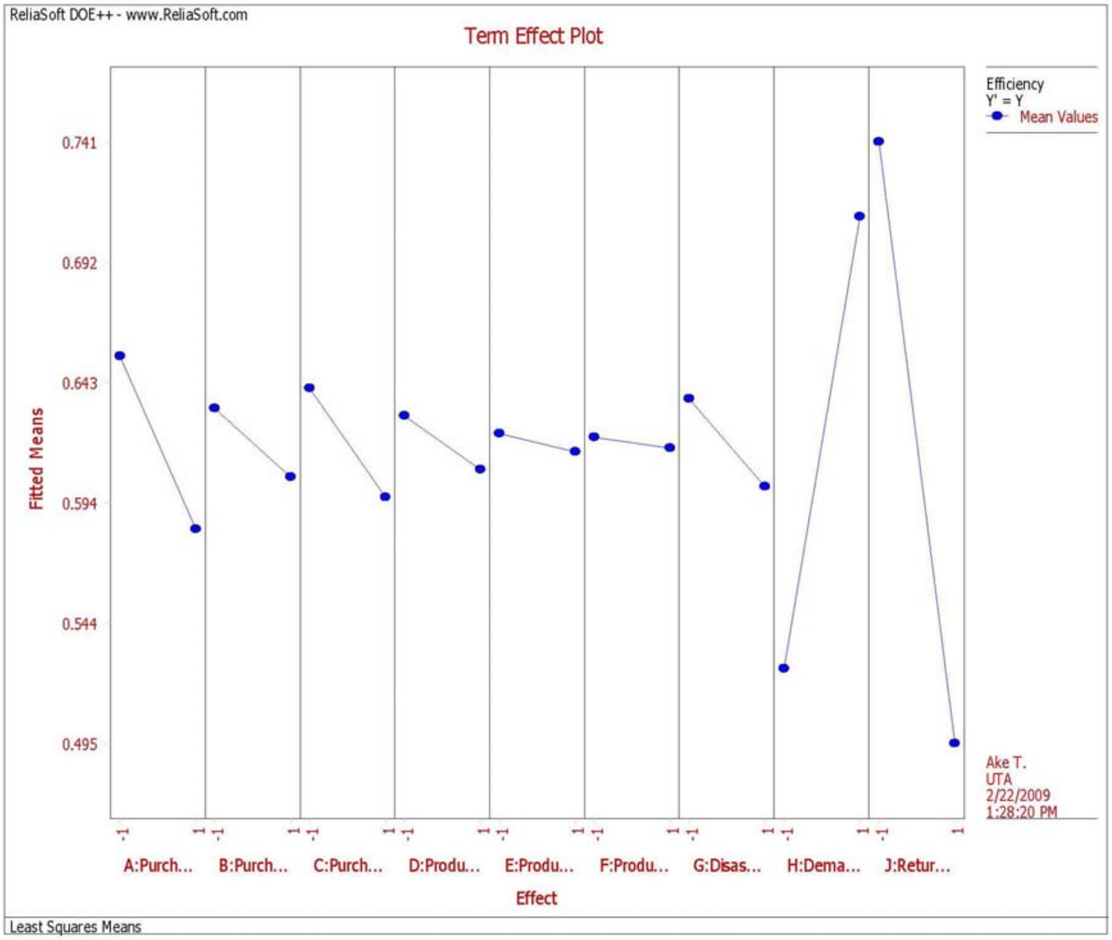

Fig B.10 Plot between effects and fitted mean

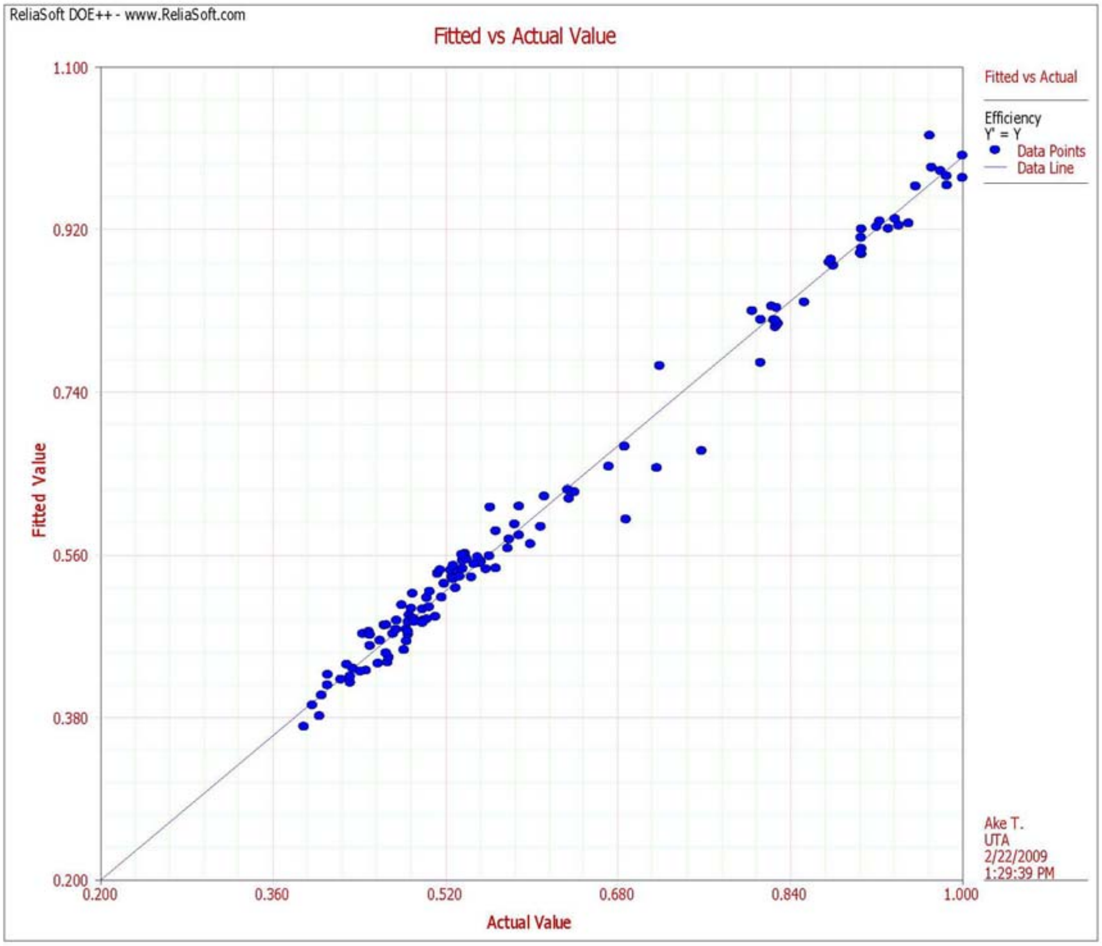

Fig B.11 Plot between predicted value (fitted model) and the actual value

APPENDIX C

SIMULATION MODEL AND PARAMETERS

1. Summary of the model

This model is an integer linear programming model (all unknown variables are integer) and Lingo software is used to generate the code to solve this model.

In summary the model will be specified as follows:

$$\text{Min} \sum_{\Omega=1}^{\Omega}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} A_{\Omega imt}Q1_{\Omega imt} + \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} B_{im}Q4_{imt} + \sum_{i=1}^{I}\sum_{w=1}^{W}\sum_{t=1}^{T} Q_{iwt}Q6^{-}_{iwt}$$

$$+ \sum_{s=1}^{S}\sum_{m=1}^{M}\sum_{p=1}^{P}\sum_{t=1}^{T} E_{smpt}Q2_{smpt} + \sum_{m=1}^{M}\sum_{p=1}^{P}\sum_{t=1}^{T} D_{mpt}Q5_{mpt} + \sum_{i=1}^{I}\sum_{w=1}^{W}\sum_{m=1}^{M}\sum_{t=1}^{T} F_{iwmt}Q3_{iwmt}$$

$$+ \sum_{i=1}^{I}\sum_{w=1}^{W}\sum_{t=1}^{T} C_{iwt}Q6^{+}_{iwt} + \sum_{m=1}^{M}\sum_{p=1}^{P}\sum_{t=1}^{T} U_{mpt}Q7_{mpt} + \sum_{p=1}^{P}\sum_{t=1}^{T} V_{pt}Q8_{pt}$$

$$+ \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{p=1}^{P} Pb_{ip}*RT_{ip}*Z_{it}*X_{ipt}$$

Subject to:

1. $Q8_{pt} = Q8_{p(t-1)} + \sum_{i=1}^{I}(Pb_{ip}*RT_{ip}*Z_{it}) - \sum_{m=1}^{M}Q7_{mpt}$

Where i = 1,...,I ; m = 1,…,M ; p = (n+1),…,P ; t = 1…T

2. $\sum_{m=1}^{M}Q7_{mpt} \leq Q8_{p(t-1)}$

Where p = (n+1),…,P ; t = 1…T

3. $Q8_{pt} \leq Y_p$

Where p = (n+1),…,P ; t = 1…T

4. $Q5_{mpt} = Q5_{mp(t-1)} + \sum_{s=1}^{S}Q2_{smpt} - [\sum_{i=1}^{I}\sum_{\Omega=1}^{\Omega} G_{\Omega ip}Q1_{\Omega imt}] + Q7_{mpt}$

Where i = 1,…,I ; m = 1,…,M ; t = 1…T ; p = 1,…,n ; s = 1,…,S ; Ω = 1,…, Ω

5. $Q5_{mpt} = Q5_{mp(t-1)} - [\sum_{i=1}^{I}\sum_{\Omega=1}^{\Omega} G_{\Omega ip}Q1_{\Omega imt}] + Q7_{mpt}$

Where i = 1,…,i ; m = 1,…,m ; t = 1…T ; p = (n+1),…,P ; Ω = 1,…, Ω

6. $H_{mp} \le Q5_{mpt} \le J_{mp}$

Where m = 1,…,M ; t = 1…T ; p = 1,…,P

7. $\sum_{i=1}^{I}\sum_{\Omega=1}^{\Omega} G_{\Omega ip}Q1_{\Omega imt} \le Q5_{mp(t-1)} + \sum_{s=1}^{S} Q2_{smpt}$

Where i = 1,…,I ; m = 1,…,M ; t = 1…T ; p = 1,…,P ; s = 1,…,S ; Ω = 1,…, Ω

8. $Q4_{imt} = Q4_{im(t-1)} - \sum_{\Omega=1}^{\Omega} Q1_{\Omega imt} - \sum_{w=1}^{W} Q3_{wimt}$

Where i = 1,…,I ; m = 1…M ; t = 1,…,T ; w = 1,…,W ; Ω = 1,…, Ω

9. $\sum_{\Omega=1}^{\Omega} Q1_{\Omega imt} + Q4_{im(t-1)} \ge \sum_{w=1}^{W} Q3_{wimt}$

Where i = 1,…,I ; m = 1…M ; t = 1,…,T ; w = 1,…,W ; Ω = 1,…, Ω

10. $HH_{im} \le Q4_{imt} \le JJ_{im}$

Where i = 1,…,I ; m = 1,…, M ; t = 1,…,T

11. $\sum_{w=1}^{W} Q6_{iw(t-1)} + \sum_{w=1}^{W}\sum_{m=1}^{M} Q3_{wimt} - R_{it} = \sum_{w=1}^{W} Q6_{iwt}$

Where i = 1,…,I ; t = 1,…,T ; w = 1,…,W ; m = 1,…, M

12. $Q6_{iwt} = Q6^{+}_{iwt} + Q6^{-}_{iwt}$

Where i = 1,…,I ; t = 1,…,T ; w = 1,…,W

13. $\sum_{\Omega=1}^{\Omega}\sum_{i=1}^{I} N_{\Omega i}Q1_{\Omega imt} \le O_{mt}$

Where $i = 1,\ldots,I$; $m = 1\ldots M$; $t = 1,\ldots,T$; $\Omega = 1,\ldots, \Omega$

14. $Q1_{\Omega imt} \geq 0$ and integer

15. $Q2_{smpt} \geq 0$ and integer

16. $Q3_{iwmt} \geq 0$ and integer

17. $Q4_{imt} \geq 0$ and integer

18. $Q5_{mpt} \geq 0$ and integer

19. $Q6^{+}_{iwt} \geq 0$ and integer

20. $Q6^{-}_{iwt} \geq 0$ and integer

21. $Q7_{mpt} \geq 0$ and integer

22. $Q8_{pt} \geq 0$ and integer

Parameters:

Ω = Number of production processes that have the product with the maximum number of production processes

I = Type of products

P = Type of materials (including assemblies and reusable parts)

M = Number of Manufacturing Plants

T = Number of periods of time to planning (normally represents week)

W = Number of Distribution Centers/Warehouses

S = Number of Suppliers

$A_{\Omega imt}$ = Production cost of one unit of product i at Manufacturing Plant m by process Ω on period t

B_{im} = Holding cost per unit of product i at Manufacturing Plant m

Q_{iwt} = Stock-out cost per unit of product i at Distribution Center/Warehouse w on period t

E_{smpt} = Cost of purchase of one unit of material p at Manufacturing Plant m from supplier s at period t

D_{mpt} = Holding cost per unit of material p at Manufacturing Plant m at period t

JJ_{im} = Security stock of product i at Manufacturing Plant m

HH_{im} = Maximum allowed stock of product i at Manufacturing Plant m

$G_{\Omega ip}$ = Quantity of material p needed to produce one unit of product i by process Ω

RT_{ip} = Number of units of material p that can be obtained from returned product i

J_{mp} = Maximum allowed stock of material p at Manufacturing Plant m

H_{mp} = Security stock of material p at Manufacturing Plant m

F_{imwt} = Transportation cost per unit of product i shipped from Manufacturing Plant m to Distribution Center/Warehouse w on period t

U_{mpt} = Transportation cost per unit of material p (including all assemblies) shipped from Recovery Facility to Manufacturing Plant m on period t

R_{it} = Demand of product i at period t

C_{iwt} = Holding cost of product i at period t on Distribution Center/Warehouse w

$N_{\Omega i}$ = Production time for manufacturing one unit of product i by process Ω

O_{mt} = Hours of production capacity in Manufacturing Plant m at period t

V_{pt} = Holding cost of material p at period t at Recovery Facility

Pb_{ip} = Probability that material p resulting from the disassembly process of product i is of good quality for remanufacturing

X_{ipt} = Disassembly cost for material or assembly p from product i at period t

Y_p = Holding capacity of reusable material or assembly p at central recovery plant

Z_{it} = Number of units of product i returned to central recovery plant on period t

Variables:

$Q1_{\Omega imt}$ = Number of units of product i to produce in plant m by process Ω on period t

$Q2_{smpt}$ = Number of units of material p to purchase in plant m from supplier s at the beginning of period t

$Q3_{iwmt}$ = Quantity of product i shipped to warehouse w from plant m at period t

$Q4_{imt}$ = Inventory units of product i in plant m at the end of period t

$Q5_{mpt}$ = Inventory units of material p in plant m at the end of period t

$Q6^{+}_{iwt}$ = Inventory units of product i at warehouse w at period t

$Q6^{-}_{iwt}$ = Number of units of stock-out of product i at warehouse w at period t

$Q7_{mpt}$ = Quantity of material p shipped from central recovery to plant m on period t

$Q8_{pt}$ = Inventory units of material p at period t on central recovery plant

1.1 Setup parameters for case study 1

Type of product: 1

Number of Manufacturing Plants: 1

Number of Distribution Centers/Warehouses: 1

Number of periods of time (weeks): 4

Table C.1 provides some setup parameters for case study1 for simulation model.

Table C.1 Setup parameters for case study 1

Product **Tufted Carpet**	133 unit / roll				
		Net Price ($)			
	Materials	Low	High	Qty/unit	Unit
Material Cost (purchased cost)	Yarn	2	4	1	Lb
	Chemicals	0.5	1	2	Lb
	Package	0.1	0.5	1	SY (square yard)
		Low	High		
Production Cost (Manufacturing Plant)	Unit production cost of product 1	1	3		
Holding Cost/unit (product,Plant)	Product 1	0.1	0.4		
Holding Cost/unit (material,Plant)	Yarn	0.1	0.5		
	Chemicals	0.1	0.5		
	Package	0.05	0.25		
Holding Cost/unit (product,WH)	Product 1	0.2			
Transportation Cost (Plant to WH)	Product 1	0.05	0.1		
Production time/unit (hours)	Product 1	0.004			
Production Capacity (hours) in 1 week	600				
Stock out Cost/unit (WH)	Product 1	0.2			
Demand of product i at period t, unit	Product 1	50000	100000		
Transportation Cost of material from Recovery to Plant	Yarn	0.05	0.1		
Holding Cost/unit (material,recovery)	Yarn	0.05			
Disassembly cost/unit for material (yarn)	Product 1	0.2	0.4		
Max holding capacity at Recovery, unit	Yarn	10000			
Return of product i at period t, unit	Product 1	2500	20000		

These setup parameters will be varied between low and high in the screening test depending on the design of the experiments. After receiving the significant parameters from the screening test, the average values of non-significant parameters will be used.

1.2 Setup parameters for case study 2

Type of product: 1

Number of Manufacturing Plants: 3

Number of Distribution Centers/Warehouses: 3

Number of periods of time (weeks): 6

Table C.2 provides some setup parameters for case study2 for simulation model.

Table C.2 Setup parameters for case study 2

Product **Tufted Carpet**	133 unit / roll				
		Net Price ($)			
	Materials	Low	High	Qty/unit	Unit
Material Cost, Plant1	Yarn	1	3	1	Lb
	Chemicals	0.3	0.8	2	Lb
	Package	0.1	0.4	1	SY (square yard)
		Net Price ($)			
	Materials	Low	High	Qty/unit	Unit
Material Cost, Plant2	Yarn	2	4	1	Lb
	Chemicals	0.5	1	2	Lb
	Package	0.2	0.5	1	SY (square yard)
		Net Price ($)			
	Materials	Low	High	Qty/unit	Unit
Material Cost, Plant3	Yarn	3	5	1	Lb
	Chemicals	0.7	1.2	2	Lb
	Package	0.3	0.6	1	SY (square yard)
		Low	High		
Production Cost (Manufacturing Plant 1)	Unit production cost of product 1	3	5		
Production Cost (Manufacturing Plant 2)	Unit production cost of product 1	2	4		
Production Cost (Manufacturing Plant 3)	Unit production cost of product 1	1	3		
Holding Cost/unit (product,Plant)	Product 1	0.1	0.4		
Holding Cost/unit (material,Plant)	Yarn	0.1	0.5		
	Chemicals	0.1	0.5		
	Package	0.05	0.25		
Holding Cost/unit (product,WH)	Product 1	0.2			
Transportation Cost/unit (Plant to WH), Plant 1		0.075	0.125		
Transportation Cost/unit (Plant to WH), Plant 2		0.025	0.075		
Transportation Cost/unit (Plant to WH), Plant 3		0.05	0.1		
Production time/unit (hours)		0.004			
Production Capacity (hours) in 1 week, Plant 1		400			
Production Capacity (hours) in 1 week, Plant 2		200			
Production Capacity (hours) in 1 week, Plant 3		600			
Stock out Cost/unit (WH)	Product 1	0.2			
Demand of product i at period t, unit	Product 1	50000	200000		
Transportation Cost/unit of material from Recovery to Plant	Yarn	0.05	0.1		
Holding Cost/unit (material,recovery)	Yarn	0.05			
Disassembly cost/unit for material (yarn)	Product 1	0.2	0.4		
Max holding capacity at Recovery, unit	Yarn	10000			
Return of product i at period t, unit	Product 1	2500	20000		

These setup parameters will be varied between low and high in the screening test depending on the design of the experiments. After receiving the significant parameters from the screening test, the average values of non-significant parameters will be used.

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BIOGRAPHICAL INFORMATION

The author received his doctorate in Industrial and Manufacturing Systems Engineering from the University of Texas at Arlington in May 2009. He received his Master of Engineering in Mechanical Engineering from Chulalongkorn University in Bangkok, Thailand, and a Bachelor of Engineering in Mechanical Engineering from Chulalongkorn University in Bangkok, Thailand.

The author is currently interested in applying the knowledge of statistical technique, linear programming, operation research, and data envelopment analysis to the areas of logistics and supply chain.