Measuring Performance in Reverse Supply Chain

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The thesis is submitted in partial fulfilment of the requirements for the award degree of Doctor of Philosophy of the University of Portsmouth.

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Declaration

Whilst registered as a candidate for the above degree, I have not been registered for any other research award. The result and conclusions embodied in this thesis are worked of the named candidate and have not been submitted for any other academic award.

Maulida Boru Butar Butar

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Research can be exciting and enlightening since it gives much freedom to explore what you find most interesting within your field. On the other hand, research can often be very frustrating since it involves a seemingly endless search that leads to many dead ends. It is during such times that your colleagues and the people around you become really important.

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Abstract

Increasing attention has been given to reverse supply chains because of the increasing value of technology and products at the end of direct supply chains and the impact of new green legislation. Design strategies for reverse supply chains have remained relatively unexplored and underdeveloped. Meanwhile measuring performance has become important.

The research described in this Dissertation investigated several industries with reverse supply chains: manufacture of aircraft, computers and carpets, and telecommunications, and retail. From that investigation, a new model was created that combined forward and reverse chains and then a general mathematical model was created to describe it. Specific models (including mathematical models) could then be created for specific companies. The new models allowed performance of both forward and reverse supply chains to be measured at the same time so that different modes of operation could be compared by testing with different data sets.

From an initial investigation of two case studies about an aeroplane company dealing with returned machines and a telecommunications company dealing with end of life products, a first initial model to describe their forward and reverse supply chains was created. This was the first time that an attempt had been made to create a general model that could be used in more than one industry and general models that included both the forward and reverse supply chains did not exist.

A general mathematical model was created to represent the new general model and from that two specific mathematical models were created to represent the computer manufacture and general retail companies. The model was modified to include new aspects found in the two new companies and then verified against another (fifth) industry, carpet manufacture.

The models were tested with sets of data including a high number of returned products and a low number of returned products, and companies were categorised according to the results. Six types of company were identified and are presented.

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Glossary of Terms

CE = Circular Economy

CLSC = Closed Loop Supply Chain

CP = Collecting Point

DSP = Disassembly Sequence Plan

EU = European Union

FSC = Forward Supply Chain

GL = Green Logistics

GSCM = Green Supply Chain Management

HP = Hewlett-Packard

MP = Manufacturing Plant

PM = Performance Measurement

PMS = Performance Measurement System

PMQ = Performance Measurement Questionnaire

PTB = Product take Back

RC = Recovery Centre

RL = Reverse Logistics

RNM = Recovery Network Model

RSC = Reverse Supply Chain

SMART = Strategic Measurement Analysis and Reporting Technique

WEEE = Waste Electrical and Electronic Equipment

Chapter 1 Introduction

This Chapter describes the research background, framework and statement of aims. Expected outcomes along with new claims are outlined and the structure of the Thesis is presented.

The research described in this Dissertation created new models that allowed performance of both forward and reverse supply chains (RSC) to be measured at the same time so that different modes of operation could be compared by testing with different data sets.

From an initial investigation of two case studies about an aeroplane company dealing with returned machines and a telecommunications company dealing with end of life products, a first initial model to describe their forward and reverse supply chains was created. This was the first time that an attempt had been made to create a general model that could be used in more than one industry. The model was modified to include new aspects found in the two new companies and then verified against another (fifth) industry, carpet manufacture.

The models were tested with sets of data including a high number of returned products and a low number of returned products, and companies were categorised according to the results. Six types of company were identified and are presented.

1.1 Background

Unlike forward supply chains, design strategies for RSC were relatively unexplored and underdeveloped (Blackburn *et al.*, 2004). However, product returns and their RSC represent an opportunity to create a value stream, not an automatic loss. Therefore, RSCs should be managed as business processes that can create value for a company.

A RSC deals with the backward flow of products returned from users. This happens for many reasons such as: the rise of electronic retailing; the rise in catalogue purchases; more self-service stores; or a lower tolerance among buyers for imperfection (Blackburn *et al*., 2004). Increasing attention has been given to the RSC due to the increasing value of products and technology at the end of direct supply chains as well as the impact of green legislation. These products, parts, subassemblies, and materials represent rapidly growing values and economic opportunities at the end of the forward supply chain (Blumberg, 2005). Product returns are also becoming a concern for many manufacturers. For most companies, product returns have been viewed as a nuisance; as a result, their legacy today is a RSC designed to minimize cost. Few companies have dealt with product returns properly (Blackburn *et al*., 2004).

According to Stock (2001), in a RSC it is important to develop and implement measurement systems to track performance. Rolstadås (1995) states performance measurement (PM) has a far more significant role than just quantification and accounting. It can provide management with feedback, monitor performance, reveal progress and diagnose problems. In addition, it has also made a contribution to decision making, particularly in re-designing business goals and strategies and re-engineering processes (Waggoner *et al*., 1999) .

A RSC is a series of activities required to retrieve a used or unused product from a customer and either dispose of it, reuse it, or resell it (Guide Jr and Van Wassenhove, 2002). In RSC, there are additional processes compared with forward supply chains. The processes are dependent on the condition (quality) of returns and appropriate collection and re-distribution channels need to be chosen based on recovery options (Rahimifard, 2004). Based on a wider survey of case studies in the field of reverse logistics, de Brito and Dekker (2004) claimed that there was not a broad knowledge about the costs associated with reverse logistics processes. Tibben-Lembke and Rogers (2002) mentioned and emphasised the importance of measuring performance in returns management process. They suggested return rates and financial impact of returns as appropriate measurements. Results suggested that evaluation of returned products was important and as it could impact on profitability.

In 2004, Herold and Kämäräinen (2004) emphasised that no previous studies were found about different performance metrics for RSC. This was despite PM for RSC being mentioned as an important research area.

Gupta and Nukala (2007) stated that traditionally, PM was defined as the process of quantifying the effectiveness and efficiency of action. Developing PM systems is a difficult aspect of performance measure selection. Due to inherent differences between forward chains and RSCs, unlike forward supply chain, operations in RSCs are complex and prone to a high degree of uncertainty (Kokkinaki *et al*., 2001). It is difficult to predict the quality, quantity, place and timing of returns, therefore performance metrics and evaluation techniques used in traditional supply chains cannot be extended to RSCs (Yellepeddi, 2007).

Besides academics, practitioners have also realised the importance of PM in a RSC and closed-loop supply chain. The use of appropriate strategies and metrics allow a RSC to play a part in product and customer life-cycle strategies, and can serve as a foundation for identifying customer loyalties and increasing market share (Moore, 2005) .

There are a large number of performance measures discussed in the literature (Taticchi *et al*., 2010). In the earlier literature (Slack *et al*., 2001), performance measures were usually divided into cost-related and non-cost-related performance measures. Stock (2001) classified a group of individual performance measures based on the terms of the five manufacturing performance objectives: quality; speed; dependability; flexibility and cost. There is a clear link between performance measures at all hierarchical levels, so that each function in a company works towards the same objectives. Flapper *et al*. (2006) clearly state, "*to have a strategic performance measure without related tactical and operational measures is not appropriate*".

Kongar (2004) indicated that RSC management demanded an appropriate evaluation approach as it differed from forward supply chain management in many aspects. PM for green supply chain management (GSCM) was introduced by Hervani *et al* in 2005 (Hervani *et al*., 2005). Meanwhile, Guide and Van Wassenhove (2003) mentioned PM as an important issue in a roadmap for redesigning RSC.

Beamon (1999) reviewed the supply chain literature and suggested directions for research on supply chain performance measures, which should include efficient resource allocation, output maximisation, and flexible adaptation to environmental changes. Different supply performance measures can be devised based on the specific nature of the problem.

Although RSC and PM have been discussed widely in the literature, PM in RSC needed further investigation. In most literature, case studies only consider specific purpose with specific performance metrics to address a particular issue. A PM able to address all issues needed to be explored. This could involve using a number of performance metrics, which can be adopted from forward supply chain performance measurement, or specific metrics applied exclusively to RSC.

Uncertainty, disruptions, and variability are challenges in manufacturing systems and supply chains as well as RSC. The design and operation of such systems has to incorporate uncertainty about the future. Adaptability and flexibility are desirable features, as are robust design and plans. It is important to treat measurement systems as dynamic entities that respond to environmental and strategic changes. Because of the gap in the research, measuring the performance of RSC was investigated (Butar Butar and Sanders, 2013) and forms the basis of the research described in this Dissertation.

1.2 Research Framework

The work conducted during this research can be represented by the framework shown in Figure 1.1. A first step was to understand RSC and PM. This was achieved by completing a literature review. Research gaps were identified. The acquisition and synthesis of knowledge involved: RSC, PM and forward supply chain performance measurement.

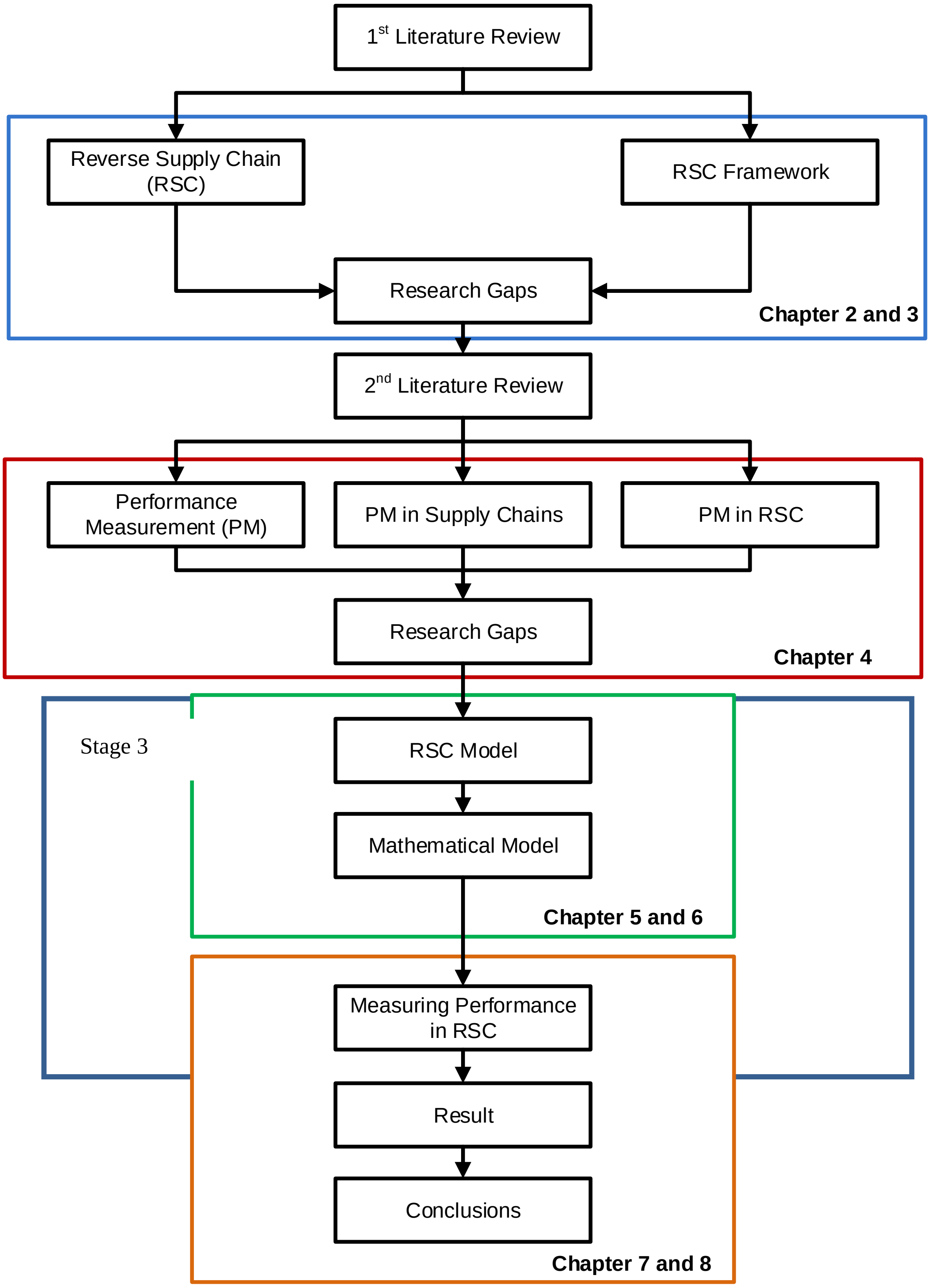

Figure 1.1 Research process overview based on Butar Butar and Sanders (2013)

From this first literature review, PM for RSC was identified as important and it was established there was lack of knowledge about this area (Butar Butar and Sanders, 2013).

A theory development phase took the form of a second literature review and investigated previous research about PM metrics and linked it with RSC characteristics. This phase covered the process of finding some characteristics of PM and some appropriate dimensions of performance. The theory was used to develop a new conceptual model to link to strategic objectives in handling product returns to recovery networks.

Although RSC and PM had been discussed widely in the literature, PM in RSC needed further investigation. In most literature, case studies only considered specific purposes with specific performance metrics to address a particular issue (Butar Butar and Sanders, 2013). A PM that able to address all issues was explored in the research described in this Dissertation.

During this stage it was concluded that measuring performance in RSC was important. Due to a lack of any general model of RSC where forward supply chain and RSC could be investigated the creation of a general model for RSC was investigated. A general model is proposed based on case studies from previous research.

The new general model provides an overview of RSC flow in the company. This model could be easily adjusted to show how return products flow in a specific company. Based on this model of a RSC, a mathematical model to measure the performance of a RSC was created. The mathematical model was based on company case studies and their RSC flow. Based on this mathematical model, a graph of company RSC performance was made. This graph could be a guideline for management to monitor their company performance in handling returned products and could be used as guidance to make further decisions.

To ensure the research achieved a reliable result, verification took place in the final stages to ensure the model that was created could be used as general model. This verification was performed against existing case studies. The new model offers a practical approach to performing and managing RSCs more effectively.

After the general model had been verified, measuring performance of RSC could be executed. Using the general model, a mathematical model was created. Results from this calculation were transferred into a graph to make the performance of RSC easier to be read. Based on this graph, suggestions could be made about how a company might improve their performance in RSC.

1.3 Statement of Aims

The aim of this research was to provide a flexible RSC model that could be measured. The research created a model where companies can measure and manage performance of their RSC systems. The new model provided:

- A better understanding for companies (or managers) about relationships between strategic company objectives and PM in RSCs.
- Support for companies in designing their PM systems in order to manage and improve their RSCs.
- An easier way to measure the performance of RSCs.

1.4 Expected Outcomes

This research was to improve the understanding of PM for RSC. Furthermore, a new conceptual framework for RSCs is proposed and developed. The research was conducted in three stages as shows in Figure 1.1 :

(a) Understanding of PM for RSC

This was the first outcome from the research. It is of significant interest to industry practicioners and academia. A literature review on PM in RSC was presented to examine methods used to measure RSC. A paper was presented to the “Business Intelligence Asia Pacific Summit 2012” in September 2012.

(b) Performance measurement (PM)

PM metrics and attributes were indentified based on several case studies.

(c) PM framework in RSC

A procedural method provided information about how to design PM. After collecting the data and analysing the RSC operations, a framework is proposed. Finally, a verified study was carried out to verify the framework.

Several novel results are claimed:

- A new general model for RSC.
- A general mathematical model of the flow model.

  Both models can be adjusted for specific companies.
- Performance of both forward chain and RSC could be measured at the same time.
- Guidance graphs were produced for management to help them in decision making about RSC performance.
- Identification of six general company types.

The following papers have been published:

a. Butar Butar, M., & Sanders, D. (2013). Improving green computing in business intelligence by measuring performance of reverse supply chains. *GSTF International Journal on Computing*, *3*(1), 75-81.

b. Butar Butar, M., Sanders, D., & Tewkesbury, G. (2014). Measuring performance of reverse supply chains in a computer hardware company. In Proceeding of *7th IEEE International Conference on Management of Innovation and Technology (ICMIT2014)* (pp. ICMIT14-P0205).

c. Butar, M. B., Sanders, D., & Frei, R. (2016). Measuring Performance of Reverse Supply Chains in a Carpet Manufacturer. *Journal of Advanced Management Science Vol*, *4*(2).

d. Butar Butar, M. In press. Measuring Performance of a Reverse Supply Chain at Aeroplane Company. *Intelligent Mobility*.

And the two papers was presented at IEEE International Conference on Management of Innovation and Technology (ICMIT2014) in Singapore and at the 4th International Conference on Industrial Technology and Management (ICITM 2014) in Paris.

1.5 Thesis outline

This Thesis is structured into eight Chapters which are divided into three distinct Sections: the research background and overview, the general model and mathematical model and, and research conclusions.

Chapter 1 introduces the reader to an understanding of the overall research that includes the objectives, research questions, the scope of research, research process and the Thesis outline.

Chapter 2 provides a background of reverse and closed-loop supply chains.

Chapter 3 investigates the literature about supply chain networks as well as early work in reverse logistic network design. A review of the types of existing conceptual frameworks is provided. This literature review was carried out to identify the appropriate methods in developing a PM.

Chapter 4 describes how to measure performance in a RSC and why it is important.

Chapter 5 investigates case studies that were used in this research. From these case studies a general model for RSC is proposed.

Chapter 6 provides a mathematical model for each of the companies described.

Chapter 7 described how performance in RSC can be explained based on the result from mathematical model and shows some results.

Chapter 8 provides the discussions, conclusions and future work.

Chapter 2 Literature Review on Reverse Supply Chains

In this Chapter, the history of reverse supply chain (RSC) research is explored. Early research only focused on reverse logistics (RL) and much of that research only focused on logistics cost. Some authors did provide environmental reasons that drive green logistic research and in green logistics (GL), much of the literature focused on how to reduce the $C0_2$ in their logistic process.

Increasing interest in RL and GL expanded RSC research in general and started new research in the area. Definitions of RL and RSC are presented in this Chapter along with an explanation of RSC and the characteristics of this process.

In order to understand more about RSC, a comparison of RSC with forward and green supply chains is explored. At the end of this Chapter, a brief explanation about closed RSC is presented in order to give an overview of RSC and the research described in this Dissertation.

2.1 Introduction

In this Section, early RSC studies about RL and GL are explored with an explanation about how RL started to gain attention and how GL became related to RL. Both fields can be viewed as the beginning of the RSC research area.

Murphy (1986) studied transportation and warehousing aspects of reverse distribution. That research was inspired by a movement of flows against traditional flows in the supply chain. Murphy and Poist (1988) published an article about empirical analysis on how to manage logistics retromovements. Both of these are identified as early studies in RL. In both articles, RL is not being used yet, however an idea about different flows apart from forward supply chains (FSC) begins to gain an interest.

Rogers *et al*. (1999) were pioneers in the literature about RL. They found that logistics costs were estimated to account for approximately 10.7% of the U.S. economy. However, the exact amount of RL activity was difficult to determine since most companies did not know how large the costs of their returns were. They concluded that RL costs accounted for approximately four percent of their total logistics costs. They defined RL as: '*the process of planning, implementing, and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods, and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal*'.

The environment issue was another crucial aspect of RL. Environmental concerns, legislative actions and increasing product disposal costs had led many companies to adopt "green manufacturing" practices, such as the recovery and remanufacturing of used products. These practices led to challenging RL problems, where the return flows of used products needed to be taken into account.

Thierry *et al*. (1995) highlighted the role of governmental action in encouraging companies towards reuse activities. Governments could take legislative action such as banning the disposal of certain products, and obliging companies to take back their products at the end of their use.

An example was the producer responsibility laws, which were a set of legislative acts in the European Union (EU) by which companies were responsible for collecting and reusing their products (Guide and Wassenhove, 2001). A prominent element in these laws was the Waste Electrical and Electrical Equipment (WEEE) directive, which compelled producers to be responsible for the handling of their end-of-life products, providing product information to the party in charge of its processing to ensure appropriate recycling, and establishing efficient collection systems where private households could dispose of unwanted products (de Koster *et al*., 2005). Besides the product take-back laws directed towards electronic and electrical equipment, Toffel (2003) specified other take-back regulations in the EU mandating packaging (Packaging and Packaging Waste Directive), batteries (Germany's Battery Ordinance), and automobiles (Directive on End-of-Life Vehicles).

Hewlett-Packard (HP), a leading company in electronics manufacturing, developed HP's hardware Product Take Back program (PTB) that allowed consumers and businesses to conveniently recycle obsolete computers and equipment from any manufacturer for a minimal fee. These programs were available around the world and allowed individuals and commercial customers to return both HP LaserJet and inkjet cartridges at no charge. PTB was created mainly to fulfil government and individual requirements which required environmentally responsible end-of-life solutions for electronics hardware and ink cartridges. A second reason was to conform with environmental procurement guidelines and the European Directive on WEEE (Degher, 2002)

In 1998, IBM established the Global Asset Recovery Services organization to provide a single, global focus for managing the disposal of returned, surplus, and excess computers and related hardware. About 10,000 "pre-owned" computers were returned to manufacturers each week at the end of lease agreements, as well as products ranging from PCs to servers (Grenchus *et al*., 2001). Another example of the way environmental legislation had an impact on RL was The Environmental Protection Administration of Taiwan. They announced a Scrap Home Appliances and Computers Recycling Regulation in March 1998 that mandated manufacturers and importers to take-back their products (Shih, 2001).

RL is different from waste management as that mainly refers to collecting and processing products or material that are to be discarded. RL concentrates on those streams where there is some value to be recovered and the outcome enters a new supply chain (Pinna and Carrus, 2012).

GL considered environmental aspects of logistics activities and focused on forward logistics (Rodrigue *et al*., 2001). The prominent environmental issues in logistics have been consumption of non-renewable natural recourses, air emissions, congestion and road usage, noise pollution, and both hazardous and non-hazardous waste disposal (Camm, 2001).

RL and GL are different but related with each other. The knowledge in each field has been growing independently but commonalities persist due to the similarities of the overall environment (Dyckhoff *et al*., 2013) .

Kokkinaki *et al*. (2001) concluded that RL was necessary for the following reasons:

- Positive environmental impact; legislation acts, also called “producer responsibility laws,” required 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 led to reduced costs, increased profits and improved customer service.
- Regaining value; efficient RL could capture values from reusing products or parts or recycling materials. There were at least 70,000 remanufacturing firms in the U.S. for jet and car engines, auto parts and copiers that amounted to total sales of US $53 billion (Lund, 1998).

In the past, RL gained little attention, as many enterprises only focused on their FSC. Recently interest in RL has increased because many firms have started to consider the benefits.

Many companies have tried to improve their RL strategy to gain competitive advantage (Elmas and Erdoğmuş, 2011). For example: Kodak has been selling remanufactured single-use photo cameras for more than a decade; and Coca-Cola uses refillable bottles. These companies profited from their RL strategies. The products in the reverse flow could come from different players in each supply chain, not necessarily from an end user or customer. Sometimes retailers needed to return their goods to a manufacturer even though there was nothing wrong with the products because those products were out of date or hard to sell.

Definitions of RSC are explored in the next section. As mentioned in this Section, RSC developed from RL and GL.

2.2 Definition of a Reverse Supply Chain

There are several authors proposing a definition for RL and RSC. This Section is not to develop new concepts or theories about RL, but to provide a brief summary of the principal statements found in the literature and to state a definition to be used for the research described in this Dissertation.

Many authors have provided a definition of RL in different ways. As mentioned in the previous Section, there was a definition of RL by Roger and Tibber-Lake in 1999. Stock and Lambert (2001), defined RL as "*going the wrong way on a one-way street because the great majority of product shipments flow in one direction*". Kroon and Vrijens (1995) and Pohlen and Theodore Farris (1992) defined RL 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. Fleischmann *et al.* (1997) defined RL as: *"a process which encompasses the logistics activities all the way from used products no longer required by the user to products again usable in a market".* Stock (1998) defined RL 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*". In the early days of RL the scope of RL was limited to the movement of material against the primary flow, from the customer toward the producer. However the definition of RL has changed to having a wider scope that no longer only looks at the logistics process but also considers the whole flow of returned products that give a sense of RSC.

The definition by Guide Jr and Van Wassenhove (2002) of RSC is '*a series of activities required to retrieve a used or unused product from a customer and either dispose of it, reuse it, or resell it*'. This was the definition used for the scope of the research described in this Dissertation, because it explains the meaning of proper disposal and recapturing value as an extension of the definition.

A circular economy (CE) is an alternative to a traditional linear economy (make, use, dispose) in which resources are kept in use for as long as possible, extracting the maximum value from them whilst in use, then recovering and regenerating products and materials at the end of their life.

In parallel to development in GL and sustainable supply chains, the CE discourse has been propagated in the industrial ecology literature and practice. CE pushes the frontiers of environmental sustainability by emphasising the idea of transforming products in such a way that there are workable relationships between ecological systems and economic growth (Genovese *et al*., 2017) .

In this context the concept of RSC Management has been developed as an adaptation of the circular economy principles to supply chain management. RSCs are either open-loop or closed-loop. Open-loop supply chains involve materials recovered by parties other than the original producers who are capable of reusing these materials or products. On the other hand, closed-loop supply chains deal with the practice of taking back products from customers and returning them to the original manufacturer or the recovery of added value by reusing the whole product or part of it (French and LaForge, 2006). Because of the benefits of RSCs, it is unsurprising that manufacturing industries have been placing, a lot more emphasis on them recently.

2.3 Characteristics of a Reverse Supply Chain

Companies have an option to close a RSC or leave it open. Leaving it open means the products in a RSC will go to different destinations from the original supply chain. Supply chains could also be made by creating a loop. This closed loop supply chain consists of a RSC and an extra loop to connect it to the original FSC (Blumberg, 2005).

Guide and Van Wassenhove (2003) stated that companies that had been most successful with their RSC were those that closely coordinated them with their FSC, creating a closed-loop system.

To make rational decisions about the structure of a RSC, Guide Jr and Van Wassenhove (2002) declared it best to divide a chain into five key components and analyse options, costs and benefits for each of them. To understand the whole concept of RSC, the characteristics were investigated. The characteristics are illustrated in Figure 2.1.

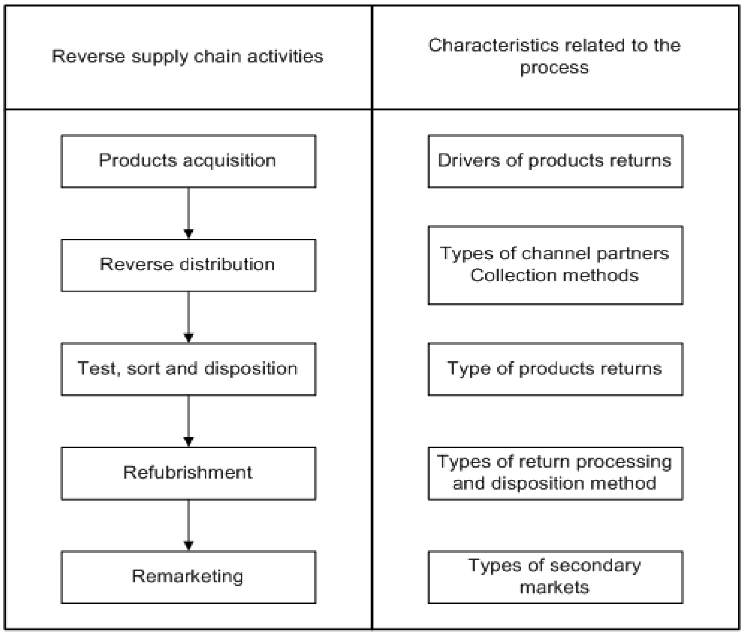

Figure 2.1 Characteristic of RSC (Guide Jr and Van Wassenhove, 2002)

These five characteristic of RSC will be described in following sub-Sections. Product acquisition is what drives product returns. The reasons for product returns could be because of the product itself (such as end-of-life products or faulty products) or from stock adjustments in different locations. Product returns will be delivered or collected at locations called recovery centres. How these products can be returned or collected will be discussed in a Section on Reverse Distribution. Returned products can be separated after testing, sorted and dispositioned. This action decides the type of product returns; and each type had a different action in the refurbrisment processes. The last characteristic of a RSC was the type of secondary markets that show how returned products were remarketed.

2.3.1 Returned Products

Products are returned for many reasons, such as defects, end of useful life, or the product does not meet a customer's needs. Elements to consider in the definition are the inputs that the RSC process uses to perform its activities. Most authors agree that they are:

- discarded products,
- used products,
- products or parts previously shipped,
- hazardous and non-hazardous waste from packages and products,
- raw materials,
- in process inventory and finished goods.

The classifications shown in Figure 2.2 systematically address the products returned at each process stage along the supply chain.

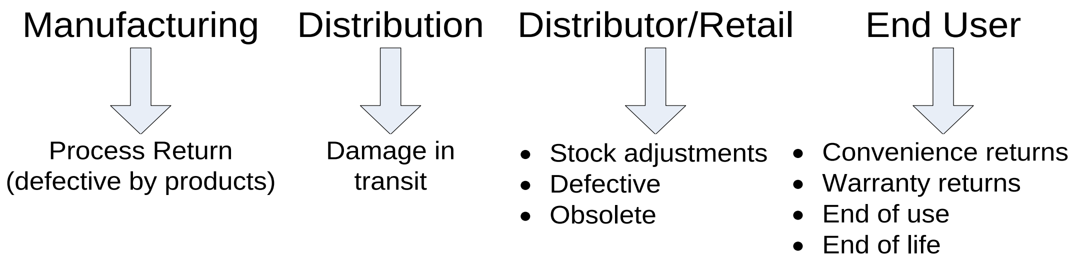

Figure 2.2 Types of products from each process stage (Saibani, 2010)

At the manufacturing stage, raw material may be left over; any finished products that do not fulfil quality specifications are rejected and refurbished before entering the manufacturing line to be tested again. Raw material surplus and production leftovers represent the 'product not needed' category, while quality control returns fit in the 'do not function' category. Manufacturing returns include:

- raw material surplus,
- quality control returns,
- and production leftovers/by-products.

(de Brito and Dekker, 2004)

Any by-products from the manufacturing process are collected and reused or recycled, especially if expensive raw materials are involved (Spengler *et al*., 2004).

During the distribution of finished products, returns can result from damage during transit to retailers or shops (Lee, 2004). At the retailer or distributor points, product returns may come from stock adjustments, defective in storage and also obsolete products; as well as product recall, commercial returns and functional returns (Blank, 2014).

Product recall refers to products collected because of safety (or health problems) with the products, usually initiated by a supplier or manufacturer (Smith *et al.*, 1996). Commercial returns can refer to wrong/damaged deliveries, or to unsold products that retailers or distributors return to a manufacturer, this includes outdated products (Tsay *et al.*, 1999). Functional returns were suggested by de Brito and Dekker (2004) as products for which their inherent function makes them go back and forward in the chain, an example is distribution using pallets. Their function is to carry other products and they can serve this purpose several times (Duhaime *et al*., 2001). Stock adjustment occurs when an actor in the chain re-distributes stocks. For instance stock adjustments could occur between warehouse or shop in the case of seasonal products (de Koster *et al*., 2002).

At the last stage (which is with the end user) products are returned because of liberal customer policies resulting in convenient returns (Lee, 2015). Other types of product returns from end customers are warranty returns, end-of-use returns and end-of- life returns. Customers benefiting from a warranty can return products that did not (seem to) meet the promised quality standard. End of use returns refer to those situations where a user has a return opportunity at a certain life stage of a product. Schultmann *et al*. (2003) explored a closed loop supply chain for end of use batteries as an example of end of use returns. End-of-life returns refers to returns for products at the end of their economical or physical life. They are returned to a producer because of legal product-take-back obligations or to other companies that collect them for value-added recovery (Toffel, 2003).

Users may return products for different reasons at different stages in the product lifecycle (Guide and Van Wassenhove, 2003). Numerous classifications of product returns have been given by several authors in the past and some are shown in Table 2.1.

Table 2.1 Classification of Product

Authors	Categories of Product Returns
Rogers and Tibben-Lembke (2001)	Reverse flow of products Reverse flow of packaging
de Brito and Dekker (2004)	Manufacturing phase Distribution phase Customer use returns

Fleischmann *et al*. (1997) gave three categories: reusable packages, rotatable spare parts and consumer goods. They identified them according to the time taken before their function ended and the reason behind the reuse activity. Return flows for each phase are listed according to the return reasons. Rogers and Tibben-Lembke (2001) broadly identify two types of reverse flows depending on the type of returns: reverse flow of products, and reverse flow of packaging. For example packages such as bottles are returned to be reused, while some products are returned to recover remaining value by processes like remanufacturing, refurbishing, etc.

One factor in achieving an effective RSC is an efficient establishment of schedules, transportation and networks (Moore, 2005). Fleischmann *et al*. (1997) described a network model for a recovery network where three facilities were involved:

- disassembly centres which house inspection and separation activities,

- factories for reprocessing and/or new production,
- distribution warehouses to keep inventory of unprocessed and processed returns.

This Dissertation concentrates on the management of product returns after they have left the manufacturer as finished products. The following Section describes the characteristics of each type of product return in a RSC system. Firstly, the reasons that products are flowing back from end customers must be studied. Users may return products for different reasons and at different stages in a product's lifecycle (Tanskanen, 2013). There are four main criteria identified by Fleischmann *et al*. (1997) to classify the situations in which reuse occurs. These are: the reuse motivation, the type of recovered goods, the form of reuse, and the actors involved.

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 and Retzlaff-Roberts (1999) provided some reasons for product returns:

- The customers changed their minds.
- The product was defective.
- The customer perceived a 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.

Prediction for unplanned product returns is difficult because companies do not know what will be returned or when. Reasons for planned product returns may include (Tonanont, 2009):

- Trade-in programs – Firms offer their customers the chance 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 environmental reasons.
- Leased or rented products – Customers return products at the end of lease.
- Service work - Products are shipped to a service location to be fixed and then they are returned to customers.

Planned returns are easier to predict and for firms to design their RSC because they know what is coming back and when.

2.3.2 Reverse Distribution

Fleischmann *et al*. (1997) defined reverse distribution as the collection and transportation of used products and packages. In the RSC, the chain is composed of all the members of the FSC, plus third parties acting as demand points, for example secondary markets, landfills, charity organizations, and many more. They have a special characteristic, which is that they do not have a previously established demand, on the contrary, they have limited their capacity by some specific constraints. In the case of landfills for instance, the government regulates the quantity of products that companies can ship to them.

The destination of the product is described as: the manufacturer, a central collection point or, the point of origin. One factor in achieving an effective RSC program is efficient establishment of schedules, transportation and networks. An example of such a strategy is that of assigning supply trucks which carry new products and materials to nearby sites to backhaul the older parts and materials to the local supply location (Moore, 2005). For a recovery network which involves a closed-loop system, the network model described by Fleischmann *et al*. (2001) is explored. There are three facilities involved:

- Disassembly centres which house the inspection and separation activities.
- Factories for reprocessing and/or new production.

- Distribution warehouses to keep the inventory of unprocessed and processed returns.

In general, the recovery networks form a 'bridge' between two markets, which act as the network boundaries, namely:

- “Disposer market" where used products are set free by their former users.
- “Reuse market" with demand for recovered products.

A high level of uncertainty complicates the RSC. This uncertainty comes from the fact that a company never knows in advance when and where the products will be returned, and how many products will be returned. Depending of the quantity of products returned, it might be better to operate with collection points in different facilities than the distribution facilities used in the FSC.

There are two major types of collection: centralised and decentralised. Retailers with shops or stores are more likely to centralise the return authorisation (de Koster et al., 2002). This allows the possibility of identifying the instant (time) for particular types and volumes of returns (quantity, quality and diversity) being collected. To study the differences between the concepts of centralisation and decentralisation, a case study was considered which involved a manufacturer and two retailers (Savaskan and Van Wassenhove, 2006).

In the centralised system, the manufacturer collected the used products directly from the consumers (for example print and copy cartridges) whereas in the decentralised system, retailers collected product returns (for example single-use cameras and cellular phones). The decentralisation of product collection activities resulted in incentives for retailers to reduce their margins with the expectation of compensation through buyback payments for returned products. In this case, the competition between two retailers drove down retail prices and the manufacturer benefited from this as sales volume increased.

Although the RSC could include the same participants as the FSC, usually the reverse flows were either supplemented or entirely supported by alternative channel participants (Prahinski and Kocabasoglu, 2006) as shown in Figure 2.3.

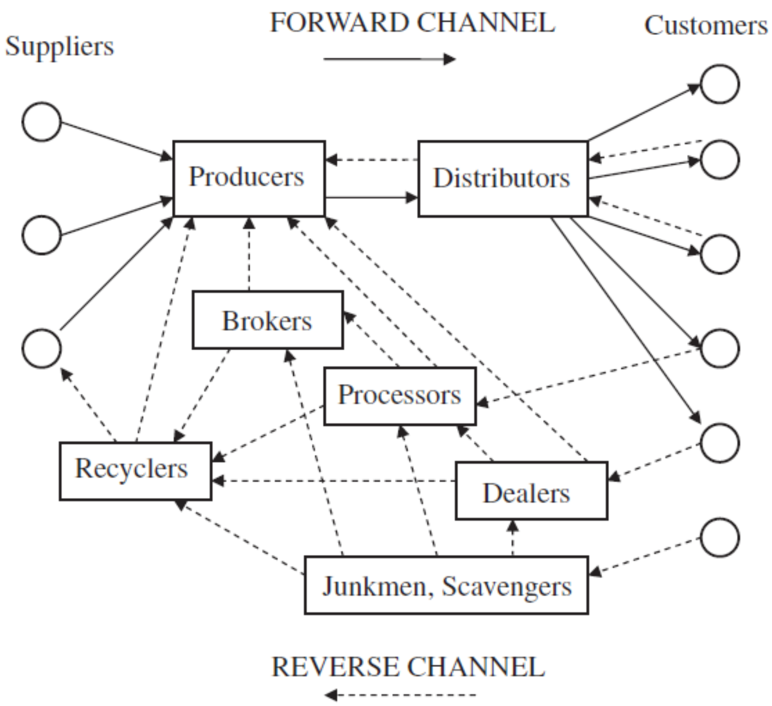

Figure 2.3 Channel partners involved in RSC and CLSC (Prahinski and Kocabasoglu, 2006)

One channel player which is involved in all links is an independent logistics provider, which is also a typical outsourcing service for FSC. When there is more than one party involved in the RSC, coordination is important. Information support is one way to develop linkages between channel partners to achieve efficient RL operations (Daugherty *et al.*, 2002).

2.3.3 Product Recovery

Another element to consider are the tasks or activities involved in the RSC process. Those activities are similar to the ones performed in the FSC processes, but RSC includes some additional tasks. RSC activities usually also introduce more elements of uncertainty in terms of the frequency in which they are performed and the quantity of products they use. Summarizing these activities they are:

- Planning, implementing and controlling an efficient and cost effective flow of products.
- Collection, transportation (backhauling), recovering, storage, processing, acceptation, reducing, managing, disposing, and shipping products.

The next element that was explored regarded the outputs or consequences of the RSC process. RSC objectives are the reusing, recycling, remanufacturing, disposal, reducing, and recapturing value of the "inputs". None of the literature considers all the activities, but in general, all of them must be included in a RSC definition. Rogers and Tibben-Lembke (2001) listed common RSCs activities as shown in Table 2.2

Table 2.2 Common reverse logistics activities (Rogers and Tibben-Lembke, 2001)

Material	Reverse Supply Chain 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 Retzlaff-Roberts (1999) and Bayles and Bhatia (2000) provided brief definitions of each disposal option of RSC 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 requiring complete disassembling of the product.

2.3.4 Types of returns processing and disposition

In RSC, there are additional processes when compared with FSC. The processes are dependent on the condition (quality) of the returns and appropriate channels are chosen based on recovery options. The selection logic is described in detail by (Rahimifard, 2004) and illustrated in Figure 2.4.

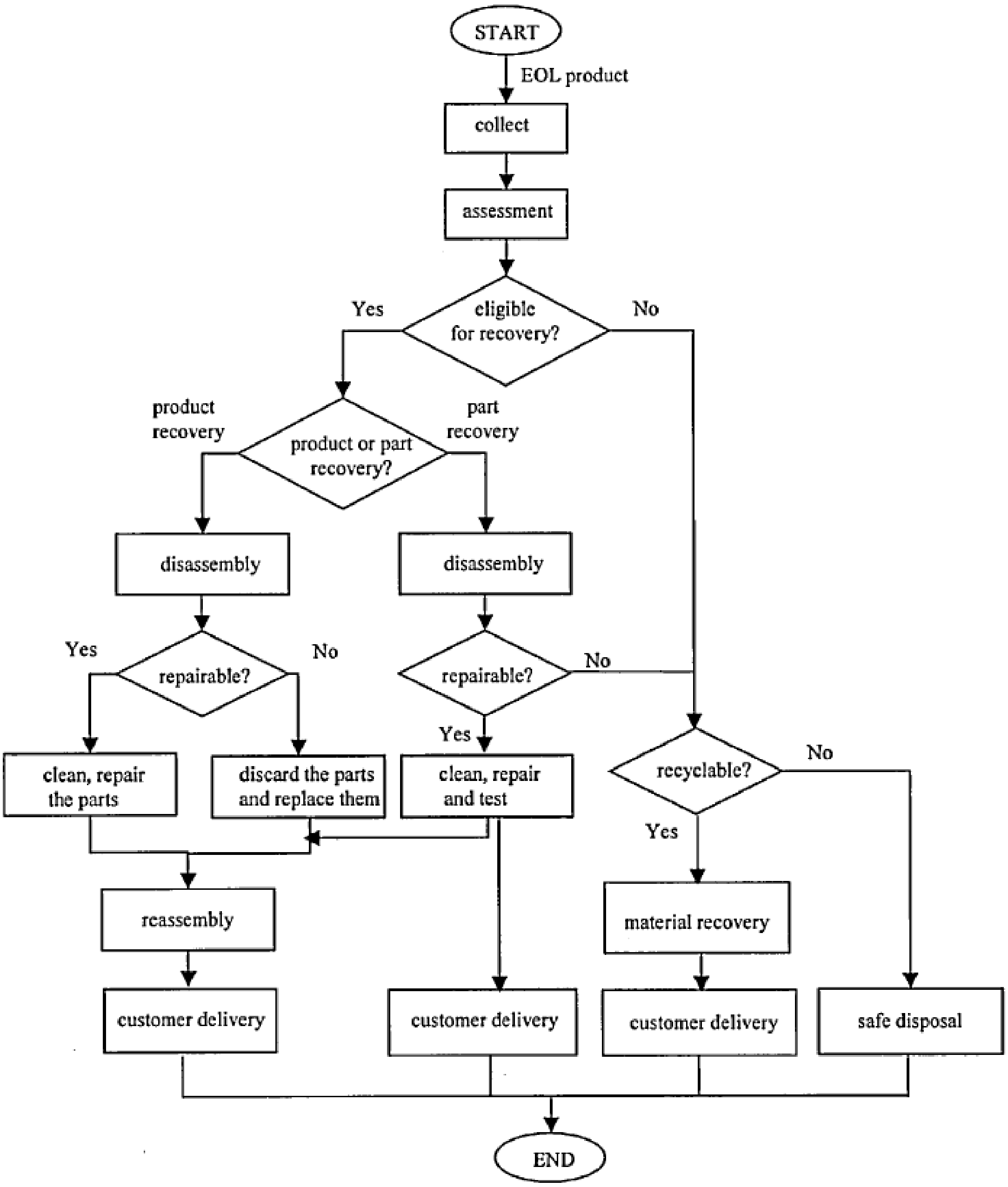

Figure 2.4 Process logic of product returns for RSC (Rahimifard, 2004)

The main activities are shown with the process routes shown to match each decision taken. Thierry *et al*. (1995) presented a categorisation of product recovery options where each of them implied collection of used products and components, reprocessing, and redistribution. The only thing that is different was the reprocessing activities. There were five main activities: repairing, refurbishing, remanufacturing, cannibalisation (in the context of component reuse) and recycling. Repair was to return used products to "working order" by fixing or replacing broken parts. The quality of repaired products was generally lower than the quality of new products.

Several authors illustrate the problem of disassembly. Zussman (1995) proposed a disassembly system where the end of life value of the product is taken in to account to evaluate the strategy to follow in the disassembly process. The process is complemented with a correct identification of the assemblies with adhesive labels, previously attached to the product when it was manufactured.

Refurbishing may require the replacement of critical modules. The quality standards of refurbished products are varied; they can be less rigorous than, or as rigorous as, those for new products. Remanufacturing transforms the product up to the 'new' quality standards through product disassembly and extensive inspection of modules and parts.

Worn-out or outdated parts and modules are replaced and those that are repairable are fixed and tested. Cannibalisation involves work to salvage some parts to be reused in repair, refurbishing, or remanufacturing of other products and components. The process in which they are reused determines the quality standards of the cannibalised parts. Cannibalisation selects the parts to be reused and the remaining parts of the product are not needed. Recycling requires disassembly of parts where they are separated to acquire distinct materials. The original physical and functional structures are not retained

In RSCs, there are additional processes compared with FSCs. The processes are dependent on the condition (quality) of returns and appropriate channels need to be chosen based on recovery options (Rahimifard, 2004). Table 2.3 presents the main characteristics of the recovery process as well as differences between them.

Table 2.3 Comparison between product recovery options (Thierry *et al.*, 1995)

	Level of Disassembly	**Quality Requirements**	**Resulting Product**
Repair	To product level	Restore product to working order	Some parts fixed or replaced by spares
Refurbishing	To module level	Inspect all critical modules and upgrades to specified quality level	Some modules repaired/replaced; potential upgrade
Remanufacture	To part level	Inspect all modules and parts and upgrade as new quality	Used and new modules/parts combined into new products; potential upgrade
Cannibalising	Selective retrieval of parts	Depends on process in which parts are reused	Some parts reused; remaining products recycled/disposed
Recycling	To material level	High for production of original parts; less for other parts	Material reused to produce new parts

2.3.5 Types of secondary markets

If the product returns fulfilled a quality standard for direct resell, they were restocked on the shelves at the premium selling price. With lower quality products, they will either be sold in store at a lower price or at designated clearance shops. Many retailers, however, opted to sell low value product returns to brokers to be sold at other markets such as flea markets. Scrapping is a popular option too as it is an easier choice.

This can be considered as an ending point of the RSC process. All authors in the literature agree that the process starts at the point of consumption; although it is important to consider the fact that, when they are referring to the point of consumption, they include distributors, retailers and consumers (Talebi and Way, 2009). In other words, if the product is, for instance, the return of a non-sold product, it may go from the retailer or distributor to the manufacturer and it is also considered as part of the RL process. This precision is important in order to clarify which are in the RL processes, since the problem increases in complexity because products can be shipped directly from customers, retailers or distributors to a manufacturer (Soto Zuluaga, 2005).

2.4 Reverse Supply Chain vs Forward Supply Chain

There are many differences between FSCs and RSCs that justify the development of different theories for each area. For the scope of this research, analysis concentrated on the operations management issues of RSCs, although all the organizational areas may be affected by the introduction of a RSC system into a company. FSC can be defined as a flow of materials, products and information from suppliers to final users or customers through production and distribution process (Schary and Skjott-Larsen, 2001). While, RSC deals with return products through recovering process (Stock *et al*., 2002).

When there is additional return flow that opposes the main business, there will be additional activities that need attention. This brings a new challenge to managing reverse flow of product and required RSC information and management (Guide Jr, 2002).

Several authors provide various examples about how RSC affects other organisational areas in companies. For instance the design process of a determined product considered the disassembly process as well. In this sense, the product must be easy to demanufacture, probably in modules that could be used in other products. Another issue is the recovery technology. It is necessary to develop technology for both economically and ecologically viable recovery of returns flows. The emergence of secondary markets is a new challenge, they are new markets to develop, but without adversely affecting the original market for the product. For a detailed discussion about the incidence of RSC in other organizational areas like technology, finance, marketing, or information management, see Krikke (1998), Thierry *et al*. (1995) and Van der Laan and Salomon (1997). To analyse the differences between forward and reverse logistics and, to organize the literature review, the following areas of work were considered:

- Location theory and logistics network design.
- Forecasting.
- Inventory control.
- Production /Remanufacturing.
- Disassembly operations.
- Reverse Distribution.

Guide Jr and Van Wassenhove (2002) suggested the differences between RL and forward logistics shown in table 2.4.

Table 2.4 The differences between reverse and forward logistics
(Guide Jr and Van Wassenhove, 2002)

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
Standardised channel	Exception driven
Disposition options clear	Disposition not clear
Pricing relatively uniform	Pricing dependent on many factors
Importance of speed recognised	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

2.5 Reverse Supply Chain vs Green Logistics

Many people confuse GL and RSC because they are similar. GL 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" (Nylund, 2012).

A problem in the common speech of logisticians is the confusion between RL and GL. The threat that actually exists due to the scarcity and deterioration of natural resources has made companies more conscious about the necessity (obligation, in some countries) of developing green alternatives or ecological ways of doing business.

RSC and GL share some activities and that generates confusion between both concepts. However, RSC is more than reusing containers or recycling packaging materials. Redesigning packaging to use less material, or reducing the energy and pollution from transportation are important activities, but they might be better placed in the realm of "Green" logistics. If no goods or materials are being sent "backward," the activity probably is not a RSC activity. However, many GLs activities lie within the RSC area.

2.6 Closed Loop Supply Chain

At the end of every RSC, companies have an option to close a loop or leave it open. Leaving it open means the products in a RSC will go to different destinations from the original supply chain. For example they might be sold to brokers, donated to charities or sent to landfills. Supply chains could also be made by creating a loop. A closed loop supply chain consists of a RSC and an extra loop to connect it to the original FSC (Blumberg, 2005). Guide and Van Wassenhove (2003) stated that the companies that have been most successful with their RSC are those that closely coordinate them with their FSC, creating a closed-loop system.

Closed-loop systems are characterised by the formation of a flow "cycle" (Fleischmann *et al*., 2001) since the sources of supply and falls in demand coincide. This is in contrast with open loops, where product flow enters and exits at two different points, in a "one way" configuration (Fleischmann *et al*., 2001). In open-loop systems, products do not return to the original producers but will be recovered by other parties willing and able to reuse the materials and products (Kopicki *et al*., 1993). Products are not returned to their original producer in open loop systems, but are used in other industries instead, such as recycling. In closed-loop systems however, products or packaging are returned to their original producers. An example of closed-loop activities would be remanufacturing and reuse (Fleischmann *et al*., 1997).

Guide and Van Wassenhove (2003) defined a closed loop supply chain (CLSC) that included the return processes, where the manufacturer had the intent of capturing additional value and further integrating all supply chain activities. Therefore, closed-loop supply chains include traditional forward supply chain activities and the additional activities of the RSC.

In a RSC or CLSC, there are a number of channel partners involved along the supply chain. For companies operating in an open-loop system, reverse distribution may also be outsourced to other parties such as dedicated third-party logistics providers. Besides logistics, outsourcing also applies to other activities such as sorting, repairing, recycling and disposal. The activities concerning customer contact, however, are less likely to be outsourced, such as complaint handling, administration and finance (Voss *et al*., 2002). Nevertheless, some companies are considering a "closed-loop" approach in order to achieve the best way to handle product returns, service contract returns, product recalls, used equipment and replacement parts for refurbishment, as well as reuse or sale as raw material (Moore, 2005).

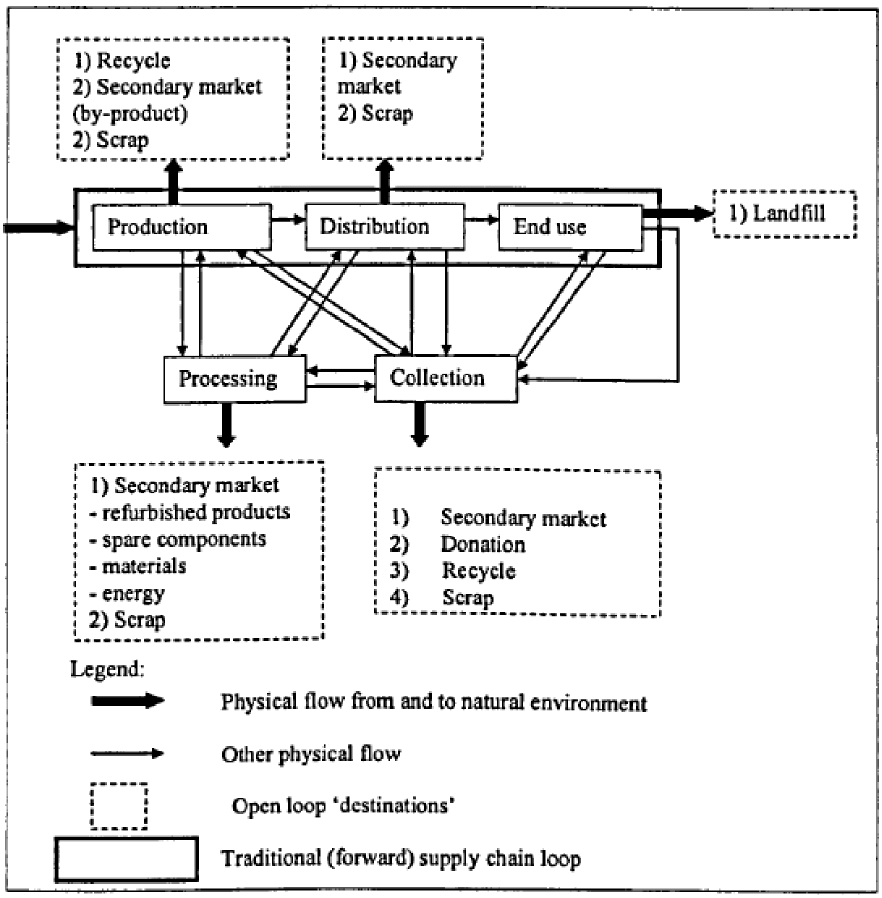

Figure 2.5 Closed-loops related to different phases in the life of a product (Flapper *et al.*, 2006).

2.6.1 Process route in reverse and closed-loop supply chains

For both open and closed-loop systems, there are extra activities involved in the overall process route in addition to the traditional FSC activities. These additional activities include:

- product acquisition to obtain the products from end-users;
- reverse distribution to move the products from the points of use to a point(s) of disposition;
- testing, sorting, and disposition to determine the product's condition and the most economically attractive reuse option;

- refurbishing to enable the most economically attractive of the options: direct reuse, repair, remanufacture, recycle, or disposal; and
- and remarketing to create and exploit markets for refurbished goods and re-distribute them.

(Guide *et al*., 2003)

For a retailer, some of the products returned by customer are collected by suppliers from the retailer's warehouse. Therefore, only the first activity (product acquisition) affects the retailer, and the rest are carried out by the brand owner. However, usually all five activities are effected by any organisations who are operating on closed-loop supply chains

In identifying success factors in managing CLSC, the type of product recovery options used and the type of product returns should be considered. Guide and Van Wassenhove (2003) used these two elements in identifying every success factor of each of their case study. For remanufacturing activities involving products such as photocopiers, these success factors were:

- Availability of the information systems that support the forecasting and control of returned goods in terms of time, quantity, and quality. The information must be accurately relayed to customers, and marketing schemes need to be developed to ensure that manufactured goods have the same quality as new goods.
- Strong supplier relationships that accommodate the reduction in the number of purchased parts and components, as well as changes in design requirements.

Flapper *et al*. (2006) highlighted the selection of operations to be outsourced or those to be performed in-house as another key element of CLSCs success. Three activities are identified where companies have to make this decision:

- Supply: In acquiring the supply of returned goods, companies have the option of a bring system, where customers are responsible for returning their products. Alternatively, a pickup system could be used to collect returns, where the company either uses its own distribution system or outsources the collection process to a specialised service provider.
- Processing: A company may outsource some operations to other dedicated parties, or even to the owners of the products themselves, such as separating different coloured glass bottles and removing metal and plastic caps in households.
- Distribution: Although some companies use their own logistics for the distribution of recovered goods, most tend to outsource this activity in order to protect their image, and to accommodate to the geographically separated markets of new and recovered goods.

2.7 Summary

This Chapter considered how RSC developed from RL and GL. Guide and Van Wassenhove (2003) mention it is important to consider creating closed-loop supply chains in RSC systems. This Chapter provided a first idea about how a general model could be created; what the locations were likely to be and what processes needed to take a place.

Chapter 3 Reverse Supply Chain Frameworks

In this Chapter, gaps in the research are identified that led to the creation of a new models of a reverse supply chain (RSC) that are described later in this Dissertation. A framework is "a basic concept structure" (de Brito and Dekker, 2004) and research that involved a RSC framework is explored. In the first Section, early work about the Reverse Logistic (RL) framework is explained. An integrated supply chain model was proposed by Krikke in 1998 and from this time onwards the literature includes research on RSC framework models. From frameworks listed in the literature, an explanation about main locations/components in RSC frameworks is presented. This Section combines and defines the components involved in RSC that were used as base components to create the new general model described in Chapter 5.

As the research described in this dissertation focused on re-manufacturing as a way to treat returned products, re-manufacturing in RSC is explained in this Chapter. In the last Section, the gap in the research is presented. Overall, this Chapter explains why a new general model of RSC was proposed.

3.1 Early Work on Reverse Logistics Framework

Some literature in the early research on RLs shows how scholars tried to structure and explain RLs. Krikke (1998) looked at reverse networks because the classic model of a forward supply chain was not applicable to RLs. Some elements considered as differences between forward and RLs systems were: *"Forward logistics systems are pull systems, while in RL there is a combination of push and pull, due to the fact that there are clients on both sides of the chain, namely the disposer and the re-user. In forward logistics, only customer markets need to be served and the entire logistic chain, including suppliers (the 'equivalent' of disposers), adjusts itself to it. As a result of the extended producer responsibility, the amount of waste supplied to the RL system (the push) cannot be influenced in the* *long run and has to be matched with demand (the pull). Disposal can serve as an escape route for unwanted waste, but the amount of disposal is limited by legislation."* (Krikke, 1998)

In addition Fleischmann *et al*. (1997) stated the following difference: *"A particularity in reverse distribution networks, is their high degree of uncertainty in supply, both in terms of quantity and quality of used products returned by the consumers. Both are determinants for a suitable network structure since, e.g. high quality products may justify higher transportation costs (and thus a more centralized network structure), whereas extensive transportation of low value products is uneconomical. Moreover, end-markets for recovered products may not be well known, exposing network planning in this context to even more uncertainty."*

Krikke (1998) proposed a model of a disassembly strategy for a single product. He proposed a two step optimisation model to solve the problem and considered the case of a television set as an example product. Figure 3.1 shows how RL systems can be set up with forward systems to result in an integral supply chain.

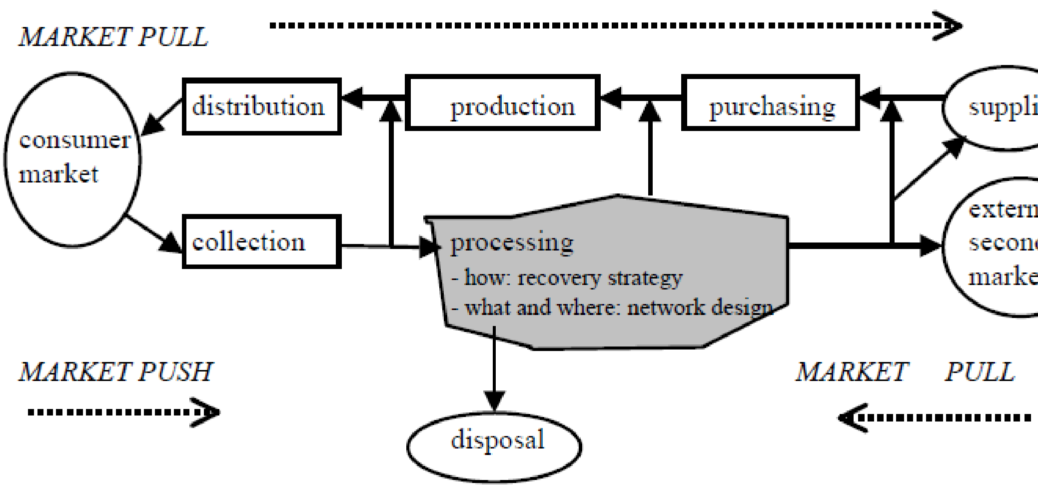

Figure 3.1 Integral supply chain (Krikke, 1998)

The design of the reverse network was concerned with the optimisation of the location and capacity of facilities as well as the flow of goods between them. In RL, demands are located not only at one side of the chain but in both, as the secondary markets, disposal facilities, etc. also receive the products of the company.

3.2 Reverse Logistics Frameworks

In this section RL frameworks found in literature are described. The main components and locations in a RSC framework are indentified and explained in the next Section.

Gungor and Gupta (1998) proposed a methodology for a Disassembly Sequence Plan (DSP). They proposed first generating a precedence disassembly matrix that represented the physical relationships between the assemblies of the products. Then an optimum DSP was proposed, and finally a third step consisted of performing the disassembly process, following the optimal DSP and adjusting the process when an unexpected situation arose.

Guide *et al*. (1999a) examined the impact of variable lead times on the control of parts released from a disassembly area to a remanufacturing area. They evaluated various disassembly release mechanisms for releasing the parts. Lead time variation was shown to have a significant impact on the choice of disassembly release mechanisms. They only considered the lead time as a source of uncertainty. To be accurate, it was also necessary to evaluate the impact of other factors such as the variation in the number of returns received and the size and location of inventory buffers.

Fleischmann *et al*. (2001) proposed a Recovery Network Model (RNM) which was a general quantitative model for RLs network design, shown in Figure 3.2. This model was adapted from the warehouse location model by adding a recovery network part. This model integrated forward logistics and RLs by using balance constraints that restricted the volume of returns to be less than production volumes. The objective of this model was to minimise the total cost of an integrated supply chain by employing a mixed integer linear programming technique which satisfied all balance constraints at each level of facilities.

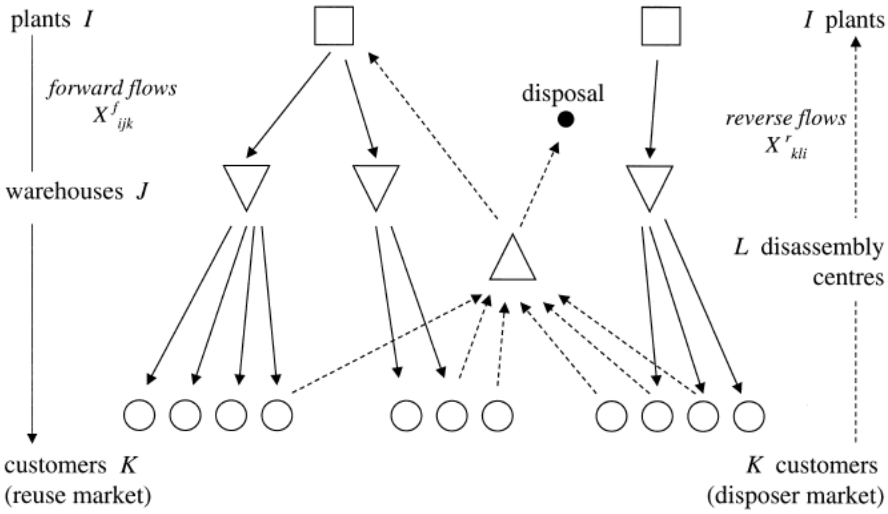

Figure 3.2 Recovery Network Structure (Fleischmann *et al*., 2001)

Salema *et al*. (2007) tried to improve the RNM model by correcting some limitations of the original model such as production/storage capacity, multi-product production and demand/returns uncertainty. The mixed integer linear programming technique was applied but added more characteristics to the model. A case study of an Iberian company was used to test the model.

Hai-jun *et al*. (2007) used the integration of genetic algorithms and a random simulation technique to model RLs networks. The logistics intelligent simulating software was used to simulate RLs networks with uncertainty of time, place, and quantity of return products, but did not consider the uncertainty of the quality of product returns.

Zuluaga and Lourenço (2002) proposed a RLs model using the concept of medium term production planning, categorised in three types: strategic planning, tactical planning, and operative planning. Strategic planning was long term planning related to business planning, while tactical planning was medium term planning related to the production level. Several techniques were used at this level, for example, master production schedule and capacity planning. The final type of planning, operative planning or short term planning was related to activities such as job-shop scheduling and material requirement planning. The multi plant production planning model with returns was developed. All returns were assumed to be processed at a centralized facility which could dispose, disassemble and ship returned parts or assemblies back to be remanufactured at plants, depending on the quality of the returns.

Zhu (2003) proposed a supply chain model composed of suppliers, manufacturers, distributors, and retailers. A supply chain system was considered as an integrated input output system, shown in Figure 3.3.

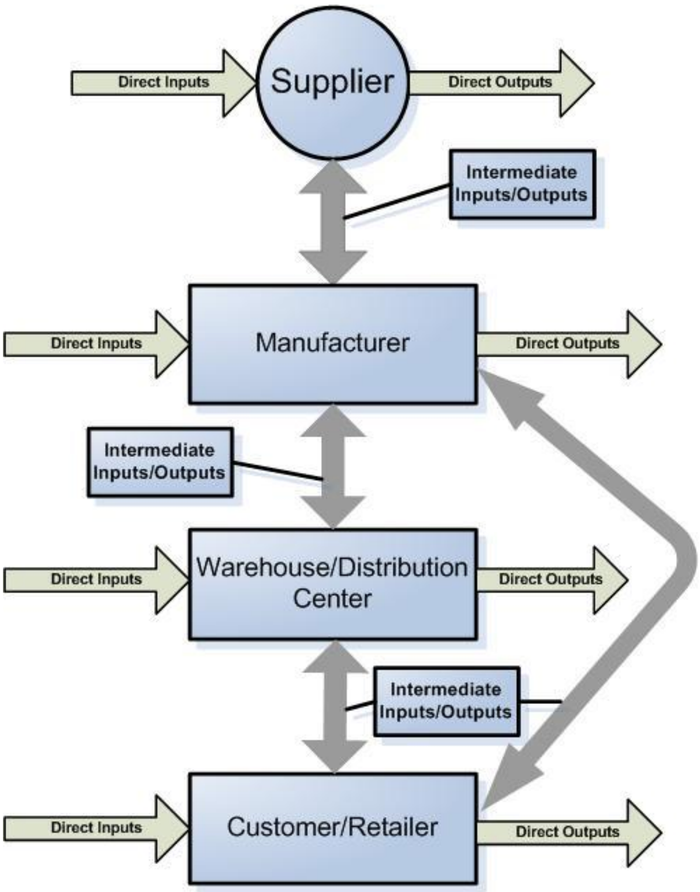

Figure 3.3 Supply Chain model (Zhu, 2003)

Figure 3.4 illustrates a framework for RLs. de Brito and Dekker (2004) proposed a framework of RLs which depended 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).

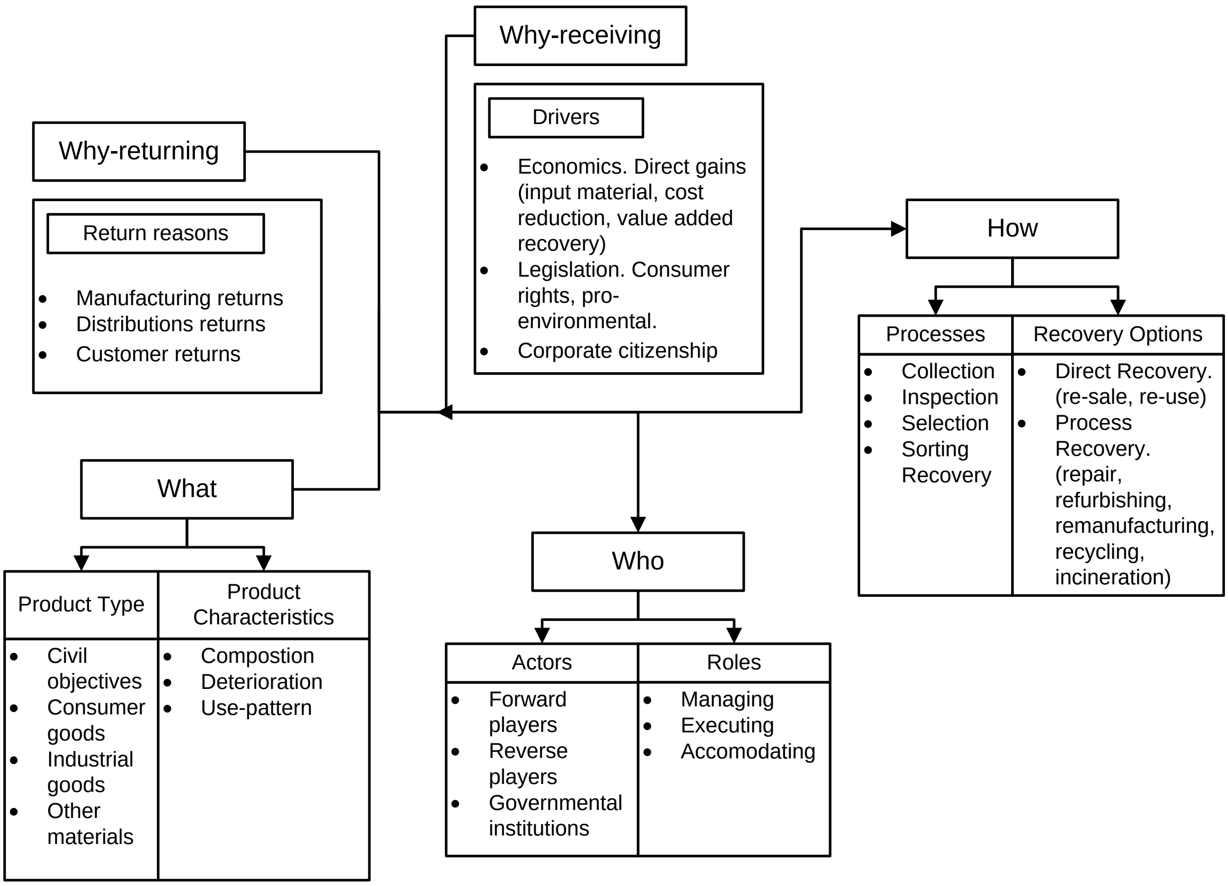

Figure 3.4 Framework for reverse logistics adapted from de Brito and Dekker (2004)

Gilmour (1999) proposed a framework for supply chain operations as shown in Figure 3.5.

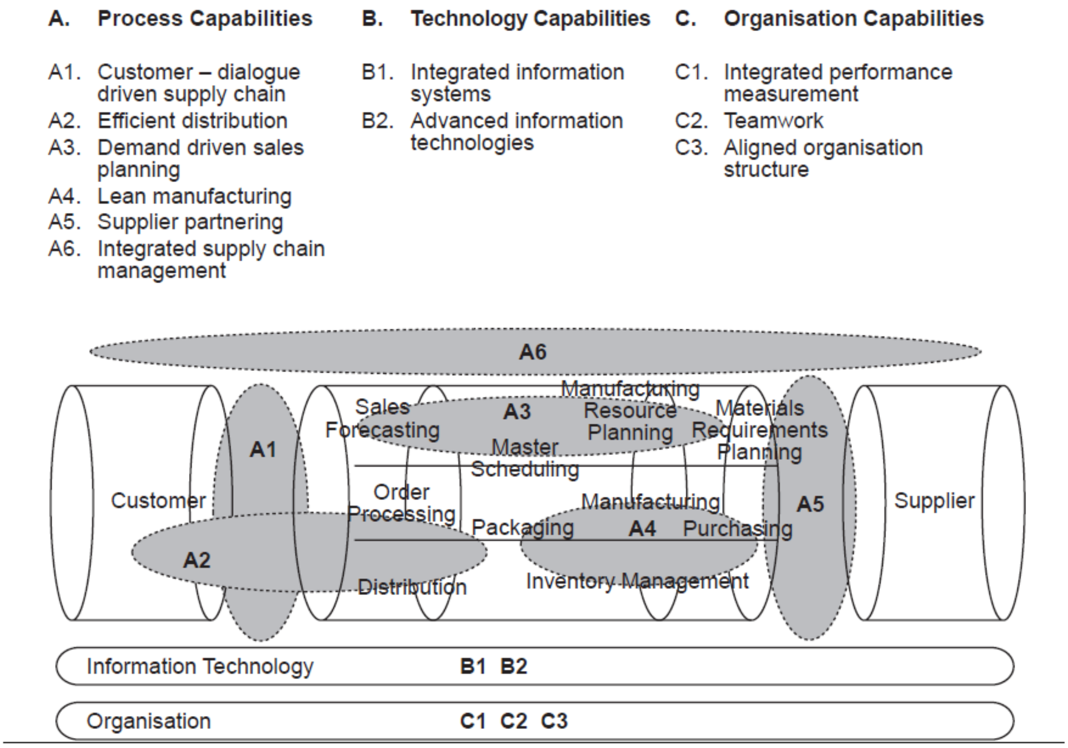

Figure 3.5 Supply chain framework (Gilmour, 1999)

This model was used to investigate logistics operations for some companies in Gilmour's research. It was composed of six functional process capabilities, two technology capabilities and three organization capabilities as shown in Figure 3.5. These eleven components were categorized in five dimensions to evaluate the logistic activities in the area of management. These dimensions were strategy and organization; planning; business process and information; product flow; and measurement. Gilmour also provided descriptions of capabilities as shown in Table 3.1.

Table 3.1 Logistics capabilities components (Gilmour, 1999)

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 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 change over times) while maintaining high levels of flexibility and quality.
5. Supplier partnering.	Integration of manufacturers' and suppliers' supply chain activities to maximise 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.	Improved 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 (2005) suggested five strategic factors that were important for RSCs. The first one is the costs, costs are related to every part of RSC design, for example, the cost of building a customer service centre for remanufacturing operations. The second one is the quality. Strategic quality are focuses on quality of remanufactured, recycled or repaired products. Customer service is the next strategic factor on the list. The point of this strategy was to meet customer expectations, for instance, how fast the firm could fix or replace defective products. Next one is environmental concerns, where communities and customers required that firms should be responsible for the environmental impact of their production, delivery or final disposal of their products

(Dowlatshahi, 2005) (Mason, 2002). RLs strategies should conform to environmental regulations and requirements. The last strategic factor is the political/legal concerns. Due to increasing government legislation, RL strategies needed to be more efficient to conform to these regulations and needed to be able to handle waste and hazardous materials from final disposal or end-of-life products.

3.3 RSC Model Components

Before designing a RSC, the components in a supply chain needed to be specified. RLs consist of the set of components shown in Figure 3.6.

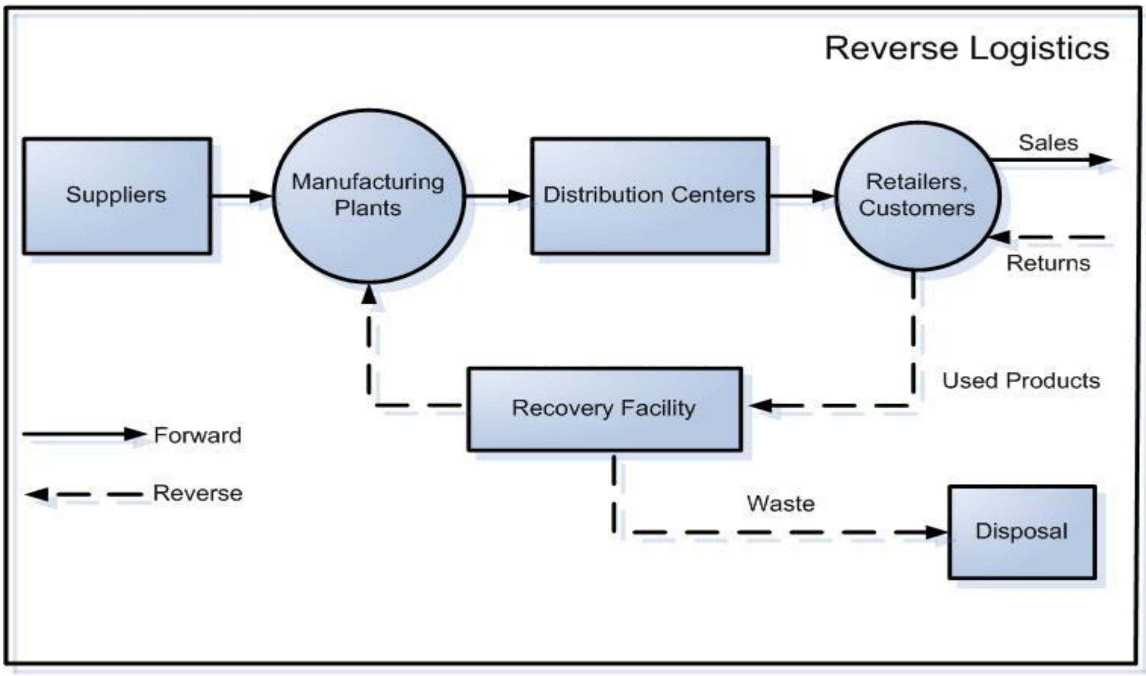

Figure 3.6 Reverse Logistics (Tonanont, 2009)

Figure 3.6 presents, RLs composed of five main components: supplier, manufacturing plant, distribution center/warehouse, retailers/customers and recovery facility. The function and assumption of each component's function in this model is explained:

- Supplier – will deliver raw materials to manufacturing plants.

- Manufacturing plant – will manufacture products using raw materials from suppliers and will employ returned parts or assemblies from a recovery facility. Manufacturing plants need to specify the quantity and type of materials that they need to buy from suppliers at each period. Products from manufacturers will be delivered to distribution centres or warehouses. Not all of the produced products are delivered to a distribution centre. 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 parts, materials or assemblies from a previous period that are kept in inventories, together with new materials purchased from suppliers to produce products. Products will be manufactured within the period.
- Distribution centre – will collect demands from customers and retailers and inform manufacturing plants. After receiving products from manufacturers, the distribution centre will distribute them to retailers or customers to fulfil the demand. In this model, stock-out can happen at a distribution centre 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 centres or warehouses. Product quantities depend on demand.
- 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 3.7.

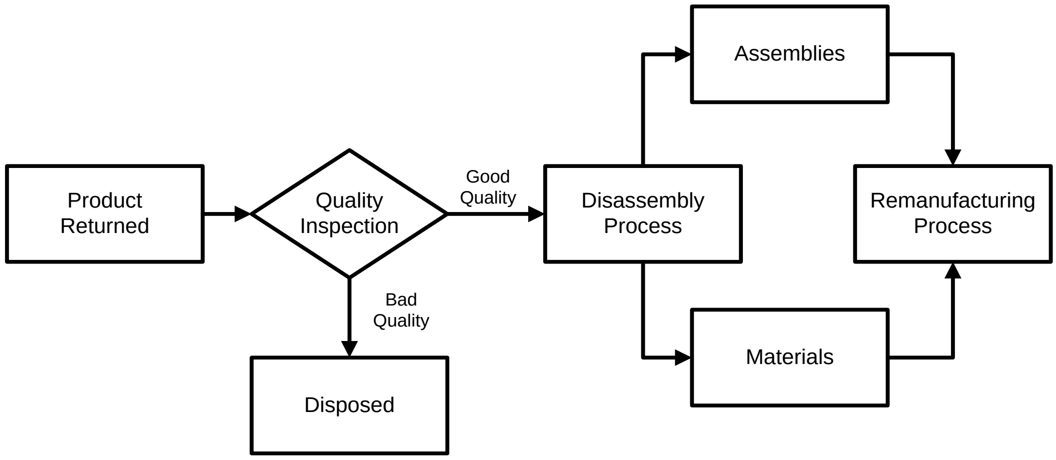

Figure 3.7 Classification process of return at a recovery facility
(Zuluaga and Lourenço, 2002)

This model implies that those assemblies and returned parts that are shipped from a recovery facility can be used to manufacture new products but employ different processes. In this case, a bill of materials for each product is required. For example, product X could be divided into assembly A and material B in the first level, while assembly A might be composed of material C and D and could be disassembled at a second level. So product X could be manufactured by all new materials B, C and D or reuse assembly A and new material B. Figure 3.8 shows an example of a bill of materials for product X.

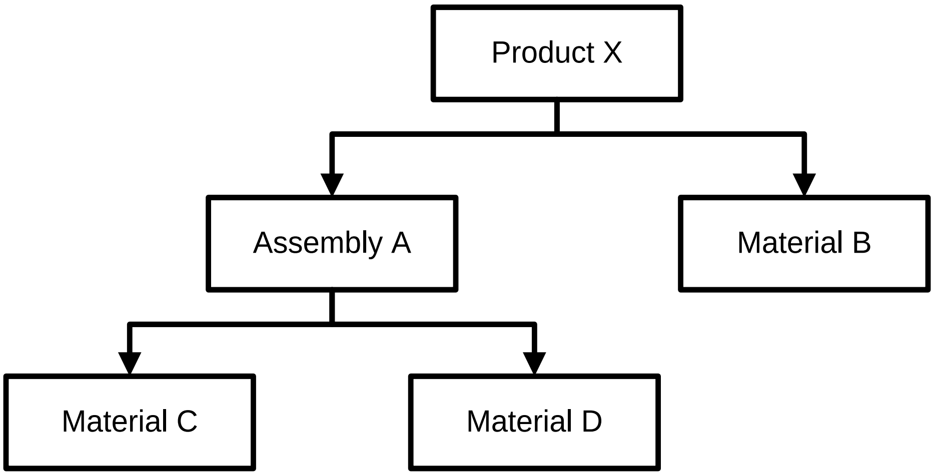

Figure 3.8 An example of bill of materials for product X
(Zuluaga and Lourenço, 2002)

This bill of materials is adapted from Zuluaga and Lourenço (2002) which needed 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.

The recovery plant is an external centre created with the objective of receiving returned products, classifying them and performing operations to either assure the proper disposal of a product or material or, reincorporate the total product or some of its components in to a manufacturing process of new products. When a returned product was received at recovery plant, the company had several options, depending on the reason for the product's return. This process is described in Rogers and Tibben-Lembke (2001) and Krikke (1998). One option was to disassemble the product and verify if its components could be used to manufacture new products.

When a product was disassembled, materials and assemblies were re-obtained. The assemblies were components composed of various parts that should be disassembled or not depending on quality. Those alternatives were different since the quality of the product was unknown and the economical viability of the disassembly process was not the same for all parts and products.

3.4 Re-manufacturing

Traditionally, suppliers competed against suppliers, factories against factories, distributors against distributors, and retailers against retailers, but that way of thinking has been changing; many companies now consider that competition in the market is not between companies but between supply chains (Ross, 2013). The final product includes all the inefficiencies and over costs generated by each company in a supply chain. If the supplier is not efficient, the inefficiency costs can be translated to the manufacturer, if a manufacturer is not efficient, these costs can be translated to the distributor, and finally the product will not be competitive in the market unless the distributor and retailer are efficient (Leih *et al*., 2014). Therefore, the competitiveness of a product is the result of good management in all the companies in a supply chain, not only in some of them. This generated new challenges for management (logistics in particular) and created new lines of research.

Manufacturing companies applied optimisation techniques to production planning with some degree of success, but only in recent years, have companies become aware of the importance of sharing plans with other companies within their supply chain (Rushton *et al*., 2014). Another important issue for manufacturing companies is sustainability. This is especially important in Europe where laws have been become more demanding, and companies have become financially responsible for contamination their products generate. In this sense, manufacturing companies will be responsible for recycling, destroying or reusing their end-of-life products. The objective of this legislation was to make companies more conscious about the environment and their responsibility to its preservation. Remanufacturing emerges as a possibility for companies in this new business environment.

The literature review in this Section considers two main areas of production planning: Supply chain collaboration and remanufacturing. Supply chain collaboration has been widely investigated. Many authors comment on the advantages of collaborative work in a Supply Chain (Holweg *et al*., 2005) (Guide Jr *et al*., 2000).

In terms of production planning, some authors have proposed models for operational collaborative planning. Kempenaers *et al*. (1996) worked on the development of an integrated automatic process planning and scheduling system based on the concept of non-linear process plans. Vercellis (1999) proposed a multi-plant production planning model with several items and depots to transport products. The model considered two stages of production at each plant. However, raw materials and purchasing costs were not considered and remanufacturing was not modelled.

Berning *et al*. (2004) considered a complex scheduling problem in the chemical process industry involving batch production. The application described a network of production plants with interdependent production schedules, multi-stage production at multi-purpose facilities, and chain production. The model was for operational purposes and did not consider remanufacturing. Previous work in the area needed to be extended to consider returns and an external supply chain.

In the area of aggregated production planning, most of the research has been concerned with traditional manufacturing. However, some authors proposed models for remanufacturing environments. Guide *et al*. (1999b) described research in production planning and inventory control. They concluded that not all areas of production planning and control had been researched adequately, and formal work was needed to link production planning and control with product return information.

Jain and Palekar (2005) proposed a configuration-based formulation for one manufacturing environment where production may involve dissimilar machines performing similar operations at different rates and equipment could be connected together to form different production lines. Mazzola *et al*. (1998) proposed a model for multi-product aggregated production planning, but without remanufacturing and without a collaborative scheme.

Guide (2000) performed a literature review about the different topics covered in remanufacturing and described the most important research in the area. He listed seven complicated characteristics in the remanufacturing environment and how different authors have dealt with the characteristics. The seven characteristics were:

1. Uncertain timing and quantity of returns.
2. Need to balance returns with demands.
3. Disassembly of returned products.
4. Uncertainty in materials recovered from returned items.
5. Requirement for a RLs network.
6. Complication of material matching restrictions.
7. Problems of stochastic routings for materials for remanufacturing operations and highly variable processing times.

For remanufacturing of short life-cycle, highly seasonal consumer electronics such as laptops and mobile phones, Guide and Van Wassenhove (2003) listed the following factors:

- Ability to forecast the flow (supply and demand) of returned goods.
- Ability to accommodate a fast and responsive recovery system, bearing in mind the perishability quality of the products.
- The use of e-commerce in acquiring worldwide trading opportunities and in identifying technology differences between different countries.

The model proposed in the research work described in this Dissertation considers more elements in the collaborative planning process. It incorporates purchasing, transportation and holding costs, and also considers multi-plant and multi-product environments. In addition, the formulation of the model is extended by introducing the possibility of planning remanufacturing at the aggregated level.

Several factors influence returns, including the life-cycle stage of a product and the rate of technological change. That has an impact on demand management, and inventory control and management. The process of receiving returned products implies some different activities of revision and control to determine the actual quality state of a product, and only after that process, is it possible to determine the best strategy to minimize the costs. In a remanufacturing environment, it is possible to use different parts from different returned products to manufacture a new product. This new product would comprise a mix of newly purchased parts and returned parts which therefore complicate the production and the manufacturing planning process.

Table 3.2 is from Guide Jr *et al*. (2000) and shows a comparison between the manufacturing and remanufacturing environment and the impact they have over the functional areas within organizations.

Table 3.2 Comparison between manufacturing and remanufacturing environment (Guide Jr *et al*., 2000)

Factors	**Recoverable manufacturing environment**	**Traditional manufacturing environment**
Environmental focus	Seeks to prevent postproduction waste	Environmentally conscious design and manufacturing, focus on Preproduction Pollution prevention and Remediation
Logistics	Forward and reverse flows Uncertainty in timing and quantity of returns Supply-driven flows	Open forward flow No returns Demand-driven flows
Production planning and control	Need to balance demands with Returns Material recovery uncertainty Stochastic routings and processing times Manufacturing system has three	No such need Certainty in planned materials Fixed routings and more stable processing times Manufacturing system has two major components: fabrication

	major components: disassembly, remanufacturing, and reassembly	and assembly
Forecasting	Forecast both core availability and end-product demand Must forecast part requirements because material recovery rates are uncertain	Forecast only end products No parts forecasting needed
Purchasing	Highly uncertain material requirements due to variable recovery rates Cores and parts and components, replacement parts, components	Material requirements Deterministic Raw materials, new parts, and Components
Inventory control and Management	Types: cores, remanufactured parts, new parts, new and remanufactured substitute parts, original equipment manufacturer parts Must track and provide accounting for all part types	Types: raw materials, work-in-process, finished goods Must track and provide accounting for work-in-process and finished goods

This is an area where the RL literature has been most widely developed. Most quantitative papers have been about production scheduling, inventory control and remanufacturing. There is a variety of work in progress and a range of issues that have been uncovered by researchers within the RL area. For instance, most papers only concentrate on one product. Also there were not any models that combined remanufacturing with supply chain planning. The actual state of development of companies makes it necessary to develop this kind of model, where integration and collaborative planning are considered together.

3.5 Gaps in the Research

Research in this area had been growing and there was an increasing number of companies deciding to introduce RSC systems. Legislation also helped to increase the importance of this field, given that companies had been forced to be responsible for the packaging and the end-of-life products they had sold.

Most of the time, returns arose from demand forecasting errors. If forecasting was not accurate, problems emerged in RSC activities. On the other hand, the lack of information of some secondary markets made it difficult to estimate the number of buyers in those markets. In some areas such as secondary packaging return, forecasting was addressed by considering the system as a closed loop, where the same elements were present in the system and there were some losses at each cycle. This approach helped forecasting as the problem was reduced to estimating the number of units lost at each cycle of the product.

There were few models in the literature. There were areas to be investigated in the RSC field, both empirically and theoretically. Some interesting fields for future research in RL have been suggested by the literature review in this Section. Dowlatshahi (2005) stated the following conclusions:

- Conceptual, quantitative, and application-case-based articles do not provide an extensive treatment of RL topics.
- The majority of articles were short and lacked the depth to demonstrate the level of integration necessary to implement RL across various functional areas.
- Most authors assume prior comprehensive understanding of the structure of a RL system and do not describe the basic structure of a RL system.
- Most authors do not define the basic concepts and terms. Most of the literature is practitioner-oriented.

The literature reviews in Chapter 2 and this Chapter suggested the following gaps in the research:

- Few models consider forward and reverse distribution simultaneously; these models consider joint locations of facilities for both networks.
- There were no models dealing with reverse routing combined with forward logistics routing.

- There was no empirical evidence of comparison between traditional and specifically adapted inventory control methods in a return flow environment.
- Almost all the models were for one product and/or one component. Few of them dealt with multiple components but none of them dealt with multiple products.

There was also a lack of appropriate models for the actual manufacturing operations where various products and materials could be considered at the same time. Other elements such as collaborative planning were not considered in the remanufacturing environment. The new research described in this dissertation contributes to the RSC area by proposing a new general model of the RSC that describes the basic structure of a RSC system and considers integrated FSC and RSC. This new general model could be adapted for different industries and is described in Chapter 5.

Chapter 4 A Review of Performance Measurement Research

In this Chapter, Performance Measurement (PM) is defined and past research will be explored. In the first Section a classification of PM is presented. Following Sections describe PM in a Forward Supply Chain (FSC) and PM in a Reverse Supply Chain (RSC). The last section describes more research gaps that were identified during the research.

This Chapter describes why a mathematical model with an objective to minimise cost could be useful for PM.

4.1 Performance Measurement Definition

PM helps companies better understand the advantages and disadvantages of their strategies and provides an opportunity for improvement. A performance metric is used to compare benchmarking efficiency and/or effectiveness of a system, for instance.

White (1996) described two basic questions to be answered when measuring: what will be measured and how will it be measured. Different performance measures are used in different cases depending on the scope of interest (Eloranta and Holmström, 1998). Data being used to measure performance was also an important issue. Objective data such as quantity, time and money are relatively easy to obtain. Subjective data is usually less accurate due to individual estimation (Tangen, 2004).

PM has often been discussed but rarely defined. Neely *et al*. (2005) described PM as the process of quantifying action, where measurement is the process of quantification. They suggested that performance should be defined as the efficiency and effectiveness of action, where action correlates with performance. A performance measure is a metric used to quantify the efficiency and/or effectiveness of an action. PM System (PMS) is the set of metrics used to quantify the efficiency and effectiveness of action.

A large number of performance measures have been described in the literature and these are discussed. Classification of performance measures can be a useful way to understand them and this Chapter attempts to classify them.

In the earlier literature, performance measures were usually divided into cost-related and non-cost-related. Fitzgerald *et al*. (1991) studied the service industry, and they concluded that there were two basic types of performance measure in any organisation:

- Relating to result (competitiveness, financial performance)
- Focusing on the determinants of the result (quality, flexibility, resource utilitisation and innovation).

Flapper *et al*. (1996) introduced a classification of performance measures involving three intrinsic dimensions:

- Decision type: strategic / tactical / operational. This dimension focused on the kind of decision the measure is meant to support.
- Aggregation level: overall / partial. This dimension described whether the measure was of overall or partial nature.
- Measurement unit: monetary / physical / dimensionless. This dimension related to the unit that the measure was expressed in.

Slack *et al*. (2001) classified a group of individual performance measures based on the terms of the five manufacturing performance objectives: quality, speed, dependability, flexibility and cost, as shown is Table 4.1.

Table 4.1 Typical individual performance measurement (Slack *et al*., 2001)

Performance objective	**Some typical performance measures**	**Performance criteria that link firm strategy to operations decisions**
Quality	Number of defects per unit. Level of customer complaints. Scrap level. Warranty claims. Mean time between failures.	% defect reduction. % scrap value reduction. % unscheduled downtime reduction. % supplier reduction. % of inspection operations eliminated.
Speed or innovation	Customer query time. Order lead time. Frequency of delivery. Actual versus theoretical throughput time. Cycle time.	% increase in annual investment in new product and process research and design. % reduction in material travel time between work centres. % increase in annual number of new products introduction. % increase in common parts per products.
Dependability	Percentage of orders delivered. Average lateness of orders. Proportion of products in stock. Schedule adherence.	% reduction in purchased lead time. % reduction in lead time per product line. % increase in portion of delivery promises met.
Flexibility	Variance against budget.	% inventory turnover increase. % reduction of employee turnover. % improvement in labour/desired labour. % reduction in total number of data transactions per product. % average set-up time improvement per product line.

Although classification of performance measures can be useful to a measurement practitioner as a source for finding potential performance measures, an important point is that a classification does not necessarily give an appropriate summary of what performance measures a particular company should include.

Performance measures could be categorised according to what type of decision they are meant to support (Flapper *et al*., 1996). This could lead to a discussion about what different performance measures are needed for different hierarchal levels in an organisation. It is important to link performance measures with hierarchal levels so that everyone in an organisation can work towards same objectives. Hierarchical levels in an organisation can be divided into three levels:

- Strategic level: performance measures are related to decisions having an effect on issues with a time scale of several years. Such measures can tell an organisation about the soundness of their strategic decisions.
- Tactical level: performance measures can cover a monthly up to a yearly period, and can encompass issues such as which suppliers are used, which overall manufacturing technologies are utilised etc. These measures are important in setting boundaries for actual operations of an organisation.
- Operational level: performance measure deals with operations and business processes of the organisation on a daily, weekly or monthly basis.

Flapper *et al*. (1996) stated that it is necessary to combine PM with related tactical and operational measures. Figure 4.1 shows that a performance measure at a strategic level should be broken down into specific measures at the tactical level and further down to the operational level (Jackson, 2000).

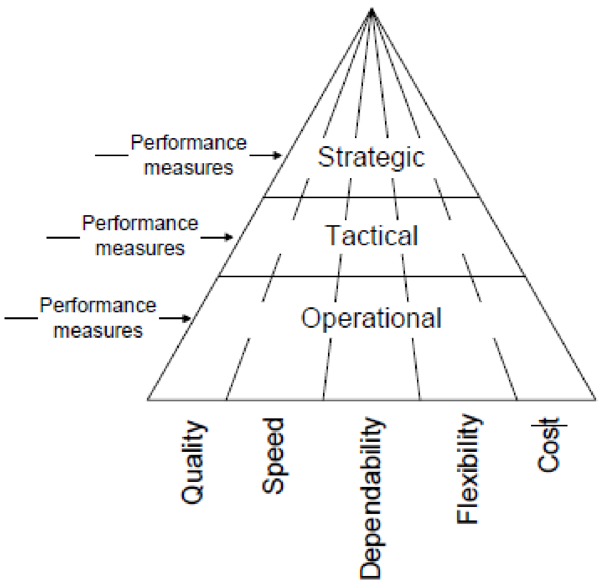

Figure 4.1 Performance measures on three different levels (Jackson, 2000)

Having discussed PM and performance measure, this Dissertation will describe PMS. PMS need to be designed according the objectives of the company. In the next

Section, some conceptual frameworks that have been developed to help measurement practitioners to design their PMS are explored.

4.2 Performance Measurement Frameworks

Tangen (2004) emphasised that a company should have a unique PMS to guide the measurement practitioners to select and design suitable performance measures. A number of frameworks have been explored that give an idea about how PMS might be used.

4.2.1 The Sink and Tuttle framework

In this framework (Sink and Tuttle, 1989) see Figure 4.2 the performance of an organisation can be expressed as a complex interrelationship between seven performance criteria.

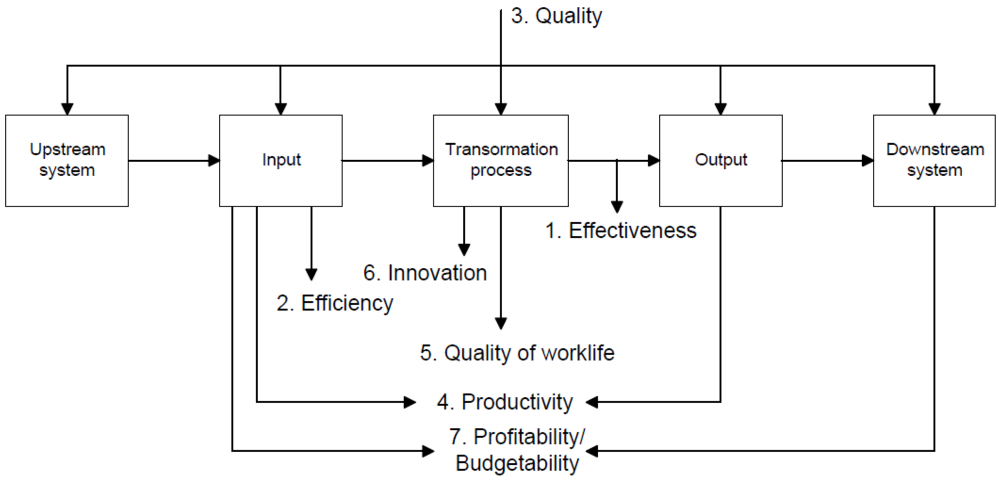

Figure 4.2 Definitions of seven performance criteria (Sink and Tuttle, 1989).

They are:

1. Effectiveness, which involves doing the right things, at the right time, with the right quality. In practice, effectiveness is often expressed as a ratio of actual output to expected output.

2. Efficiency, defined as a ratio of resources expected to be consumed to resources actually consumed.
3. Quality, where quality is a wide concept. To make the term more tangible, quality is measured at several checkpoints.
4. Productivity, which is defined as the traditional ratio of output to input.
5. Quality of work life, which is an essential contribution to a well performing system.
6. Innovation, which is a key element in sustaining and improving performance.
7. Profitability/budget-ability, which often represents the ultimate goal for most organisations.

This model has a limitation in that it does for not consider the need for flexibility or a customer perspective.

4.2.2 Balanced Scorecard

One of the most well known conceptual PMS frameworks is the Balanced Scorecard (Kaplan and Norton, 1992) which allows managers to take a quick but comprehensive view of business from four important perspectives (see Figure 4.3).

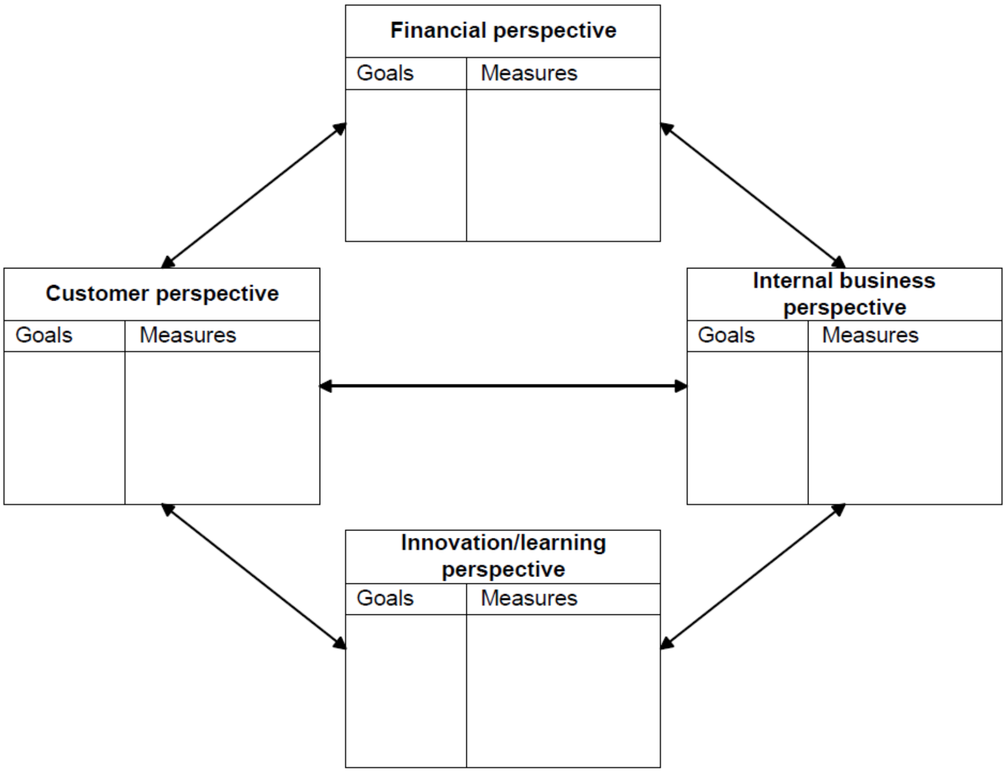

Figure 4.3 Balanced scorecard(Kaplan and Norton, 1992)

Kaplan and Norton (1992) stated that these perspectives answered four fundamental questions:

- Financial perspective: how do we look to our shareholders?
- Internal business perspective: what must we excel at?
- The customer perspective: how do our customers see us?
- Innovation and learning perspective: how can we continue to improve and create value?

The balanced scorecard limits the number of measures used. By doing this, information overload can be minimised and managers can be forced to focus on the handful of measures that are most critical.

4.2.3 Performance Pyramid

An important requirement of a PMS is that there must be a clear link between the performance measures at the different hierarchical levels in the company, so each function and department strives towards the same goals. One example of how this link can be achieved is through a performance pyramid (Cross and Lynch, 1992) (Figure 4.4), called SMART - strategic measurement analysis and reporting technique.

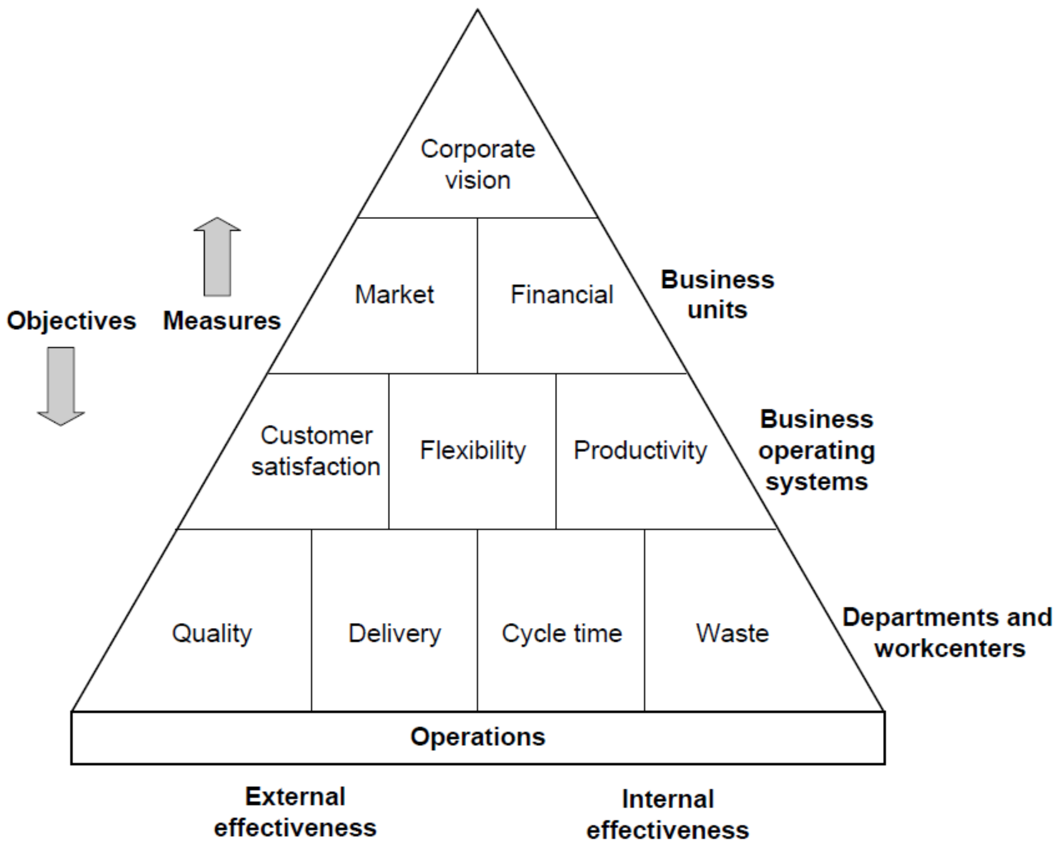

Figure 4.4 The performance pyramid (Cross and Lynch, 1992)

SMART proposed breaking down the objectives of a company along four levels, starting at the top of the pyramid with the company's vision. The second level, business units, comprised the company's key results, objectives and was measured in two ways: reaching short-term targets of cash flow and profitability; and achieving long-term goals of growth and market position. The business operating system bridged the gap between top-level and day-to-day operational measures. Finally, four key performance measures are used at departments and work centres on a daily basis.

The main strength of this framework is its suggestion to integrate corporate objectives with operational performance indicators (Ghalayini *et al*., 1997).

4.2.4 Performance Measurement Questionnaire

The Performance Measurement Questionnaire (PMQ) framework was developed to help managers identify three areas (Dixon *et al*., 1990), to:

- help managers identify the improvements needs of their organisation;
- determine to which extent the existing performance measures support improvements;
- establish an agenda for performance measure improvements.

The result of the PMQ is evaluated in four types of analysis: alignment, congruence, consensus and confusion. The PMQ has an advantage of providing a mechanism for identifying the improvement areas of a company and their associated performance measures.

The framework is structured in two main parts. Part 1 is aimed at evaluating the specific improvement areas of the organization and how effectively the current performance measures evaluate improvement. Part 2 is aimed at evaluating how achieving excellence for different performance improvement factors (= measures) will lead to long-term health of the organization and to what extent the organization already places emphasis on the most crucial factors (Bourne *et al*., 2003).

However, the PMQ is not built around a fixed framework. PMQ does not provide identification of specific performance measures that are related to the strategy of the organization (Jagdev *et al*., 2004).

4.2.5 Performance Prism

The performance prism was developed by Neely *et al*. (2001). They argued that performance measures need not be strictly derived from company strategy. They stated that the needs and wants from stakeholders must be considered first, then the strategies could be formulated.

This framework emphasises five distinct but linked perspectives of performance, as shown in Figure 4.5:

1. Stakeholder satisfaction: who are the stakeholders and what do they want and need?

   In the Performance Prism, the impact of employees, suppliers, the local community, etc. on performance plays a more prominent role.
2. Strategies: what are the strategies required to ensure the wants and needs of stakeholders?
3. The starting point when selecting a measures was: "Who are the stakeholders and what do they want and need?". When these questions have been answered is it possible to start to explore the issue of what strategies should be put in place to ensure the wants and needs of the stakeholders are satisfied. In other words, strategy means how the goal will be achieved.Processes: what are the processes to put in place in order to allow strategies to be delivered?
4. Many organizations classify four business processes: (1) develop products and services, (2) generate demand, (3) fulfil demand, (4) plan and manage the enterprises. These processes can be sub-divided into more detailed processes. Management will have to identify which are the most important processes, and

focus attention on these, rather than simply measuring the functioning of all processes.Capabilities: what are the capabilities required to operate our processes?

Capabilities are the combination of people, practices, technology and infrastructure that together enable execution of the organization's business processes. They are the fundamental building blocks of the organization's ability to compete.

5. Stakeholder contributions: what is wanted and needed from stakeholders to maintain and develop those capabilities?

   This frameworks recognised the fact that organizations not only have to deliver value to their stakeholders, but also enter into a long-term relationship with their stakeholders. This relationship should involve the stakeholders contributing to the organization.

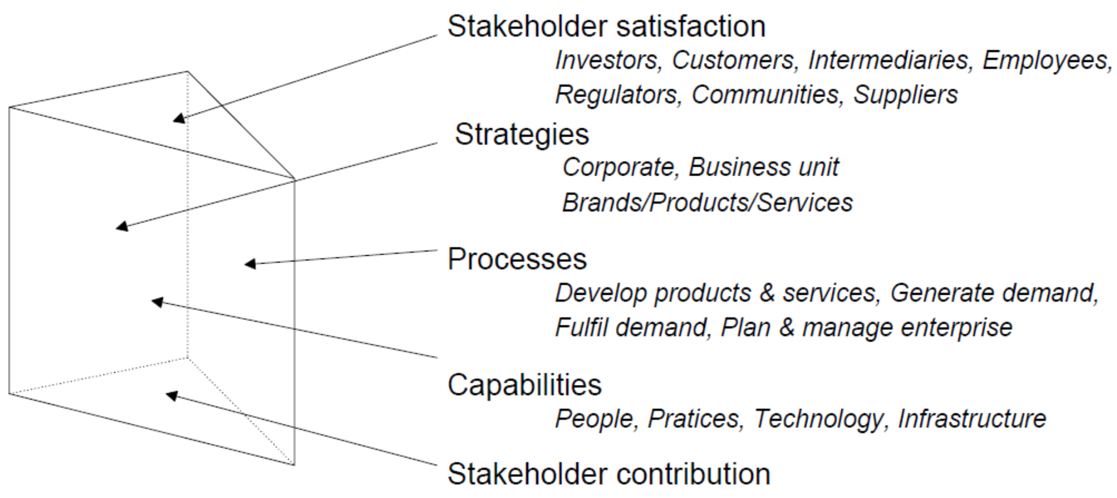

Figure 4.5 The performance prism (Neely *et al*., 2001)

The strength of this framework is that the first question for the company to consider about their strategy exists even before the process of selecting measures is started (Najmi *et al*., 2012). This framework also considers stakeholders that are usually neglected when choosing performance measures. However, the framework does not offer any information about how these performance measures are going to be implemented (Striteska and Spickova, 2012).

4.3 Methods to Design a Performance Measurement System

In this Section, the methods to design an appropriate performance measure are explored. These methods are needed by a company to be able to create PMS that are suitable to their own needs and circumstances (Sink and Tuttle, 1989).

Methods to design performance measures provide step-by-step guidance for developing performance measure management. There are in general three objectives for developing and implementing a PMS: monitoring, controlling and directing (Bowersox *et al*., 1996). Monitoring measures track historical performance for reporting to management and customers. Controlling measures track ongoing processes and are used to refine a logistic process in order to bring it into compliance. Directing measures are designed to motivate personnel, where the measures are usually designed to encourage personnel to achieve higher levels of performance, for example productivity. In designing an effective PMS, several aspects must be considered. A method needs to create a PMS suited to special requirements and circumstances rather than a standard set of measurements created by experts and imposed on organisations (Sink and Tuttle, 1989).

Sink and Tuttle (1989) also presented guidelines about the design of operational performance measures:

- Measure what is important, not what is easy.
- Create visibility and ownership for the resulting measurements systems in order to ensure effective long-term use.

- What is needed is not a standard set of measurements created by experts and imposed on organisations, but rather a method by which organisations can create PMSs suited to their own inevitably special needs and circumstances.
- The greater the participation in the process of creating a PMS, the greater the resulting performance change, and the greater the ease of implementation of future changes based upon PM.
- A PMS must not appear to those involved as simply a passing fad.
- To be useful, a system must be credible to behaviours and not seen as a game.
- Boundaries of the organisational unit to be measured must be clearly defined.

Wisner and Fawcett (1991) have shown that a firm's strategy should be the origin of a PMS and present the following nine-step process:

1. Clearly define the firm's mission statement.
2. Identify the firm's strategic objectives using the mission statement as a guide (profitability, market share, quality, cost, flexibility, dependability and innovation).
3. Develop an understanding of each functional area's role in achieving the various strategic objectives.
4. For each functional area, develop global performance measures capable of defining the firm's overall competitive position to top management.
5. Communicate strategic objectives and performance goal to lower levels in the organisation. Establish more specific performance criteria at each level.
6. Assure consistency with strategic objectives among the performance criteria used at each level.
7. Assure the compatibility of performance measures used in all function areas.
8. Use the PMS to identify competitive position, locate problem areas, assist the firm in updating strategic objectives and making tactical decisions to achieve these objectives, and supply feedback after the decisions are implemented.

9. Periodically re-evaluate the appropriateness of the established PMS system in view of the current competitive environment.

Thor (1993) presented ten different rules for building performance measures:

1. Clearly identify your purpose for measuring.
2. Choose an appropriate balance between individual and group measures.
3. Measure all the key elements of performance.
4. Be sure the measures adequately reflect the customer's point of view - whether the customer is external or internal.
5. Use care in generating competitive benchmarks.
6. Give some time to tedious technical adjustments.
7. Develop or modify the system as particularly as possible.
8. Cost/benefit analysis also applies to data availability.
9. If strategies change, so can measures.
10. Performance improvement is a long-term process; top management patience is needed toward newly measured results.

Neely *et al*. (2005) suggested guidelines about the design of PMS which incorporated the selection of measures and the actual structure of PM.

1. Clearly define the firm's mission statement.
2. Identify the firm's strategic objectives using the mission statement as a guide (profitability, market share, quality, cost, flexibility, dependability and innovation).
3. Develop an understanding for each functional area's role in achieving the various strategic objectives.
4. For each functional area, develop global performance measures capable of defining the firm's overall competitive position to top management.

5. Communicate strategic objectives and performance goals to lower levels in the organisation. Establish more specific performance criteria at each level.
6. Assure consistency with strategic objectives among the performance criteria used at each level.
7. Assure the compatibility of performance measures used in all functional areas
8. Use the PMS.
9. Periodically re-evaluate the appropriateness of the established PMS in view of the current competitive environment.

Medori and Steeple (2000) proposed an integrated framework for auditing and enhancing PMS. This process approach consisted of six stages (see Figure 4.6).

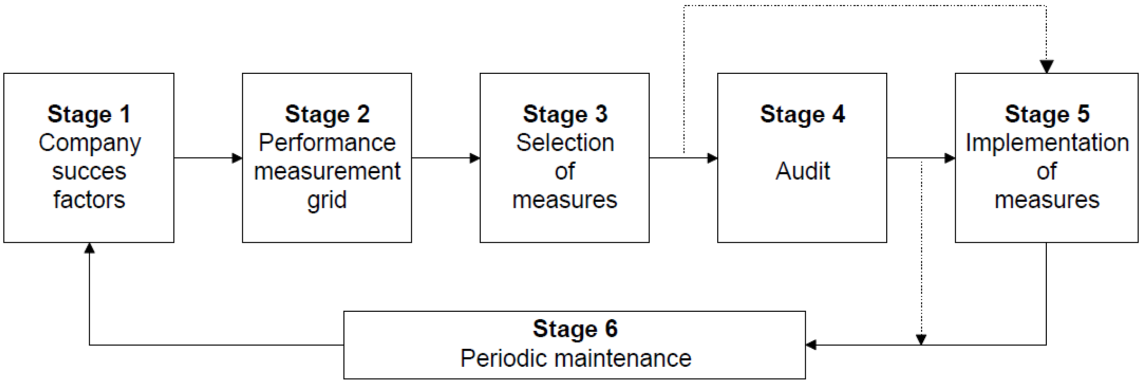

Figure 4.6 A PMS audit and enhancing method (Medori and Steeple, 2000)

Similar to other frameworks, the starting point begins with defining a company's manufacturing strategy and success factors (stage 1). In the next stage, the primary task is to match the company's strategic requirements from the previous stage with six defined competitive priorities (e. g. quality cost, flexibility, time, delivery and future growth (stage 2). Then, the selection of the most suitable measures takes place by the use of a checklist that contains 105 selection of measures with full descriptions (stage 3). After the selection of measures, the existing PMS is revised so it can be decided what existing measures will be kept (stage 4). An essential activity is the actual implementation of the measures in which each measure is described in detail by eight elements: title, objective, benchmark, equation, frequency, data source, responsibility and improvement (stage 5). Finally the last stage concerns periodically reviewing the company's PMS (stage 6).

In conclusion, when designing a PMS, the most advanced measurement system is not always the best (Tangen, 2004). Baines (1997) explains that too much attention to detail can be misleading and take attention away from the main issues, and argues for simplicity.

4.4 Performance Measurement in Forward Supply Chains

There are many reasons why companies measure their performance. Cuthbertson and Piotrowicz (2008) mention measuring supply chain performance to increase understanding, collaboration and integration between supply chain members. It also helps companies to target profitable market segments or identify a suitable service definition. Furthermore, PM is an activity to reach predefined goals derived from company's strategy objectives (Lohman *et al*., 2004).

The works of various authors in academic journals, publications in practitioner-oriented papers and in books have been used in establishing the need for supply chain PM and to describe in general terms how it should be addressed - emphasis is on measurement systems and approaches as opposed to specific measures. Neely *et al*. (2005) defined a performance measurement system (PMS) as the set of metrics used to quantify both the efficiency and effectiveness of actions.

Beamon (1999) presented a framework for the selection of a PMS for manufacturing supply chains and provided a useful performance measures evaluation. An appropriate supply chain performance should be inclusive, where it must measure all pertinent aspects of the supply chain; there are interactions among important supply chain characteristics and the performance measures are related to the strategic goals of the organisation. This Section presented a number of conceptual frameworks in the field of PM to assess the existing practice in FSC. Extensive reviews of other frameworks have been widely investigated by de Toni and Tonchia (2001), Neely *et al*. (2005), Folan and Browne (2005) and Gunasekaran and Kobu (2007).

According to Beamon (1999), PM research should focus on three outlines: analysing PMSs that are already in use; categorising performance measures and then studying the measures within a category; and building rules of thumb / frameworks by which PMSs can be developed for various types of systems.

Bititci *et al*. (2000) acknowledged the need for PMSs to be dynamic to reflect changes in the internal and external environment; review and prioritise objectives as the environment changes; deploy changes in objectives and priorities; and ensure gains achieved through improvement programmes are maintained.

4.5 Performance Measurement for a Reverse Supply Chain

Based on a wider survey of case studies in the field of RSCs, de Brito and Dekker (2004) concluded that there was not a broad knowledge about the costs associated with RSC processes. Herold and Kamarainen (2004) emphasised that no previous studies were found about different performance metrics for RSCs. This was despite PM for RSC being mentioned as an important research area.

Nukala and Gupta (2007) stated that, traditionally, PM was defined as the process of quantifying the effectiveness and efficiency of action. Developing PMSs is a difficult aspect of performance measure selection. Due to inherent differences between forward chains and RSCs, performance metrics and evaluation techniques used in traditional supply chains cannot be extended to RSCs.

RSCs have not been investigated at company level and this was identified as a gap in the research. Much of the literature has been related to Reverse Logistic (RL) and RSC performance including:

- Autry *et al*. (2001) found that RLs performance can be significantly impacted by sales volume and that customers' satisfaction with RLs service varies by industry. They found that neither the location of nor the responsibility for disposal affects either RLs performance or the customers' level of satisfaction.
- Richey *et al*. (2005) discovered that resource commitment made RLs more efficient and more effective if it was used to develop innovative capabilities/approaches to handling returns. Large firms could provide greater resources than small firms in the automotive aftermarket industry.
- Marien (1998) pointed out six categories of companies who dealt with their RLs 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 RLs costs, while firms with low costs of goods sold had little motivation to improve their RSC. This paper identified the fact that industry segments reacted in different ways with their RSC; as a result RLs performance varied by industry.
- Langley Jr and Holcomb (1992) explained that logistics created customer value in three dimensions: effectiveness, efficiency, and differentiation. Effectiveness referred to a level of performance of logistics and whether the logistics function met customer requirements in critical result areas. Efficiency referred to the ability of firms to provide desired products or services that could satisfy customers, while differentiation meant the ability of logistics to create value for a customer through the uniqueness and distinctiveness of logistical service.
- Johnson and Leenders (1997) investigated factors that influenced scrap disposal strategies. They found that volume was one of the important drivers of RLs.

Each company reacted to their RSC in different ways. Some firms hired third party logistics companies to take care of their reverse products, while others handled it themselves. Whether in-house operations or outsource strategies, an effective RSC led to overall cost reduction.

- Johnson (1998) stated that many organizations started to realize the importance of effective RLs systems. Volume played an important role for RLs strategies because when firms received high volumes of return, they needed to improve their RSC to handle their return flows efficiently and effectively.
- Blumberg (1999) explained that due to legislation imposed by governments and increasing customer concerns about the environment, firms needed effective RSCs to handle waste and hazardous materials. Effective transportation and distribution firms such as FedEx and UPS helped organisations improve their RLs services for rapid and efficient return shipping to end-users or to a company for repair, recovery, or final disposal.

To consider the performance of a supply chain, inputs and outputs of each member needed to be considered. Inputs and outputs were classified into two categories: direct inputs/outputs and intermediate inputs/outputs. Direct inputs/outputs were independent variables while intermediate inputs/outputs were dependent variables. For example, intermediate outputs of a supplier could be considered as intermediate inputs of a manufacturer.

Flapper *et al*. (2005) stated, "*to have a strategic performance measure without related tactical and operational measures is not appropriate*". In other words, it is important that a performance measure can be divided and correlated between these three levels: strategic; tactical and operational. Therefore, in order to derive the maximum benefit from RSC operations, a company should monitor its RSC through a PMS that gives true results, according to the characteristics of return types and the nature of its RSC network.

4.6 Gap in the Research

Besides academics, practitioners also realised the importance of PM in a reverse and closed-loop supply chain. The use of appropriate strategies and metrics allow a RSC to play an important part in customer life-cycle strategies, and can serve as a foundation for identifying customer loyalties and increasing market share (Moore, 2005).

The purpose of the research was to create a system such that PM in RSC could be used in any company. That had not been explored, existing literature was only available for specific companies or specific aspects. Pochampally and Gupta (2004) explored how to design RSC based on metric of drivers participation. Kongar (2004) and Hong *et al*. (2008) studied how to determine the evaluation critetia for RSC. Tonanont (2009) explored the RSC in a carpet company by optimising the number recovery centres needed and Björklund *et al*. (2012) studied the Swedish reverse chain for aluminium and plastic drinking bottles and measured logistics combined with environmental performance.

There was no literature about general PM in RSC at the time of writing. Literature about PM in RLs or RSC have been developed since 2012. Shaik and Abdul-Kader (2012) wrote how to develop a comprehensive PM framework and scorecard for RL enterprise. Agrawal (2014) wrote about how to measure performance in RLs and their effect on a product lifecycle. The author, wrote about how it's important to measure the performance in a RSC (Butar Butar and Sanders, 2013). And later in 2014 the author suggested a PM in RSC at a computer company (Butar Butar *et al*., 2014).

This Dissertation discusses how to measure performance in RSC in a simple yet reliable way. The literature that was available either focused on how to find the right metrics for measuring performance or was only suitable for specific companies with specific processes.

With a lack of literature about measuring performance in a RSC, this Dissertation makes a first attempt to create an easy way to look at RSC systems in companies. A model for returned product flow in a company is initially created, then a mathematical model is created with total cost used as a performance metric. This metric can give a company an idea to the whole system of RSC is operating.

Chapters 2, 3 and 4 explored the literature about RSC, RSC frameworks and RSC PM. Some of the important literature is listed in Table 4.2.

Table 4.2 Literature for PM in RSC

Authors (Year)	**Title**
Pochampally and Gupta (2004)	Efficient design and effective marketing of a RSC: A fuzzy logic approach
Kongar (2004)	PM for supply chain management and evaluation criteria determination for RSC management
Hervani et al. (2005)	PM for green supply chain management
Rajagopalan and Yellepeddi (2007)	Development of methodology for measuring and reducing value recovery time of returns
Zu-hai and Feng (2007)	Study on choosing RLs operating modes of enterprises-based on AHP method
Hong *et al*. (2008)	Identifying the factors influencing the performance of RSC
Tonanont (2009)	Performance evaluation in RLs with data envelopment analysis
Kannan (2009)	A metaheuristics-based decision support system for the PM of RSC management
Pochampally *et al*. (2009)	Metrics for PM of a reverse/closed-loop supply chain
Tu *et al*. (2010)	Study of the performance of RLs for supply chain management
Xiao-le *et al*. (2010)	Interrelationship between uncertainty and performance within RLs operations
Olugu *et al*. (2011)	Development of key performance measures for the automobile green supply chain
Björklund *et al*. (2012)	Performance measurements in the greening of supply chains

Based on the research gaps identified during the literature searches, the next Chapter will explore modelling of the RSC. Several case studies are considered before a general model of RSC is proposed. A mathematical model of that new general model is then introduced in Chapter 6 and Chapter 7. This model shows how to measure the performance in a RSC using the new model.

Chapter 5 Model

In this Chapter the creation of a new general model is explained. An overview of the research process is shown in Figure 5.1.

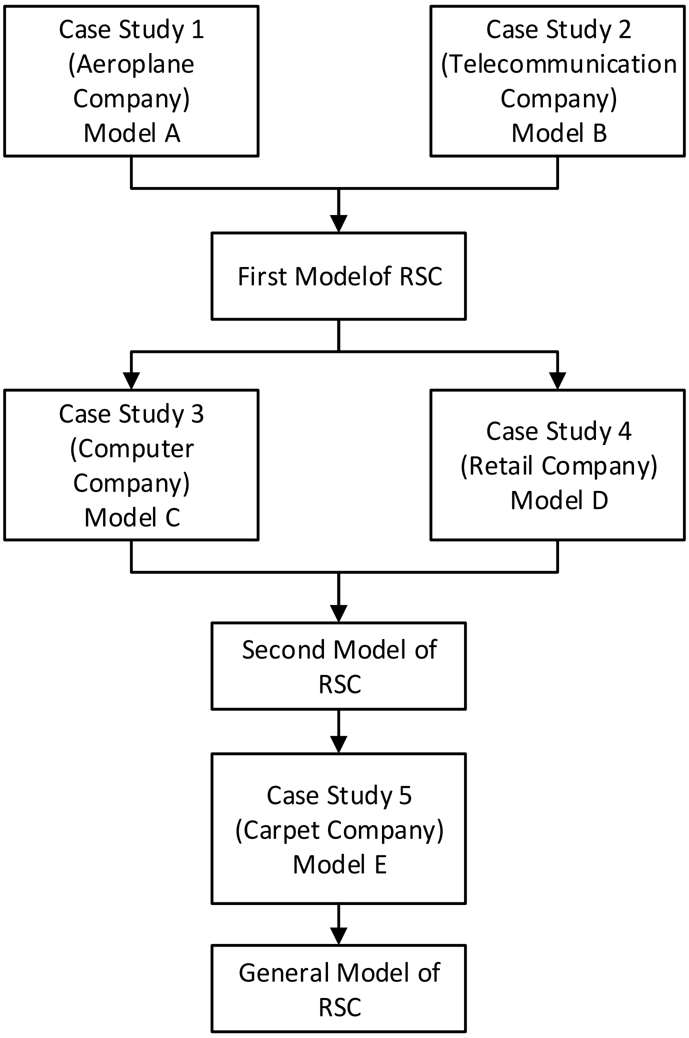

Figure 5.1 Chapter 5 overview

Several industries were investigated to see how product returns flowed in each. From an initial investigation of two case studies about an aeroplane company dealing with returned machines and a telecommunications company dealing with end of life products, a first model to describe the flow through their forward chains and reverse supply chains was created.

That first model was verified against case studies about a computer company dealing with returned computer hardware, and a retail company. The first model needed to be modified to include some of the processes in the new case studies. A second model was created. The second model was successfully verified against a carpet recycling company. From this process it is arguable that the second model can be considered as a first simple general model of return product flow in a RSC process. The first four case studies used in this Chapter are based on studies by Saibani (2010). Four companies were investigated to explore their performance metrics in a RSC. That research included a general overview of each company as well as an interview with management about company objectives and policies. Based on this information, models that represent each company were produced during the new research described in this dissertation. Case study 5 (used as verification) is based on Tonanont (2009) which available and based on primary data therefore could be used as verification models. Models were created to represent the case studies. Case study 1 was represented by Model A; case study 2 was represented by Model B; case study 3 was represented by Model C; case study 4 was represented by Model D and case study 5 was represented by Model E.

5.1 Case Studies 1 and 2

The first and second case studies are explored in this Section. Both case studies were used to create the first model of a RSC. This was a first attempt to create a model for a company with FSC and RSCs activities.

5.1.1 Aeroplane Company (Case Study 1)

The company was described in a case study in Saibani (2010). The company bought aeroplane engines from flight operators to extract useful parts and use them again in aeroplane manufacture. The company was a leading company in civil aerospace markets. It bought back surplus engines owned by flight operators for the purpose of taking the engines apart for useful parts (called part cannibalization). The company overhauled the useful parts and refitted them to engines. Any excess material needing to be scrapped was disposed of through a third party company.

The objective of this activity was economic. The company made a profit by supplying a used part, where the cost of buying a surplus engine and overhauling the part only formed two thirds of the selling price, which made a profit of one third. Furthermore, by supplying a cheaper part than a new one, the company passed the cost reduction to its customer when overhauling engines. The customer who owned the engine saw the savings and this helped to put the company reputation above that of it's competitors.

An aeroplane engine was sent to and received at a recovery centre for the recovery process. First, the aeroplane engine stayed at a warehouse to await the next process, then, was disassembled to separate the useful parts from other parts. Useful parts were engine parts that could be reused in the next manufacturing process. Useful parts were refurbished, repairing and overhauling as necessary. Then, repaired parts that needed to be tested went through a testing process.

Rejected parts were sent to third parties for scrapping. That process produced useful raw materials to be sold to second markets. Meanwhile, other materials were sent to a landfill for disposal. Useful parts that passed the testing process were sent to the manufacturing process to be reused. Other parts that were needed for production were purchased from third party suppliers. The new product was then sent to a distributor for sale. The product was either classed as a new product or a second hand product; either way it did not matter as quality control checks were completed.

Figure 5.2 shows a simple flowchart to explain how a returned product was processed in the Recovery Centre.

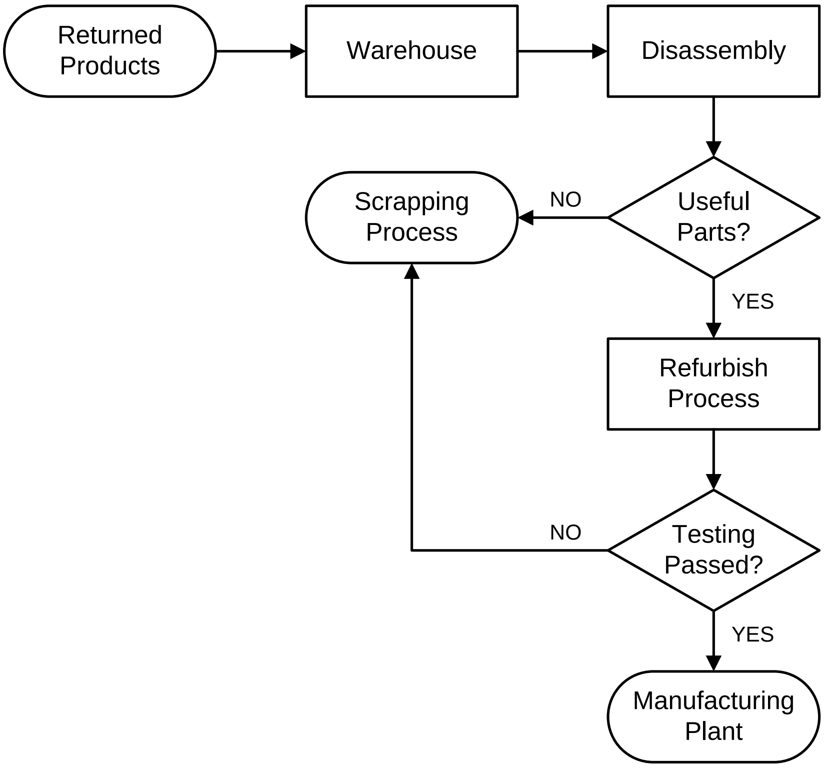

Figure 5.2 Flowchart of returned products at the recovery centre.

Figure 5.3 shows the model created to represent returned products through the company in case study 1, named as Model A.

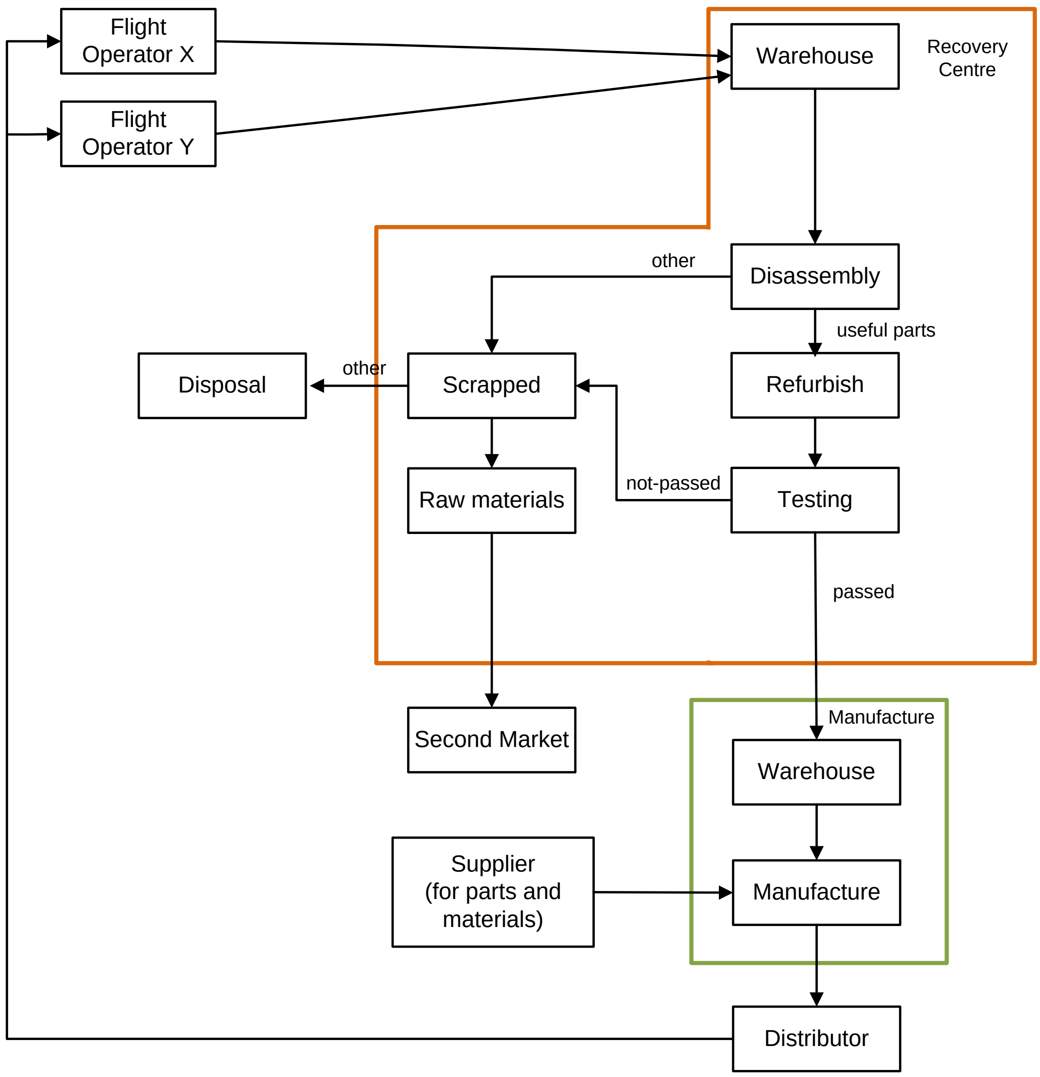

Figure 5.3 Model A (based on case study 1)

5.1.2 Telecommunication Company (Case Study 2)

The second company was a telecommunication company dealing with the recycling activity of end-of-life products such as telephones, fax machines, cables, switches and telegraph poles. This company was bounded by the Waste Electrical and Electrical Equipment (WEEE) directive which required manufactures in the European Union to collect and recycle electronic waste from homes and businesses.

The company was responsible for returned products. All returned products were sent directly to a recovery centre from home or businesses customers. Free delivery of the products was provided by the company in order to encourage more product returns and reduce collection cost.

At the recovery centre, returned products were collected at a warehouse to be used in the next process. Returned products were sorted into products that could be used as raw material and other. Items that could be used as raw material were sent to a scrapping processes, while the others products went to disassembly. Useful parts were refurbished for second market demand.

From a scrapping process, raw materials were produced and sold to second markets. Any residue and other materials from this process were delivered to disposal, as shown in Figure 5.4.

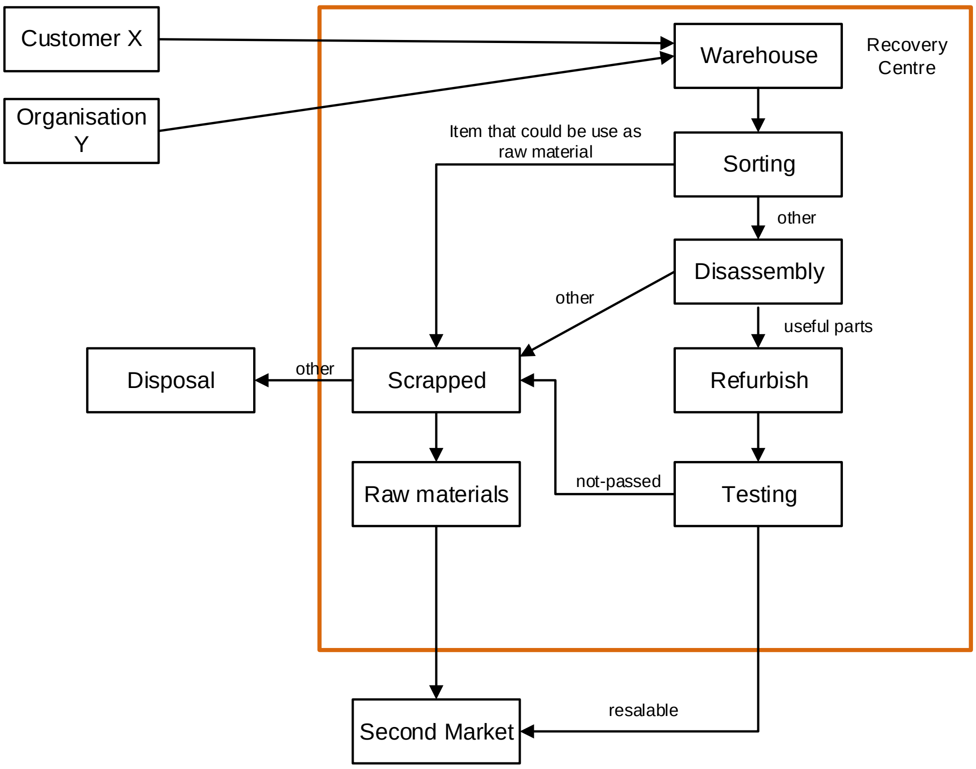

Figure 5.4 Model B (based on case study 2)

While company A dealt with a RSC for purely economical reasons, company B dealt with return products as an obligation to regulations.

5.2 First Model of RSC

A first model of RSC was created to represent all the processes in Model A and Model B. The first model is shown in Figure 5.5.

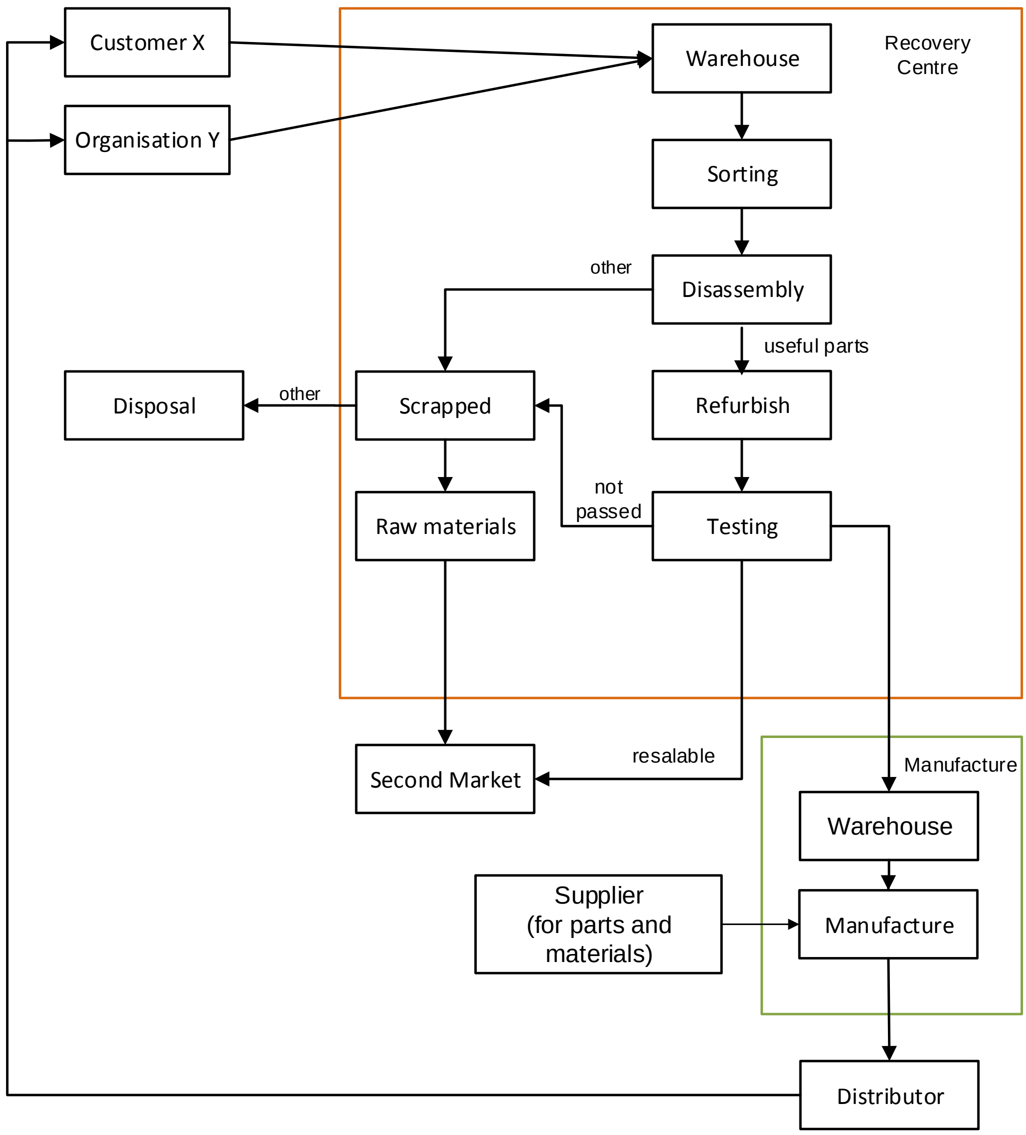

Figure 5.5 First model

This model described return product flow for both companies. In both companies, the returned product was received at a recovery centre warehouse. Either the returned products were collected by the company or sent by customers. Recovery processes were conducted on returned products based on the condition of the products. A sorting process took place when returned products needed to be separated. Sorting processes were only carried out by company B since at company A, all returned engines were useful for parts and raw materials.

After the sorting process, a disassembly process was the next step. A returned product was disassembled to create separate useful parts. The next process was refurbishment. The refurbishing process could be repair or overhaul depending on the type and condition of the returned product. From the refurbishing process, all products or parts that resulted from this process needed to be tested before going to a second market or manufacturing plant. Products that did not passed the testing were disassembled. Testing was necessary to maintain quality, company reputation and brand image. Resalable parts and product that passed testing process was sold to a second market. The second market could be broker, or a company that deals with refurbished product that acts like a third party. Failed items were sent to the scrapping process.

Items that passed the testing process were delivered to a manufacturing plant and used as components in the production process. Items could also be sold at second market as second hand products. Raw material produced from the scrapping process was sold to second markets or delivered to a manufacturing plant to be used as production components. The residue from all processes was disposed of in landfill.

Production at a manufacturing plant was carried out by company A only. In company B, returned products were end-of-life products, therefore none of the returned products took part in the production process. Returned product paths in both companies were included in the first model shown in Figure 5.5.

5.3 Case Study 3 and 4

In this Section a third and fourth case study are explored. This step was carried out to see how the first model performed as a general model. By exploring more companies, the 'new' model could be improved.

5.3.1 Refurbishment of Computer Hardware (Case Study 3)

Company C offered consumers a wide range of computing products and services but focused on refurbishment of returned laptops and computer hardware. The life cycle of a typical laptop was 6 months, making the product obsolescence rate high (Saibani, 2010). Returned laptops were received from customers as convenience returns when they changed their mind or as defective returns. There were also channel returns, usually from overstock or stock adjustment, as well as demonstration returns.

Computer hardware was categorised as electronic waste or e-waste. The key factors in recycling of e-waste were collection, sorting and recovery, recycling and disposal, as shown in Figure 5.6.

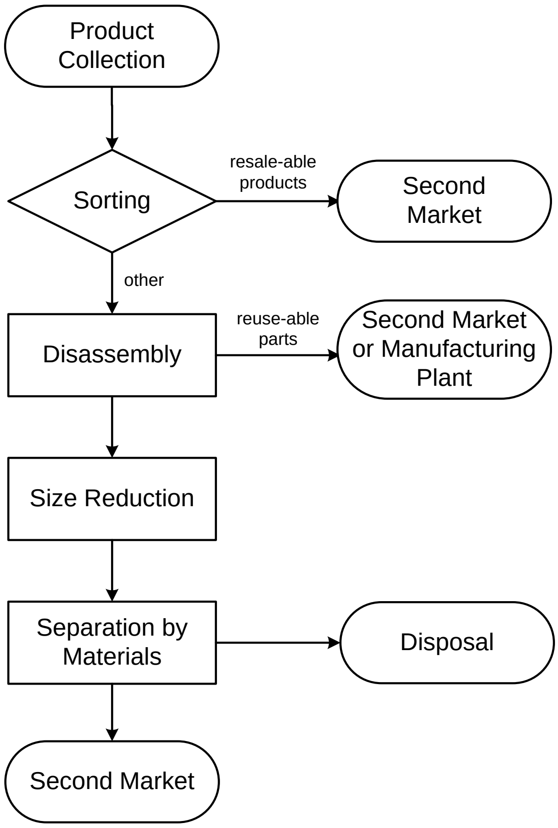

Figure 5.6 Simplified flow diagram for the recycling of an electronic product based on Butar Butar et al. (2014)

Figure 5.6 is a simplified flow diagram representing the recycling of an electronic product. The returned products were collected from many widespread sources and consolidated for further inspection, handling and processing.

Computer hardware RSCs had a complexity which made them challenging. There was uncertainty of both demand and supply. Both the arrival times and the quantities of returned computers were usually unknown ahead of time and generally difficult to predict. Computers could be returned from a variety of heterogeneous scattered sources such as individual computer owners as well as small or large businesses and organisations owning significant computer parks. Overall, the disposal and return rates were difficult to predict. The demand rates for computer hardware, from brand new to refurbished and recycled, were also difficult to predict. Because the quality of a returned product or part was hard to assess and varied significantly, that directly impacted on potential market value (Marcotte *et al*., 2008). Those returns were periodically collected by resellers and were shipped to a recovery centre. All used products underwent technical testing and repair as necessary.

Based on existing literature, a first prototype of a RSC network for the Company C was created as shown in Figure 5.7.

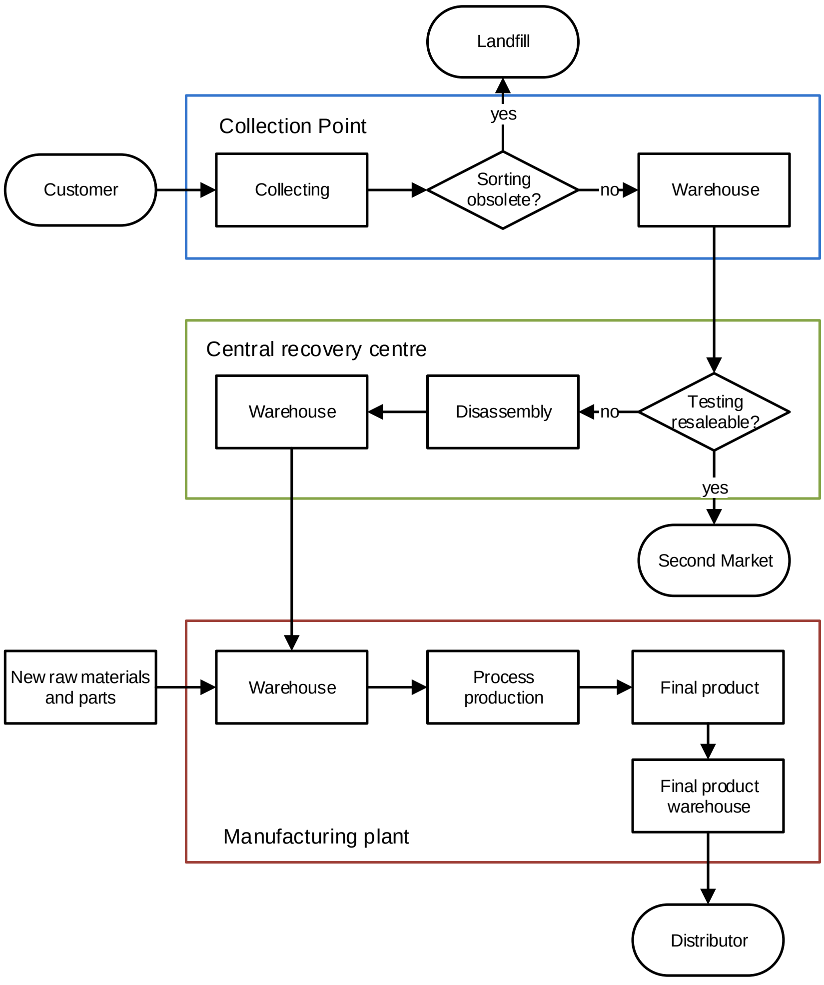

Figure 5.7 First prototype reverse supply chain network based on Butar Butar et al. (2014)

Marcotte *et al*. (2008) described several parties involved in the RSC such as the computer user, re-transformers and brokers. In this Dissertation, the computer user is considered to be the input for returned products. Re-transformers where all recovery activities took place was called a central recovery centre and brokers were the second market. In this model, if only sorting took place without any refurbishment then the location was named as a collection point and not a recovery centre. Only re-transformation processes are carried out in a recovery centre, for example refurbishment and repackaging processes.

First prototypes of RSC networks were created before case study 3 (Company C) was investigated. The prototype was made based on an existing literature review that described the recycling process for electronic products such as monitors (LCD and LED).

Based on case study 3, model C was created to describe returned products through the company. Figure 5.8 shows returned product path in Company C.

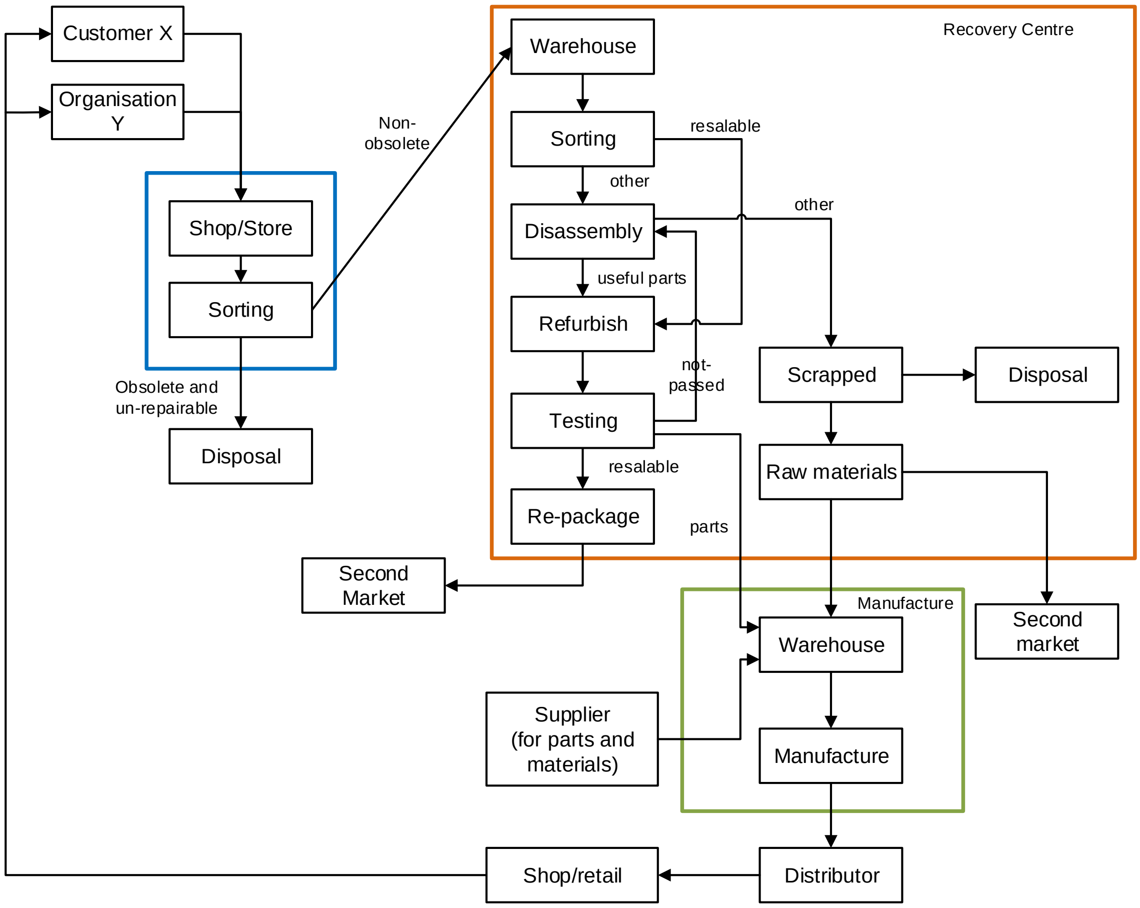

Figure 5.8 Model C (based on case study 3)

Model C describes the return products flow for the company described in case study 3. Returned products were received by a shop or store, and sorted between obsolete and non-obsolete products. This step was important to ensure that all returned products that entered the recovery process were non-obsolete (still able to be sold) and repairable. Non-obsolete and unrepairable products were sent to a third party. In the process flow itself, disposal was the next process taken by this product.

An non-obsolete product was delivered to a warehouse for a set of recovery processes. The first step of the recovery process was sorting. Returned products that arrived at the warehouse were sorted again, and products that could be resold were separated. These products were refurbished as necessary to meet the standards of second hand products. After refurbishment, products were tested to ensure that products met the required criteria. Failed products were returned to the disassembly process for further process. Passed products were re-packaged before being sent to the second market to be sold.

Products that could not be resold were disassembled to extract useful parts. Other parts were delivered to scrapping processes. From the scrapping processes, raw material was extracted and sold to second market or sent to manufacturers as raw material for production. Any residue from this process was disposed of in landfill.

Useful parts were refurbished to meet the criteria for parts used for production. After refurbishment, testing took place to ensure they met the criteria as parts for production. Passed parts were delivered to a manufacturing warehouse for the next process. Production processes were carried out at a manufacturing plant using re-usable parts and raw materials from recovery processes and additional materials from suppliers. Production processes produced new products that were sent to distributors for sale.

In this company (Company C), the sorting process was important. The sorter decided which product was still could be resold and repaired. From the condition of returned product (identified in the sorting process), different types of refurbishment processes were carried out. The company needed to protect their brand image, so testing processes were carried out on every product and part before they were sent to second market or to manufacturing.

5.3.2 Retail Company (Case Study 4)

Case study 4 investigated a retail company. The company was selling over 10,000 different products, ranging from car parts, cycles to the latest in-car technology, child seats, roof boxes and outdoor leisure and camping equipment. This company had two types of supplier for its merchandise: local suppliers and Far East suppliers.

Returns from locally-sourced products were returned to the supplier. Products sourced from Far East countries went through different disposition routes. High value products, for example satellite navigation systems, were sent to a recovery centre and underwent refurbishment processes. Less expensive products sourced from the Far East, such as introductory price radios, cheap DVD players, tents and spanners, were sold. The products were mixed into boxes and sold to third party.

The company focused on the avoidance of all types of returns as a main key objective in handling its return products, especially on no-fault-found returns from customers. This objective was shared with its partners, especially with suppliers so that they could contribute towards the implementation of technical help-lines. The company also ensured that there were clear agreements with suppliers regarding returns to avoid misunderstanding during the process of handling returns from customers, as any reduction in product returns benefited both parties. The returned products in Company D is shown in Figure 5.9.

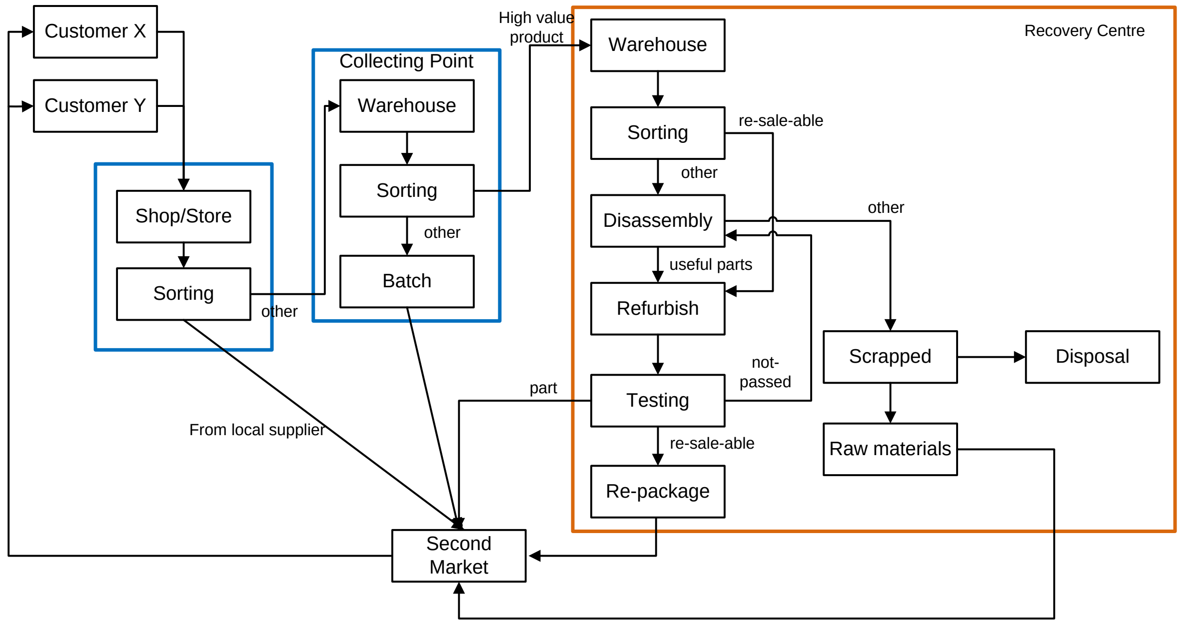

Figure 5.9 Model D (based on case study 4)

Most products were returned at a shop or store by customers. At this point returned products from local suppliers were sent directly to a local supplier with the agreement of both parties. Returned products from Far East suppliers were collected at a collection point and sorted. Less expensive products were sold as a mixed box, while high value products were carried through the recovery processes.

The recovery process for high value returned products started with a sorting process. At this step, resalable products were separated from others and underwent refurbishment. Testing was carried out to make sure the product met a criteria or a standard to be sold on the second market. Passed products were repackaged before being sold. Unresalable products were disassembled to separate useful parts from others.

5.4 Second Model

The first model of a RSCs were created based on case studies 1 and 2. This first model was verified against two completely different companies (case studies 3 and 4). Model C represents case study 3 about computer companies dealing with returned laptops and Model D represents case study 4 about retail companies dealing with returned merchandise. From an investigation of C and D, it was realised that returned products were received at shops or stores from customers. In the first model, the entire returned product arrived at the warehouse to undergo recovery processes.

By comparing the first model with models C and D, the first model did not cover all the processes in the returned product flow for models C and D. Therefore, the first model needed to be adjusted before it could be considered as a general model. A second model was created. The second model was based on: the first model; model C; and model D. The new model included all the processes for returned products in all the companies represented by the four case studies. Figure 5.10 shows the new model that was created.

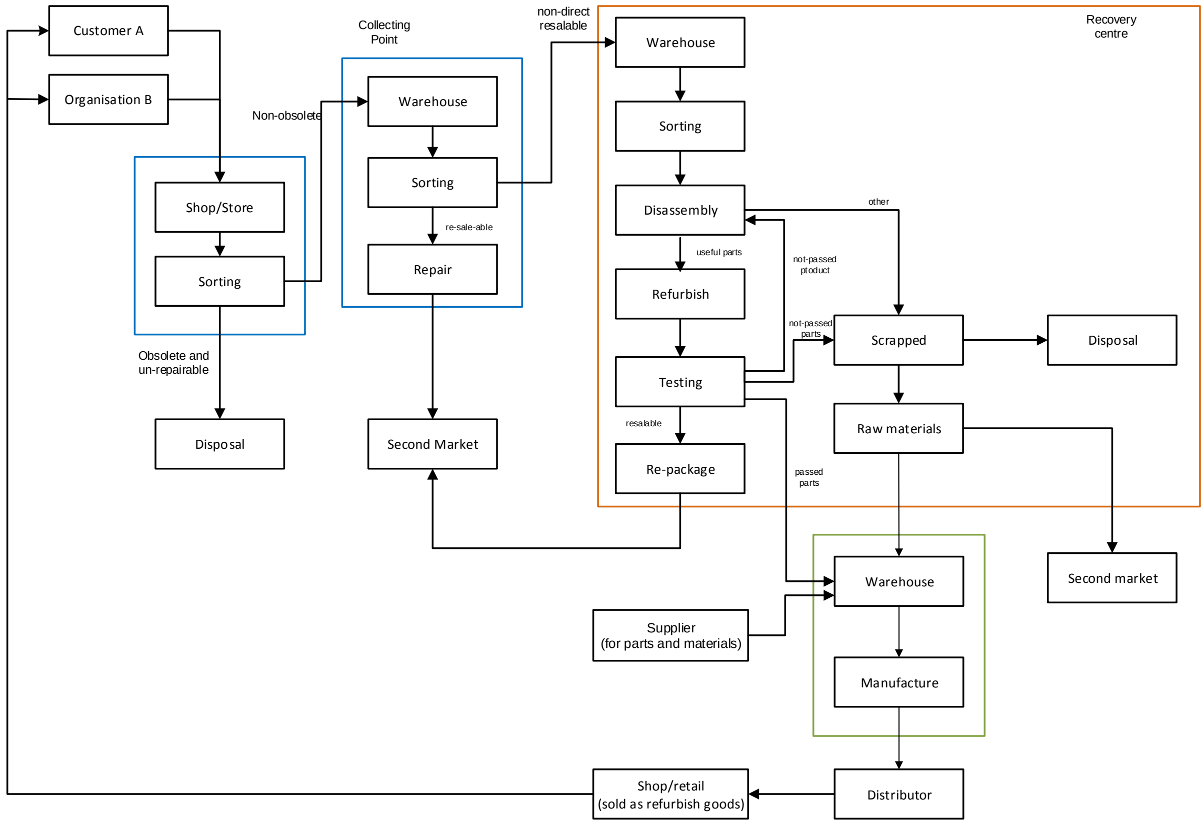

Figure 5.10 Second model

5.5 Verification of the model

The second model was then verified using a case study about a company that was completely different to the first four companies. The case study was from a previous investigation about a carpet company (Tonanont, 2009). The company focused on carpet manufacturing and recycling as the main activities, concentrating on the refurbishment of returned carpets.

A large amount of fibrous waste is generated from carpets each year. The activities of this industry must be economically competitive and environmentally beneficial (Wang et al., 2003) and increasing the rate of recycling has been one of the goals for resource conservation and environmental protection.

The fibrous waste consisted of a variety of synthetic and natural polymers. Frequently, different types of polymers and other material were integrated to form an article, such as blended textiles, carpet, conveyer belts, etc. Much textile waste could be re-used directly, used as wipes, or shredded for filling or nonwoven applications. Post consumer carpet, on the other hand, was more complex and often required extensive processing to convert it into useful products (Wang et al., 2003).

Over 4.7 billion pounds of post-customer waste carpet were being discarded in the US per year in 2003/2004. 95% of that was going to landfill as disposal each year in the US (Effort, 2004). Increasing concerns about disposal capacity combined with carpet bulks that made it difficult and expensive to handle, have contributed to a search for alternative means for carpet disposal. Recovery processes are needed in the carpet industry. Not only could it save numerous production costs and increase profit but it could also satisfy some environmental concerns. Key factors in recycling are collection, sorting and recovery, recycling and disposal, as shown in Figure 5.11. This figure is a simplified flow diagram for carpet recycling.

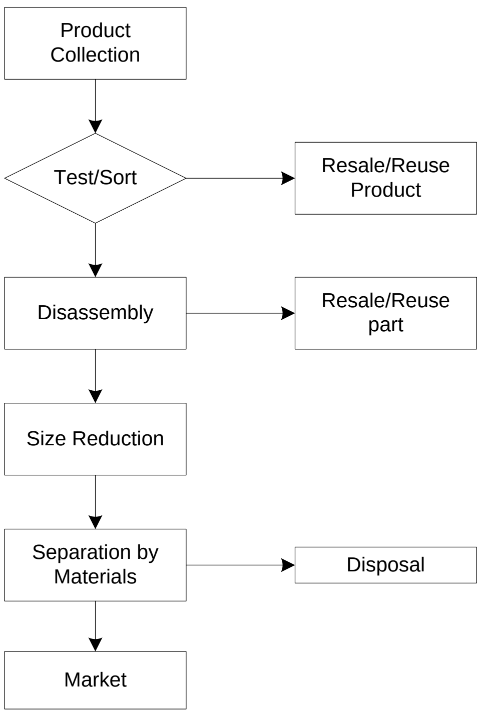

Figure 5.11 Simplified flow diagram for carpet recycling (Butar Butar *et al*., 2016)

Designing a RSC for carpet recycling is a challenging task for a company; not only can it save a lot of money and increase revenue by using recycled materials from returned carpets, but it also encourages environmental concern. Returned carpets are sent back from retail/costumers to a recovery centre for refurbishment. They are sorted, disposed or disassembled based on the condition of returns. The mechanical and chemical process converts nylon carpet to raw materials. The conversion process (referred to as the disassembly process) converts nylon polymer from used carpet to monomer units which can be used as raw materials to produce carpet again. This process is also called depolymerisation. There are three main types of materials related to carpet manufacturing; yarn, which is nylon; chemical products such as polypropylene and polyester; and packaging (Tonanont, 2009).

Only nylon can be used to remanufacture; everything else needs to be disposed of. Manufacturers will purchase raw materials from suppliers then ship finished products to a warehouse. Then the products will be shipped to retails/customers. All of the returns due to end of use or end of life will be shipped to a recovery facility. The recovery facility will process returns and send the reusable parts to manufacturers, depending on the demand requested from them.

The returned products are collected from many widespread sources and consolidated for further inspection, handling and processing. Therefore, RLs tend to be more complex than forward logistics as there are many actors involved in the processes. Because the reverse shipments tend to be smaller, less frequent and mixed, the costs of transportation, handling and inventory holding for reverse logistics are always higher than forward logistics for new products (Rogers and Tibben-Lembke, 2001).

Remanufacturing is used as a way to reduce production cost compared to producing new products (in terms of less new material and less manufacture process required) while reducing environmental cost at the same time. Based on existing literature, a model of a reverse supply chain network for the carpet industries is presented in Figure 5.12. Re-transformers where all recovery activities took place (also called a central recovery centre) and brokers were a second market.

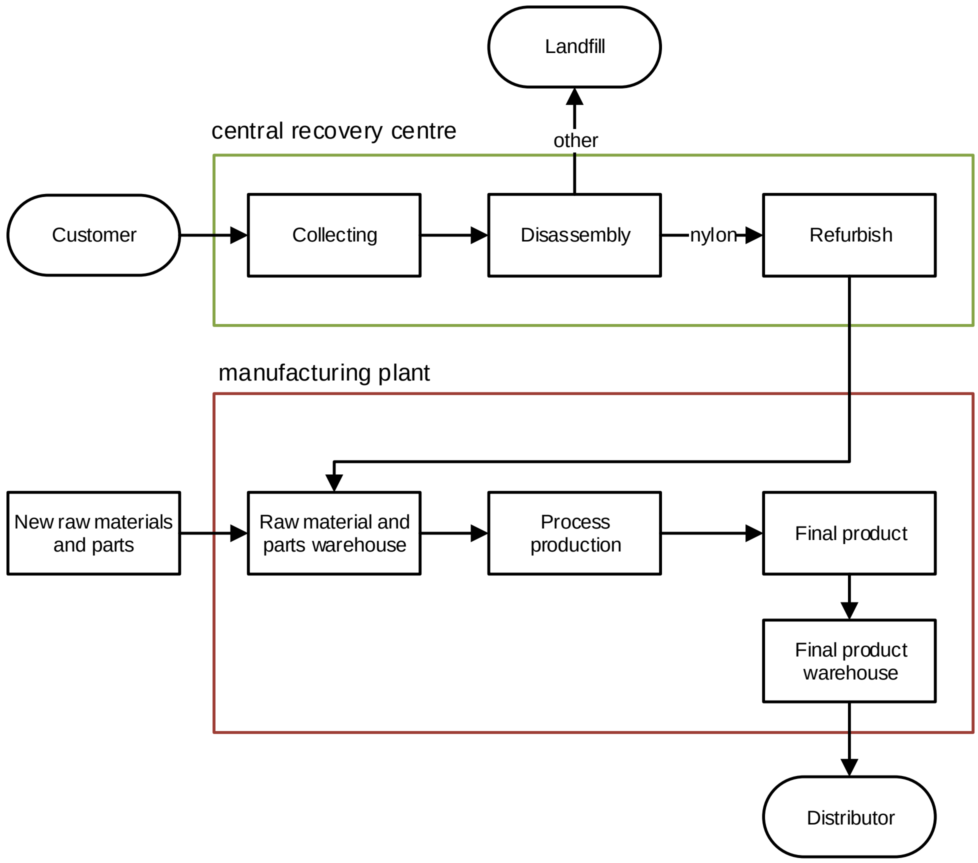

Figure 5.12 First prototype carpet reverse supply chain network based on Butar Butar *et al.* (2016)

Carpet RSCs have an obstacle which is challenging. There is uncertainty about both demand and offer. Both the arrival times and the quantities of returned carpet are usually unknown ahead of time and generally difficult to predict.

A warehouse in the recovery centre received all returned carpets from the customer. Products were disassembled at the recovery centre and processed until they became raw materials ready to be shipped to manufacturing plants. All of the returns due to end of life type products were shipped to the recovery centre. The recovery facility processed the returns and sent the reusable materials as raw material to manufacturers, depending on the demand requested from them.

For return parts, only nylon could be used to re-manufacture; all else was disposed. Manufactures purchased raw materials from suppliers and then shipped finished products to the warehouse according to the demand requested, then the products were shipped to retailers/customers.

Returned products underwent a few stages of disassembly. The first stage was usually carpet size reduction, followed by chemical separation of carpet components. Separated nylon was processed to be used as raw material (Wang, 2006). Figure 5.13 shows the returned product in the company. Useful materials were refurbished for re-use at a manufacturing plant. Other parts were sent to landfill. All raw materials from the recovery centre were sent to a manufacturing plant to be used as raw material in the production process.

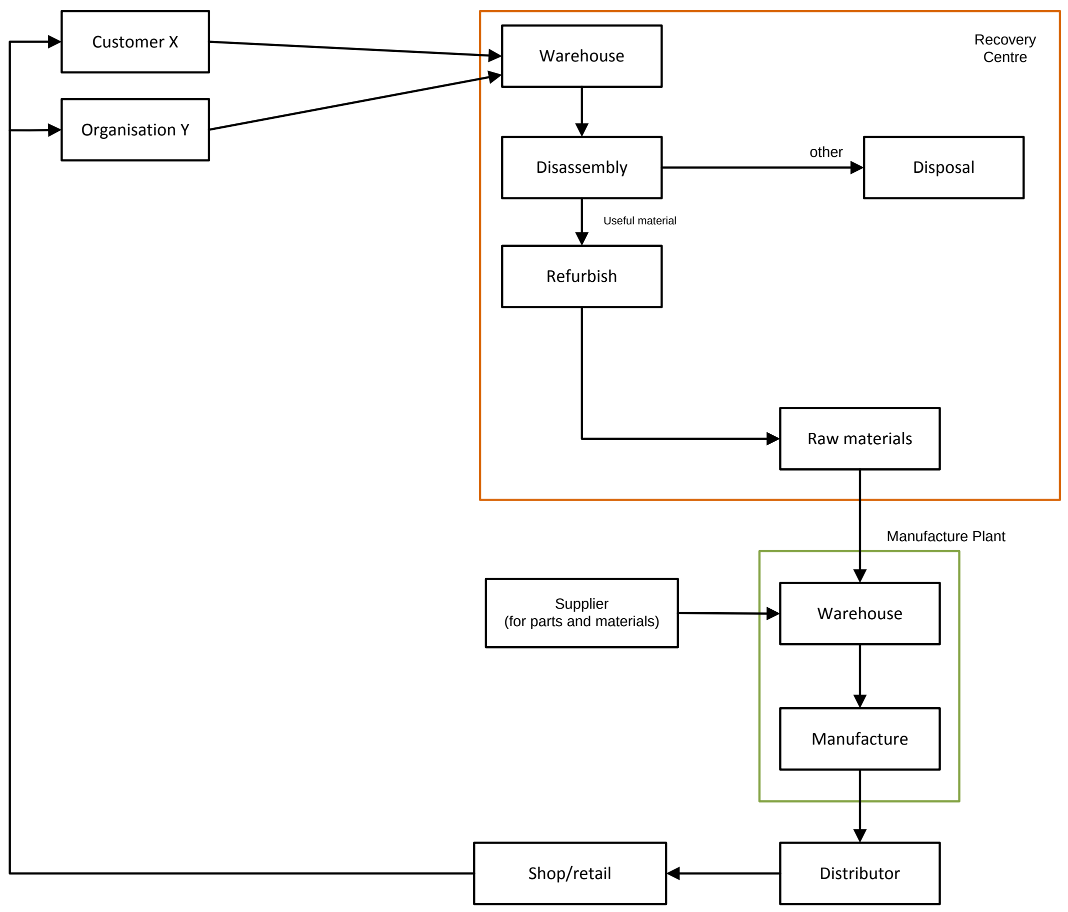

Figure 5.13 Model E (based on carpet company)

Model E shows that the second model covered all the activities in model E. By eliminating some processes in the second model, returned product flow in model E could be covered. Based on this verification, the second model has verified to represent a general model of a RSC.

The difference between the general model and existing RSC models is that the general model included forward supply chain flow as well as performance of the reverse supply chain. That means it could give a company a clearer idea about how their returned product will affect their system performance.

Based on the model of each company, a mathematical model was produced. A total cost for a whole system included forward and reverse flow in each company. That was to see how the company performed. Mathematical modelling of total cost was a simple way to start measuring performance in RSC. The mathematical model is described in Chapter 6.

Chapter 6 Mathematical Model

In this Chapter, a mathematical model for each company is explored. The mathematical models describe the total cost of all processes included in forward and reverse routing. Based on the models produced in Chapter 5, overall activity in each company was investigated. From this investigation, costs arising from activities were included in a general expression for total cost.

6.1 Company A

Company A was an Aeroplane Company. The mathematical model described here was based on Model A, described in section 5.1. The model could be used to minimise the total cost.

In this company two types of locations were main locations in the reverse supply chain. The recovery centre was the main location where all recovery processes for returned products were placed, and the manufacturing plant was where all re-usable parts of returned products were used.

At the recovery centres, returned products arrived at a warehouse and were stored to be disassembled. From the disassembly process, useful engines and parts were separated from others. These useful engines and parts underwent refurbishment processes depending on their condition. A testing procedure made sure engines and parts were ready to be used in manufacturing processes or to be sold to a second market.

Unused parts were scrapped and raw materials delivered to manufacture plants or sold to a second market. All residues from this process were sent to landfill as disposal. In the model for company A, the company only had one manufacturing plant. The total cost was composed of the following:

6.1.1 Holding cost of returned products at a recovery centre warehouse.

All retuned products were received at one of the recovery centre warehouses. Here, returned products were held at the warehouse to wait in a queue for the next process.

$$\text{Holding Cost} = \text{returned product unit x holding cost per unit at warehouse}$$

$$Holding\ Cost = \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{rit}H1_{rit}$$

Equation 6.1

Where *RP* is number of returned products and *H1* is holding cost for each returned product at the recovery centre warehouse. The holding cost in the recovery centre was for each returned product type *i*, per period of time *t* and multiplied by the *r* number of recovery centres used by the company. Each recovery centre had one warehouse for returned products.

6.1.2 Disassembly cost

Disassembly cost was for each returned product per period of time. Disassembly cost included labour cost and utility cost. Disassembly processes might take several stages to separate useful parts from others. In this mathematical model, costs for each stage of disassembly were combined and presented as one numerical cost.

$$\text{Dissassembly Cost} = \text{returned product unit x disassembly cost per unit at warehouse}$$

$$Disassembly\ Cost = \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{rit}DC_{rit}$$

Equation 6.2

After the disassembly processes, useful parts underwent re-furbishing while others were scrapped. From the refurbishing process, each part was tested before it could be used in the manufacturing process. From one scrapping process, useful raw material was sold to second market, and disposal from that process was sent to landfill. As company A had one manufacturing plant, the total cost at a recovery centre is:

$$\text{Recovery Centre Total Cost} = \text{Total holding cost} + \text{Total disassembly cost} + \text{Total refurbishment cost} + \text{Total testing cost} + \text{Total scrapping cost} + \text{Total transportation cost to manufacture plant} + \text{Total transportation cost to second market} + \text{Total transportation cost to landfill}$$

$$Recovery\ Centre\ Total\ Cost = \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{rit}H1_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{rit}DC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RF_{rit}FC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RF_{rit}TC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RS_{rit}SC_{rit} + \sum_{r=1}^{R}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} RM_{rmit}\,T1_{rmit} + \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RSM_{roit}\,T2_{roit} + \sum_{r=1}^{R}\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T} RL_{rlit}\,T3_{rlit}$$

Equation 6.3

Where:

R = number of recovery centres

M = number of manufacturing plants

O = number of second markets

L = number of landfill sites

I = number of types of product

T = number of periods of time

H1 = holding cost for returned product at recovery centre warehouse

DC = disassembly cost

FC = refurbish cost

TC = testing cost

SC = scrapping cost

$T1$ = transportation cost to manufacture

$T2$ = transportation cost to second market

$T3$ = transportation cost to landfill

RP = number of units of returned product

RF = number of units being refurbished

RS = number of units being scrapping

RM = number of units sent to manufacture plant

RSM = number of units sent to second market

RL = number of units sent to landfill

Useful engines and parts from recovery centre arrived at the manufacturing process to be used again in the production process. Based on demand, shortage parts were purchased from suppliers. All parts from the recovery centre and supplier were placed into storage to wait for the production process. After the final product was produced, it was delivered to a warehouse before being sent to distributors and customers.

6.1.3 Production Cost

In the manufacturing plant, production cost was per returned product type *i*, per period of time *t*. In this model, production cost included costs that might occur in making a new product, except purchasing of raw materials and parts for the final product from a supplier.

$$\begin{aligned}
&\text{Total Cost at Manufacturing Plant}\\
&= \text{Total holding cost of parts at manufacture plant} + \text{Total purcashing cost}\\
&+ \text{Total production cost} + \text{Total holding cost of final product}\\
&+ \text{Total transportation cost to distributor}
\end{aligned}$$

$$Total\ Cost\ at\ Manufacturing\ Plant$$
$$= \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU1_{mit}\ H2_{mit} + \sum_{m=1}^{M}\sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{t=1}^{T} PU2_{msit}\ NC_{msit}$$
$$+ \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU3_{mit}\ PC_{mit} + \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU3_{mit}\ H3_{mit}$$
$$+ \sum_{m=1}^{M}\sum_{d=1}^{D}\sum_{i=1}^{I}\sum_{t=1}^{T} PU4_{mdit}\ T4_{mdit}$$

Equation 6.4

Where;

M = number of manufacturing plant

S = number of suppliers

D= number of distributors

I = number of types of product

T = number of periods of time

H2 = holding cost for parts at manufacture plant warehouse

NC = new part cost from supplier

PC = production cost

H3 = new product holding cost at manufacture plant warehouse

T4 = transportation cost from manufacture plant to distributor

PU1 = number of parts at manufacture plant warehouse

PU2 = number of new parts from supplier

PU3 = number of final product

PU4 = number of unit that transported to distributor

From the returned product flow in Company A, Model A was created in Chapter 5. From Model A, a mathematical model was created:

$Total\ Cost$

$=$ Total holding cost at recovery centre warehouse

$+$ Total disassembly cost at recovery centre

$+$ Total refurbishment cost at recovery centre $+$ Total testing cost at recovery centre

$+$ Total scrapping cost at recovery centre

$+$ Total transportation cost from recovery centre to manufacture plant

$+$ Total transportation cost from recovery centre to second market

$+$ Total transportation cost from recovery centre to landfill

$+$ Total holding cost of parts at manufacture plant $+$ Total purcashing cost

$+$ Total production cost $+$ Total holding cost of final product at manufacture plant

$+$ Transportation cost from manufacture plant to distributor

$$
\begin{aligned}
Total\ Cost
&= \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{rit}H1_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{rit}DC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RF_{rit}FC_{rit} \\
&+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RF_{rit}TC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RS_{rit}SC_{rit} + \sum_{r=1}^{R}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} RM_{rmit}\,T1_{rmit} \\
&+ \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RSM_{roit}\,T2_{roit} + \sum_{r=1}^{R}\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T} RL_{rlit}\,T3_{rlit} \\
&+ \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU1_{mit}\,H2_{mit} + \sum_{m=1}^{M}\sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{t=1}^{T} PU2_{msit}\,NC_{msit} \\
&+ \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU3_{mit}\,PC_{mit} + \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU3_{mit}\,H3_{mit} \\
&+ \sum_{m=1}^{M}\sum_{d=1}^{D}\sum_{i=1}^{I}\sum_{t=1}^{T} PU4_{mdit}\,T4_{mdit}
\end{aligned}
$$

Equation 6.5

The mathematical model was the sum of costs associated with the process. *R* is the number of recovery centres. *M* is the number of manufacturing plant with assumption the company only has 1 manufacturing plant. *O* is the number of routes to second markets and L is the number of landfill sites. S is the number of suppliers. D is number of distributors. I is the number of types of products and T is the number of periods of time.

$H1$ is the holding cost for returned products at the Recovery Centre warehouse and DC is the disassembly cost. FC is the refurbishment cost and TC is the testing cost. SC is the scrapping cost.

The transportation costs are: $T1$ = transportation cost to manufacture; $T2$ = transportation cost to second market; $T3$ = transportation cost to landfill; $T4$ = transportation cost from manufacturing plant to distributor.

$H2$ is the holding cost for parts at the Manufacture Plant warehouse and NC is the new part cost from a supplier. PC is the production cost and $H3$ is the new product holding cost at the manufacture plant warehouse.

RP is the number of units of returned products and RF is the number of units being refurbished. RS is the number of units being scrapped. RM is the number of units sent to the manufacturing plant and RSM is the number of units sent to second markets. RL is the number of units sent to landfill and $PU1$ is the number of parts at the Manufacturing Plant warehouse. $PU2$ is the number of new parts from suppliers and $PU3$ is the number of final products. $PU4$ is the number of units transported to distributors.

Using this mathematical model, the way that total cost was affected by returned products in the reverse supply chain could be investigated. This could be a first step in performance measurement, subject to the capacity of the recovery centre warehouse; manufacture plant warehouse; recovery centre labour available;

manufacture production capacity; and demand for new products. That investigation is described in Chapter 7.

6.2 Company B

Company B dealt with end-of-life telecommunication products and was driven by environmental regulations. Returned products were delivered and processed at a recovery centre. At the recovery centre, returned products were received at a warehouse. These returned products were usually sent by a customer directly to a recovery centre with support from the company.

Company B did not have a manufacturing plant because Company B only dealt with end-of-life products. The final product from their reverse supply chain system process either went to second market or landfill. In this model, Company B only had 1 recovery centre.

There is only one location in the reverse supply chain system for Model B, which is a recovery centre. In this recovery centre, all processes took place. Returned products were received by the recovery centre in the warehouse. A mathematical model was created to represent all processes in the recovery centre as well as the whole reverse supply chain system for Model B. The following costs were considered:

6.2.1 Holding Cost

Holding cost in the recovery centre was per returned product type *i* and per period of time *t*. The recovery centre had a warehouse for returned products.

$$\text{Holding Cost} = \text{returned product unit x holding cost per unit at warehouse}$$

$$Holding\ Cost = \sum_{r=1}^{R} \sum_{i=1}^{I} \sum_{t=1}^{T} RP_{rit} H1_{rit}$$

Equation 6.6

Where;

R = number of recovery centres

I = type of product

T = number of periods of time

$H1$ = holding cost for returned product at recovery centre warehouse

RP = number of units of returned product

6.2.2 Sorting Cost

Sorting cost represented cost that occurred from the sorting processes. In this model, total sorting cost was the cost for sorting returned products that arrived at the recovery centre. Returned products which had useful parts were separated from each other. Other returned products were scrapped and any raw materials produced from this process were sold to second markets. Scrapping cost, transportation cost of raw material to second market and transportation disposal to landfill, all added to total cost.

Products that had useful parts underwent a disassembly process. Useful parts underwent refurbishment, while others were scrapped and joined the flow of returned products that could be processed to take the raw materials. The useful parts from the refurbishment process were tested before being sold to second markets. From this action, disassembly cost, refurbishing cost, testing cost and transportation cost of useful parts to second market arose. The disassembly cost represented all disassembly stage costs as well as labour and utilities costs.

In this model, the company objective was to apply the environmental regulations from government regulations. This objective made the company tend to reduce the disposal from the whole process by maximising the refurbishment and scrapping process. An economic opportunity also came from useful parts and raw material that could be sold to second markets.

The mathematical model for Model B:

$$Total\ Cost$$
$$= \text{Total holding cost} + \text{Total sorting cost} + \text{Total disassembly cost}$$
$$+ \text{Total refurbishment cost} + \text{Total testing cost} + \text{Total scrapping cost}$$
$$+ \text{Total transportation cost to second market} + \text{Total transportation cost to landfill}$$

$$Total\ cost$$
$$= \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{rit}H1_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RB_{rit}BC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RF_{rit}DC_{rit}$$
$$+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RF_{rit}FC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RF_{rit}TC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RS_{rit}SC_{rit}$$
$$+ \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RSM_{roit}\, T1_{roit} + \sum_{r=1}^{R}\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T} RL_{rlit}\, T2_{rlit}$$

Equation 6.7

Where;

R = number of recovery centres

O = number of second markets

L = number of landfill sites

I = types of product

T = number of periods of time

H1 = holding cost for returned products at the recovery centre warehouse

BC = sorting cost

DC = disassembly cost

FC = refurbishment cost

TC = testing cost

SC = scrapping cost

T1 = transportation cost to second market

T2 = transportation cost to landfill

RP = number of units of returned product

RB = number of units being sorted

RF = number of units being refurbished

RS = number of units being scrapping

RSM = number of units sent to second market

RL = number of units sent to landfill

This model could be used to minimise cost subject to the capacity of the recovery centre warehouse and recovery centre labour available. From this mathematical model, the way total cost was affected by returned products in the reverse supply chain could be investigated. This was a second step in performance measurement and is described in Chapter 7.

6.3 Initial Model

An initial model was created to represent both models (model A and model B). In this initial model, several locations were identified, including recovery centres and manufacture plants.

In both company models, returned products were sent directly to recovery centres in several ways. Company A received returned products that were sent directly by a customer or that had been bought by the company. This action was driven by a customer business deal. At Company B, products were received directly by a recovery centre from their individual customers or organisational customers. In Company B, this action was driven by the environmental regulations that bounded

Company B. Company B asked organisational customers to send their end-of-life products via a pick-up service or discount service. While for individual customers, at the end of a contract, every customer had to send back the device as part of regulations and Company B provided free delivery to return the product.

$$\begin{aligned} &\mathit{Total\ Cost\ at\ Recovery\ Centres} \\ &= \text{Total holding cost} + \text{Total sorting cost} + \text{Total disassembly cost} \\ &+ \text{Total refurbishment cost} + \text{Total testing cost} + \text{Total scrapping cost} \\ &+ \text{Total transportation cost to manufacture plant} \\ &+ \text{Total transportation cost to second market} + \text{Total transportation cost to landfill} \end{aligned}$$

$$\begin{aligned} &\mathit{Total\ cost\ at\ recovery\ centres} \\ &= \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{rit}H1_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RB_{rit}BC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RB_{rit}DC_{rit} \\ &+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RF_{rit}RC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RF_{rit}TC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RS_{rit}SC_{rit} \\ &+ \sum_{r=1}^{R}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} RM_{rmit}\, T1_{rmit} + \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RSM_{roit}\, T2_{roit} \\ &+ \sum_{r=1}^{R}\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T} RL_{rlit}\, T3_{rlit} \end{aligned}$$

Equation 6.8

The variable are listed at the end of Section 6.3.

$$\begin{aligned} &\text{Total Cost at Manufacture Plants} \\ &= \text{Holding cost of raw material} + \text{Purcashing cost} + \text{Production cost} \\ &+ \text{Holding cost of final product} + \text{Transportation cost} \end{aligned}$$

$$Total\ cost\ at\ manufacture\ plants$$
$$= \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU1_{mit}\ H2_{mit} + \sum_{m=1}^{M}\sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{t=1}^{T} PU2_{msit}\ NC_{msit}$$
$$+ \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU3_{mit} PC_{mit} + \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU3_{mit} H3_{mit}$$
$$+ \sum_{m=1}^{M}\sum_{D=1}^{D}\sum_{i=1}^{I}\sum_{t=1}^{T} PU4_{mdit}\ T4_{mdit}$$

Equation 6.9

The variable are listed at the end of Section 6.3.

The mathematical model of the initial model is total cost at recovery centre plus total cost at manufacturing plant:

$$Total\ Cost$$
$$= \text{ Total holding cost} + \text{ Total sorting cost } + \text{Total disassembly cost}$$
$$+ \text{Total refurbishment cost} + \text{Total testing cost } + \text{Total scrapping cost}$$
$$+ \text{Total transportation cost to manufacturing plant}$$
$$+ \text{Total transportation cost to second market} + \text{Total transportation cost to landfill}$$
$$+ \text{Holding cost of raw material at manufacturing plant} + \text{Purcashing cost}$$
$$+ \text{Production cost} + \text{Holding cost of final product at manufacturing plant}$$
$$+ \text{Transportation cost to distributor}$$

$$
\begin{aligned}
Total\ cost &= \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{rit}H1_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RB_{rit}BC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RB_{rit}DC_{rit} \\
&+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RF_{rit}RC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RF_{rit}TC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RS_{rit}SC_{rit} \\
&+ \sum_{r=1}^{R}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} RM_{rmit}\, T1_{rmit} + \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RSM_{roit}\, T2_{roit} \\
&+ \sum_{r=1}^{R}\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T} RL_{rlit}\, T3_{rlit} + \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU1_{mit}\, H2_{mit} \\
&+ \sum_{m=1}^{M}\sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{t=1}^{T} PU2_{msit}\, NC_{msit} + \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU3_{mit}PC_{mit} \\
&+ \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU3_{mit}H3_{mit} + \sum_{m=1}^{M}\sum_{D=1}^{D}\sum_{i=1}^{I}\sum_{t=1}^{T} PU4_{mdit}\, T4_{mdit}
\end{aligned}
$$

Equation 6.10

Where:

R = number of recovery centres

M = number of manufacturing plants

O = number of second markets

L = number of landfill sites

S = number of suppliers

D = number of distributor

I = types of product

T = number of periods of time

H1 = holding cost for returned product at recovery centre warehouse

BC = sorting cost

DC = disassembly cost

RC = refurbish cost

TC = testing cost

SC = scrapping cost

T1 = transportation cost to manufacture

T2 = transportation cost to second market

T3 = transportation cost to landfill

H2 = holding cost for parts at manufacture plant warehouse

NC = new part cost from supplier

PC = production cost

H2 = new product holding cost at manufacturing plant warehouse

T4 = transportation cost from manufacture plant to distributor

RP = number of units of returned product

RB = number of units being sorted

RF = number of units being refurbished

RS = number of units being scrapping

RM = number of units sent to manufacture plant

RSM = number of units sent to second market

RL = number of units sent to landfill

PU1 = number of parts at manufacturing plant warehouse

PU2 = number of new parts from supplier

PU3 = number of final products

PU4 = number of units transported to distributor

This initial model was verified against two other companies in two other industries, Company C and Company D. This was to test whether this model could be proposed as a general model.

6.4 Company C

In this model, a collection point such as a shop received the returned products from third parties (customers). Products were sorted and either the product was obsolete or not.

The products were revised, classified and organised using a disposal and re-manufacturing strategy. Products of good quality for remanufacturing were disassembled and processed until they became materials and assemblies ready to be shipped to manufacturing plants. This action took place at the Recovery Plant. The following costs were considered:

6.4.1 Shop costs

At a store or a shop, returned products were collected and sorted as a first stage. An obsolete product was sent to landfill, while other products went to a central recovery plant for the next process.

Most customers returned items through a shop. The sorting process began with obsolete and un-repairable products. These were separated and sent to a landfill or third party for disposal. A shop acted as a collection point for the whole process of the reverse supply chain for company C.

$$\begin{aligned}&\text{Total cost at Collection Point}\\&= \text{Total sorting cost at collection points} + \text{Total transportation cost to landfill}\\&+ \text{Total transportation cost to recovery centres}\end{aligned}$$

$$Total\ cost\ at\ Collecting\ Point$$
$$= \sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{zit}\ BC1_{rit} + \sum_{z=1}^{Z}\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RU_{zrit}\ T1_{zrit}$$
$$+ \sum_{z=1}^{Z}\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T} RO_{zlit}\ T2_{zlit}$$

Equation 6.11

Where;

Z = number of collection point

I = type of products

T = period of time

R= number of recovery centres

L = number of landfill

RP = Returned products

RU = Un-obsolete products

RO = Obsolete products

BC1 = Sorting cost at collection point

T1= Transportation cost from collection point to recovery centre

T2 = Transportation cost from collection point to landfill

The cost at the shop was per returned product type *i*, per each period of time *t* and multiplied by the shop quantity *z*. From this location, sorting cost, transportation of obsolete product to disposal and transportation of un-obsolete product to recovery centre occurred. Transportation cost was affected by landfill quantity as well as recovery centre quantity. In this model, obsolete products were sent to a landfill or sent to a third party that dealt with end-of-life products.

6.4.2 Recovery centre costs

Returned products from a shop or store arrived at a recovery plant. Here returned products were sorted between resalable products and other products. Resalable products were refurbished before entering the second market. While, other products underwent disassembly processes. In that processes, few stages were needed. Figure 6.1 shows the disassembly process in the recovery centre. Useful parts were separated from other parts. Useful parts were refurbished and tested for reuse at manufacturing plants. Other parts were scrapped to extract useful raw material from the parts. All parts and material from a recovery centre were sent to a manufacturing plant to be used as raw material and parts.

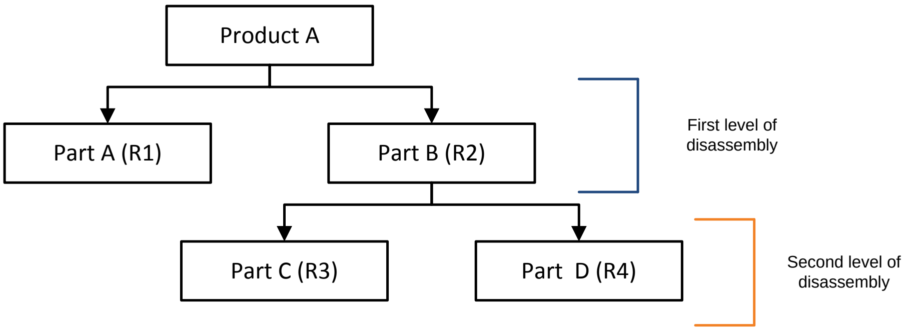

Figure 6.1 Level of disassembly process

Total cost at Recovery Centre

= Total holding cost + Total sorting cost

+ Total cost of refurbishment for resalable product + Total testing cost

+ Total repackaging cost + Total disassembly cost

+ Total cost of refurbishment for part + Total scrapping cost

+ Total transportation cost of residue to landfill

+ Total transportation cost resalable products to second markets

+ Total holding cost for reusable parts

+ Total transportation cost reusable parts to manufacturing plant

+ Total transportation cost raw material to second market

+ Total transportation cost raw material to manufacturing plant

$$
\begin{aligned}
&\mathit{Total\ cost\ at\ Recovery\ Centre} \\
&= \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RC_{rit}H1_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RC_{rit}BC2_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}RC1_{rit} \\
&+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}TC1_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}KC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RD_{rit}DC_{rit} \\
&+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{rit}RC2_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RS_{8rit}SC_{rit} + \sum_{r=1}^{R}\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T} RJ_{rlit}T3_{rlit} \\
&+ \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{roit}T4_{roit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{rit}H2_{rit} \\
&+ \sum_{r=1}^{R}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{rmit}T5_{rmit} + \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RW1_{roit}T6_{roit} \\
&+ \sum_{r=1}^{R}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} RW2_{rmit}T7_{rmit}
\end{aligned}
$$

Equation 6.12

Where:

R = number of recovery centres

M = number of manufacturing plants

O = number of second markets

L = number of landfill sites

I = types of product

T = period of time

RC = returned products from collection points

RR = resalable unit

RD = number of products being disassembled

RP = number of parts at recovery centre

RS = number of units being scrapping

RJ = number of residue

RUP = number of reusable parts

$RW1$ = number of raw material to be sold to second market

$RW2$ = number of raw material to be sent to manufacturing plant

$H1$ = holding cost of products from collection point at recovery centre

$H2$ = holding cost of reusable units at recovery centre

$BC2$ = sorting cost at recovery centre

$RC1$ = refurbishment cost for resalable unit at recovery centre

$TC1$ = testing cost for resalable unit at recovery centre

KC = re-packaging cost for resalable unit at recovery centre

DC= disassembly cost at recovery centre

$RC2$ = refurbishment cost for parts at recovery centre

SC = scrapping cost

$T3$ = transportation cost of residue to landfill

$T4$ = transportation cost of resalable units to second markets

$T5$ = transportation cost of reusable parts to manufacturing plant

$T6$ = transportation cost of raw material to second market

$T7$ = transportation cost of raw material to manufacturing plant

6.4.3 Manufacturing plant costs

At the manufacturing plant, the additional material from returned products was used together with new materials to make new products that were stored and then shipped to distributors for sale. The objective of the company was to minimise cost and a mathematical model was created based on the case study. The model could be used to consider minimising cost.

At a manufacturing plant there will be new material and parts purchased from suppliers. Demand for new products was based on prediction of orders to be fulfilled. Reusable parts and materials from a central recovery plant were used to make new products. An illustration of this process is shown in Figure 6.2. Production cost was considered as one cost, including the assembly process.

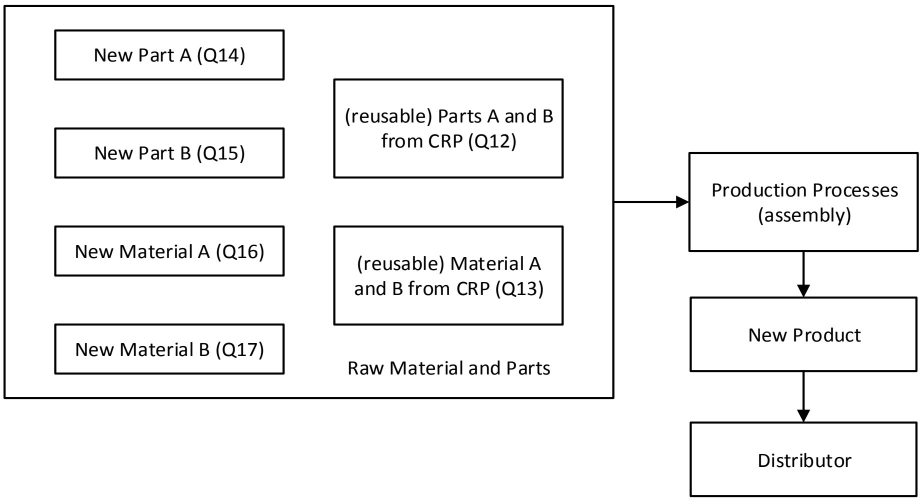

Figure 6.2 Illustration of reusable part and material in production process

Total sorting cost at the collection point was the quantity of returned products, sorting cost for each product and quantity of collection points in the system. In the manufacturing plant, new products were produced based on demand for the product. The cost function in the mathematical model of the manufacture plant is:

Total Cost at Manufacturing Plant

= Total purcashing cost for parts + Total purchasing cost for raw materials

+ Total holding cost of parts at manufacture plant

+ Total holding cost of raw materials at manufacture plant + Total production cost

+ Total holding cost of final product + Total transportation cost to distributor

$$Total\ cost\ at\ manufacturing\ plants$$
$$= \sum_{m=1}^{M}\sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{t=1}^{T} PU1_{msit}NC1_{msit} + \sum_{m=1}^{M}\sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{t=1}^{T} PU2_{msit}NC2_{msit}$$
$$+ \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU3_{mit}H3_{mit} + \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU4_{mit}H4_{mit}$$
$$+ \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU5_{mit}PC_{rit} + \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU6_{mit}H5_{mit}$$
$$+ \sum_{m=1}^{M}\sum_{d=1}^{D}\sum_{i=1}^{I}\sum_{t=1}^{T} PU7_{mdit}T8_{mdit}$$

Equation 6.13

Where:

R = number of recovery centres

M = number of manufacturing plants

O = number of second markets

S = number of suppliers

D = number of distributor

I = types of product

T = period of time

PU1 = purchased number of parts

PU2 = purchased number of raw materials

PU3 = number of parts at manufacturing plant warehouse

PU4 = number of raw material at manufacturing plant warehouse

PU5 = number of final product

PU6 = number of final product at warehouse

PU7 = number of final product sent to distributor

NC1 = new part cost from supplier

NC2 = new raw material cost from supplier

H3 = holding cost of parts

H4 = holding cost of raw material

H5 = holding cost of final products

PC = production cost

T8 = transportation cost to distributor

6.4.4 Total costs

The mathematical cost function for whole process in Company C is:

Total Cost

= Total sorting cost at collection points

+ Total transportation cost from collection point to recovery centres

+ Total transportation cost from collection point to landfill

+ Total holding cost at recovery centre + Total sorting cost at recovery centre

+ Total refurbishment cost for resalable product at recovery centre

+ Total testing cost for resalable product at recovery centre

+ Total repackaging cost for resalable product at recovery centre

+ Total disassembly cost at recovery centre

+ Total refurbishment cost for part at recovery centre

+ Total scrapping cost at recovery centre

+ Total transportation cost of residue from recovery centre to landfill

+ Total transportation cost resalable products from recovery centre to second markets

+ Total holding cost for reusable parts at recovery centre

+ Total transportation cost reusable parts from recovery centre to manufacturing plant

+ Total transportation cost raw material from recovery centre to second market

+ Total transportation cost raw material from recovery centre to manufacturing plant

+ Total purcashing cost for parts + Total purchasing cost for raw materials

+ Total holding cost of parts at manufacture plant

+ Total holding cost of raw materials at manufacture plant + Total production cost

+ Total holding cost of final product + Total transportation cost to distributor

$Total\ cost\ for\ Company\ C$

$$= \sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{zit}\, BC1_{rit} + \sum_{z=1}^{Z}\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RU_{zrit}\, T1_{zrit}$$

$$+ \sum_{z=1}^{Z}\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T} RO_{zlit}\, T2_{zlit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RC_{rit}H1_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RC_{rit}BC2_{rit}$$

$$+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}RC1_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}TC1_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}KC_{rit}$$

$$+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RD_{rit}DC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{rit}RC2_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RS_{8rit}SC_{rit}$$

$$+ \sum_{r=1}^{R}\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T} RJ_{rlit}T3_{rlit} + \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{roit}T4_{roit}$$

$$+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{rit}H2_{rit} + \sum_{r=1}^{R}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{rmit}T5_{rmit}$$

$$+ \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RW1_{roit}T6_{roit} + \sum_{r=1}^{R}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} RW2_{rmit}T7_{rmit}$$

$$+ \sum_{m=1}^{M}\sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{t=1}^{T} PU1_{msit}NC1_{msit} + \sum_{m=1}^{M}\sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{t=1}^{T} PU2_{msit}NC2_{msit}$$

$$+ \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU3_{mit}H3_{mit} + \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU4_{mit}H4_{mit}$$

$$+ \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU5_{mit}PC_{rit} + \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU6_{mit}H5_{mit}$$

$$+ \sum_{m=1}^{M}\sum_{d=1}^{D}\sum_{i=1}^{I}\sum_{t=1}^{T} PU7_{mdit}T8_{mdit}$$

Equation 6.14

Where:

.

Z = number of stores or shops

R = number of recovery centres

M = number of manufacturing plants

O = number of routes to second markets

L = number of landfill sites.

S = number of suppliers and

D = number of distributors.

I = number of types of products.

T = number of periods of time.

$BC1$ = sorting cost for returned products at the collection point.

$H1$ = holding cost at a recovery centre warehouse and

$BC2$ = sorting cost at the recovery centre

$RC1$ = repairing cost for resalable units at a recovery centre

$TC1$ = testing cost for resalable units at a recovery centre

KC = repackaging costs for resalable units at a recovery centre

DC = disassembly process cost at a recovery centre

$RC2$ = refurbishing cost at a recovery centre

SC = cost of the scrapping process at a recovery centre

$H2$ = holding cost for reusable parts at a recovery centre

$T1$ = transportation cost from collection point to recovery centre

$T2$ = transportation cost from collection point to landfill

$T3$ = transportation cost to landfill

$T4$ = transportation cost for resalable units from recovery centre to second market $T5$

= transportation cost from recovery centre to manufacturing plant

$T6$ = transportation cost for raw material from recovery centre to second market

$T7$ = transportation cost for raw material from recovery centre to manufacture plant

$T8$ = transportation cost for final product from manufacture plant to distributor

$NC1$ is the purchasing cost of parts from a supplier

$NC2$ is the purchasing cost of raw materials from a supplier

H3 = holding cost of parts at a manufacture plant

H4 = holding cost of raw materials at a manufacture plant

PC = production cost at a manufacture plant

H5 = holding cost for final products at a manufacturing plant warehouse

RP = number of units of returned products

RU = number of units being refurbished

RO = number of obsolete units

RC = number of units at a recovery centre and

RR = number of resalable units.

RD = number of units being disassembled and

RP = number of parts at the recovery centres that are being refurbished.

RS = number of units being scrapped and

RJ = residue transported to landfill.

RUP = number of reusable parts.

RW1 = amount of raw material transported to second market

RW2 = amount of raw material sent to a manufacturing plant.

PU1 = number of parts purchased from suppliers and

PU2 = number of raw materials purchased from suppliers.

PU3 = number of parts at the manufacturing plant warehouse

PU4 = raw material at a manufacturing plant warehouse.

PU5 = number of units produced and

PU6 = number of final product units at a manufacturing plant warehouse

PU7 = number of unit that being transported to distributor from manufacture plants

This model could be used to measure cost subject to the capacity of the recovery centre warehouse; manufacture plant warehouse; recovery centre labour available; manufacture production capacity; and demand of new products.

6.5 Company D

Company D was a retailer company that sold over 10,000 different products, ranging from car parts and cycles to the latest in-car technology, child seats, roof boxes and outdoor leisure and camping equipment. Company D had two types of suppliers for its merchandise: local suppliers and Far East suppliers. Returns from locally-sourced products were sent back to the supplier. Products sourced from Far East countries went through different disposal routes.

The model in the previous Chapter shows that returned products were returned by customers directly to the store where they had bought the items. In the store, products produced by local suppliers were returned to local suppliers. Other products were sent to collection points for more processing.

6.5.1 Shop Costs

At a shop, products from local suppliers were returned back to local suppliers. While products from other suppliers went to a collection point.

$$\text{Total cost at shop}$$
$$= \text{Total sorting cost} + \text{Total transportation cost to second market}$$
$$+ \text{Total transportation cost to collection point}$$

$$Total\ cost\ at\ shop$$
$$= \sum_{y=1}^{Y}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{yit}BC1_{yit}$$
$$+ \sum_{s=1}^{Y}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RLS_{yoit}\,T1_{yoit} + \sum_{y=1}^{Y}\sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T} RFE_{yzit}\,T2_{yzit}$$

Equation 6.15

Where;

Y= number of shops/stores

Z = number of collection points

O = number of second markets

I = number of types of product

T = number of periods of time

$BC1$ = sorting cost

$T1$ = transportation cost from shop to second market

$T2$ = transportation cost from shop to collection point

RP= number of units of returned product

RLS= number of units from local suppliers

RFE= number of units from Far East suppliers

Because it was a retail company, a shop was the first collection point.

6.5.2 Collection point costs

Returned products sourced from the Far East were sorted and high value products were separated. High value products were delivered to a recovery centre, other products were collected at a collection point and sold as a batch to a third party. Each collection point only had one warehouse as storage for returned products.

$$\text{Total cost at collection point}$$
$$= \text{Total holding cost} + \text{Total sorting cost} + \text{Total transportation cost to second market}$$
$$+ \text{Total transportation cost to recovery centre}$$

$$Total\ cost\ at\ collection\ point$$

$$= \sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T} REF_{zit}H1_{zit} + \sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T} REF_{zit}BC2_{zit}$$

$$+ \sum_{z=1}^{Z}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RLV_{cit}\,T3_{cit} + \sum_{z=1}^{Z}\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RHV_{crit}\,T4_{crit}$$

Equation 6.16

Where;

Z = number of collection points

R = number of recovery centres

O = number of second markets

I = number of types of product

T = number of periods of time

H1= holding cost at collection point warehouse

BC2= sorting cost at collection point

T3= transportation cost from collection point to second market

T4 = transportation cost from collection point to recovery centre

REF= number of units from Far East suppliers

RLV= number of units of low value product

RHV= number of units of high value product

6.5.3 Recovery centre costs

High value returned products were received at recovery centre warehouses. Necessary action was taken based on the product condition. Resalable products were separated from others, and underwent refurbishment processes and testing before being re-packaged to be sold to second markets. Un-resalable products were disassembled to separate useful parts from others. From the disassembly process, un-useful parts went to a scrapping process. Raw materials from this process went to second market and others went to landfill for disposal.

In this company recovery centre, there were two types of refurbishment cost; the first one was refurbishment cost for resalable products from the sorting process; and the second one was refurbishment cost for reusable parts from a disassembly process. Repacking cost was for repackaging resalable products only.

$$\begin{aligned}&\text{Total cost at recovery centre}\\&= \text{Total holding cost} + \text{Total sorting cost} + \text{Total refurbisment for resalable products}\\&+ \text{Total disassembly cost} + \text{Total refurbisment for useful parts} + \text{Total srapping cost}\\&+ \text{Total testing cost for resalable products} + \text{Total testing cost for reusable parts}\\&+ \text{Total repackaging cost for resalable products}\\&+ \text{Total transportation cost for resalable products to second market}\\&+ \text{Total transportation cost for useful parts to second market}\\&+ \text{Total transportation cost for raw material to second market}\\&+ \text{Total transportation cost for disposal to second market}\end{aligned}$$

$$\begin{aligned}&Total\ cost\ at\ recovery\ centre\\&= \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RHV_{rit}H2_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RHV_{rit}BC3_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}RC1_{rit}\\&+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RD_{rit}DC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{rit}RC2_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RS_{rit}SC_{rit}\\&+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}TC1_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{rit}TC2_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}KC_{rit}\\&+ \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{roit}\,T5_{roit} + \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{roit}\,T6_{roit}\\&+ \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RW_{roit}\,T7_{roit} + \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RJ_{roit}\,T8_{roit}\end{aligned}$$

Equation 6.17

Where:

R = number of recovery centres

O = number of second markets

L = number of landfill sites

I = number of types of product

T = number of periods of time

H2= holding cost at recovery centre warehouse

BC3= sorting cost at recovery

DC= disassembly cost

RC1= refurbish cost for resalable units

RC2= refurbish cost for useful parts

SC = scrapping cost

TC1= testing cost for resalable units

TC2= testing cost for useful parts

KC = repackaging cost

T5= transportation of resalable units form recovery centre to second market

T6= transportation of useful parts form recovery centre to second market

T7= transportation of raw material form recovery centre to second market

T8= transportation of disposal form recovery centre to second market

RHV= number of units of high value product

RR= number of resalable units

RD= number of disassembled units

RUP= number units of useful parts

RS= number units of un-useful parts

RW= number of raw material produced from scrapping process

RJ= number of residue from scrapping process

The mathematical cost function for whole process in Company D is:

Total cost

= Total sorting cost at shop + Total transportation cost from shop to second market

+ Total transportation cost from shop to collection point

+ Total holding cost at collection point + Total sorting cost at collection point

+ Total transportation cost from collection point to second market

+ Total transportation cost form collection point to recovery centre

+ Total holding cost at recovery centre + Total sorting cost at recovery centre

+ Total refurbisment for resalable products

+ Total disassembly cost at recovery centre + Total refurbisment for useful parts

+ Total srapping cost + Total testing cost for resalable products

+ Total testing cost for reusable parts + Total repackaging cost for resalable products

+ Total transportation cost for resalable products from recovery centre to second market

+ Total transportation cost for useful parts from recovery centre to second market

+ Total transportation cost for raw material from recovery centre to second market

+ Total transportation cost for disposal from recovery centre to second market

$$
\begin{aligned}
&Total\ cost\ at\ company\ D \\
&= \sum_{y=1}^{Y}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{yit}BC1_{yit} \\
&+ \sum_{s=1}^{Y}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RLS_{yoit}\,T1_{yoit} + \sum_{y=1}^{Y}\sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T} RFE_{yzit}\,T2_{yzit} \\
&+ \sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T} REF_{zit}H1_{zit} + \sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T} REF_{zit}BC2_{zit} \\
&+ \sum_{z=1}^{Z}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RLV_{cit}\,T3_{cit} + \sum_{z=1}^{Z}\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RHV_{crit}\,T4_{crit} \\
&+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RHV_{rit}H2_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RHV_{rit}BC3_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}RC1_{rit} \\
&+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RD_{rit}DC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{rit}RC2_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RS_{rit}SC_{rit} \\
&+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}TC1_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{rit}TC2_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}KC_{rit} \\
&+ \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{roit}\,T5_{roit} + \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{roit}\,T6_{roit} \\
&+ \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RW_{roit}\,T7_{roit} + \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RJ_{roit}\,T8_{roit}
\end{aligned}
$$

Equation 6.18

Processes in Models C and D were used to create a General Model and this is presented in the next section.

6.6 General Model

Because some of the processes that occurred in companies C and D were not represented in the initial model, a more general model was produced to include the differences. The new general model aimed to represent all reverse supply chain processes in all the companies that had been studied.

All collection points were represented in this general model. Some companies had a shop as their collection point (for example company D), other companies had separate collection points (for example company B). Therefore, two location; shops and collection points were included in the new general model.

6.6.1 Shop costs

At a shop, the processing separated obsolete products from others. Obsolete products were sent to landfill as disposal. While other products went to a recovery centre for the next process.

$$\text{Total cost at shop} = \text{Total holding cost} + \text{Total sorting cost} + \text{Total transportation cost to collection point} + \text{Total transportation cost to landfill}$$

$$Total\ cost\ at\ shop = \sum_{y=1}^{Y}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{yit}\, H1_{yit} + \sum_{y=1}^{Y}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{yit}\, BC1_{yit} + \sum_{y=1}^{Y}\sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T} RU_{yzit}\, T1_{yzit} + \sum_{y=1}^{Y}\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T} RO_{ylit}\, T2_{ylit}$$

Equation 6.19

Where;

Y= number of shops

Z= number of collection point

L= number of landfills

I = number of types of product

T = number of periods of time

H1= holding cost at shop

BC1 = sorting cost at shop

T1 = transportation of non-obsolete products form shop to collection point

T2 = transportation of obsolete products form shop to landfill

RP = number of returned products

RU = number of un-obsolete products

RO = number of obsolete products

6.6.2 Collection point costs

At a collection point, second sorting processes took place. Resalable products with minor faults were separated from others and were refurbished before going to second market. At this point resalable products usually went for direct resale.

$$\begin{aligned}&\text{Total cost at collection point}\\&=\text{Total holding cost at collection point}+\text{Total sorting cost at collection point}\\&+\text{Total refurbishment cost at collection point}\ +\text{Transportation cost to second market}\\&+\text{Total transportation cost to recovery centre}\end{aligned}$$

$$\begin{aligned}&Total\ cost\ at\ collecting\ points\\&=\sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T}RU_{yit}H2_{yit}\ +\sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T}RU_{yit}BC2_{yit}\ +\ \sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T}RR_{rit}RC1_{rit}\\&+\ \sum_{z=1}^{Z}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T}RR_{yoit}\ T3_{yoit}+\sum_{z=1}^{Z}\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T}RD_{yrit}\ T4_{yrit}\end{aligned}$$

Equation 6.20

Where;

Z= number of collection points

O= number of second markets

R= number of recovery centres

I = number of types of product

T = number of periods of time

H2= holding cost at collection point warehouse

BC2 = sorting cost at collection point

RC1 = refurbishment cost at collection point

T3= transportation cost from collection point to second market

T4= transportation cost from collection point to recovery centre

RU= number of un-obsolete products

RD = number of direct resal-able products

RND= number of non-direct resalable products

6.6.3 Recovery centre costs

Returned products from collection points arrived at a recovery plant where returned products were sorted between resalable products and other products. Resalable products were refurbished before entering the second market. Other products underwent disassembly processes. Useful parts were separated from other parts. Useful parts were refurbished and tested for reuse at manufacturing plants. Other parts were scrapped to extract useful raw material from the parts. All parts and material from a recovery centre were sent to a manufacturing plant to be used as raw material and parts.

Total cost at recovery centre

= Total holding cost at recovery centre + Total sorting cost at recovery centre

+ Total disassembly cost + Total refurbishment cost for useful parts

+ Total refurbishment cost for resalable products

+ Total testing cost for resalable products + Total testing cost for useful parts

+ Total repackaging cost + Total scrapping cost + Total transportation cost to landfill

+ Total transportation cost to second market for resalable products

+ Total transportation cost to second market for raw materials

+ Total transportation cost to manufacturing plant for raw material

+ Total transportation cost to manufacturing plant for useful parts

$$
\begin{aligned}
&Total\ cost\ at\ recovery\ centres \\
&= \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RND_{rit}H3_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RND_{rit}BC3_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RUS_{rit}DC_{rit} \\
&+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{rit}RC2_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}RC3_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}TC1_{rit} \\
&+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{rit}TC2_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}KC_{rit} \\
&+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RNP_{rit}SC_{rit} + \sum_{r=1}^{R}\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T} RJ_{rlit}T5_{rlit} \\
&+ \sum_{r=1}^{R}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} RW1_{rmit}T6_{rmit} + \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RW2_{roit}T7_{roit} \\
&+ \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{roit}T8_{roit} + \sum_{r=1}^{R}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{rmit}T9_{rmit}
\end{aligned}
$$

Equation 6.21

Where;

R = number of recovery centres

M = number of manufacturing plants

I = number of types of product

T = number of periods of time

$H3$ = holding cost at recovery centre

$BC3$ = sorting cost at recovery centre

DC= disassembly cost at recovery centre

$RC2$= refurbish cost for useful parts at recovery centre

$RC3$= refurbish cost for resalable products at recovery centre

$TC1$= testing cost for resalable products at recovery centre

$TC2$= testing cost for useful parts at recovery centre

KC = re-packaging cost for resalable products

SC = scrapping cost at recovery centre

$T5$ = transportation cost for waste from recovery centre to landfill

$T6$= transportation cost for raw material from recovery centre to manufacturing plant

$T7$ = transportation cost for raw material from recovery centre to second market

$T8$= transportation cost for resalable products from recovery centre to second market

$T9$= transportation cost for useful parts from recovery centre to manufacturing plant

RND= number of non-direct resalable products

RUS = number of un-resalable products

RUP = number of useful parts

RR= number of resalable products

RNP= number of un-useful parts

RJ= number of residue/waste

$RW1$= number of raw materials that useful for production process

$RW2$= number of raw materials that un-useful for production process

6.6.4 Manufacturing plant costs

In a manufacture plant, production cost is per returned product type i and per period of time t for each manufacture plant that a company has. In this model, production cost includes all cost that might occur in making a new product except purchasing of raw materials and parts for the final product from a supplier.

$$\begin{aligned}&\text{Total Cost at Manufacturing Plant}\\&= \text{Total purcashing cost for raw materials} + \text{Total purchasing cost for parts}\\&+ \text{Total holding cost of parts at manufacture plant}\\&+ \text{Total holding cost of raw materials at manufacture plant } + \text{Total production cost}\\&+ \text{Total holding cost of final product} + \text{Total transportation cost to distributor}\end{aligned}$$

$$\begin{aligned}&Total\ cost\ at\ manufacturing\ plants\\&= \sum_{m=1}^{M}\sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{t=1}^{T} PU1_{msit}NC1_{msit} + \sum_{m=1}^{M}\sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{t=1}^{T} PU2_{msit}NC2_{msit}\\&+ \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU3_{mit}H4_{mit} + \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU4_{mit}H5_{mit}\\&+ \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU5_{mit}PC_{rit} + \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU6_{mit}H6_{mit}\\&+ \sum_{m=1}^{M}\sum_{d=1}^{D}\sum_{i=1}^{I}\sum_{t=1}^{T} PU7_{mxit}T10_{mxit}\end{aligned}$$

Equation 6.22

Where;

M = number of manufacturing plants

S = number of suppliers

D = number of distributor

I = number of types of product

T = number of periods of time

$NC1$= purchasing cost for raw materials from supplier

NC2= purchasing cost for parts from supplier

H4 = holding cost for raw materials at manufacturing plant

H5= holding cost for parts at manufacturing plant

PC= production cost per unit at manufacturing plant

H6= holding cost for new products

T10= transportation cost for new product from manufacturing plant to distributors

PU1= number of new raw materials

PU2= number of new parts

PU3 = number of raw materials for production process

PU4 = number of parts for production process

PU5 = number of new products being produced

PU6 = number of new product in warehouse

PU7 = number of new product that sent to distributor for sale

6.6.5 Total cost for the general model

The total cost for the general model combined all costs from all locations and all processes.

Total cost

= Total holding cost at shop + Total sorting cost at shop

+ Total transportation cost from shop to collection point

+ Total transportation cost from shop to landfill

+ Total holding cost at collection point + Total sorting cost at collection point

+ Total refurbishment cost at collection point

+ Transportation cost from collection point to second market

+ Total transportation cost from collection point to recovery centre

+ Total holding cost at recovery centre + Total sorting cost at recovery centre

+ Total disassembly cost + Total refurbishment cost for useful parts

+ Total refurbishment cost for resalable products

+ Total testing cost for resalable products + Total testing cost for useful parts

+ Total repackaging cost + Total scrapping cost

+ Total transportation cost from recovery centre to landfill

+ Total transportation cost from recovery centre to second market for resalable products

+ Total transportation cost from recovery centre to second market for raw materials

+ Total transportation cost from recovery centre to manufacturing plant for raw material

+ Total transportation cost from recovery centre to manufacturing plant for useful parts

+ Total purcashing cost for raw materials + Total purchasing cost for parts

+ Total holding cost of parts at manufacture plant

+ Total holding cost of raw materials at manufacture plant + Total production cost

+ Total holding cost of final product + Total transportation cost to distributor

$Total\ cost\ for\ General\ Model$

$$= \sum_{y=1}^{Y}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{yit}\, H1_{yit} + \sum_{y=1}^{Y}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{yit}\, BC1_{yit} + \sum_{y=1}^{Y}\sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T} RU_{yzit}\, T1_{yzit}$$

$$+ \sum_{y=1}^{Y}\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T} RO_{ylit}\, T2_{ylit} + \sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T} RU_{yit} H2_{yit} + \sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T} RU_{yit} BC2_{yit}$$

$$+ \sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit} RC1_{rit} + \sum_{z=1}^{Z}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{yoit}\, T3_{yoit} + \sum_{z=1}^{Z}\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RD_{yrit}\, T4_{yrit}$$

$$+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RND_{rit} H3_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RND_{rit} BC3_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RUS_{rit} DC_{rit}$$

$$+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{rit} RC2_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit} RC3_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit} TC1_{rit}$$

$$+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{rit} TC2_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit} KC_{rit}$$

$$+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RNP_{rit} SC_{rit} + \sum_{r=1}^{R}\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T} RJ_{rlit} T5_{rlit} + \sum_{r=1}^{R}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} RW1_{rmit} T6_{rmit}$$

$$+ \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RW2_{roit} T7_{roit} + \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{roit} T8_{roit}$$

$$+ \sum_{r=1}^{R}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{rmit} T9_{rmit} + \sum_{m=1}^{M}\sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{t=1}^{T} PU1_{msit} NC1_{msit}$$

$$+ \sum_{m=1}^{M}\sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{t=1}^{T} PU2_{msit} NC2_{msit} + \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU3_{mit} H4_{mit}$$

$$+ \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU4_{mit} H5_{mit} + \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU5_{mit} PC_{rit} + \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU6_{mit} H6_{mit}$$

$$+ \sum_{m=1}^{M}\sum_{d=1}^{D}\sum_{i=1}^{I}\sum_{t=1}^{T} PU7_{mxit} T10_{mxit}$$

Equation 6.23

6.7 Generation of parameters in the summation equations

This Section explores the generation of the parameters for the 30 mathematical equations in the mathematical model.

6.7.1 Holding cost at shop

Holding cost at shop was calculated by multiplying the number *RP* of returned units with the holding cost *H1* for each unit.

$$RP_{zit}\ H1_{zit}$$

Equation 6.24

This equation was based on the total holding cost in the common Inventory Model described by Vohra (2006) where the holding cost equation is:

$$H = h * q$$

Equation 6.25

Where, *H* is total annual holding cost; *h* is the holding cost per unit per annum; and *q* is average number of units held in inventory (Vohra, 2006). Holding (or carrying) costs must be expressed as a cost per unit, but often textbook problems state holding costs as a percentage of the purchase cost (Muckstadt and Sapra, 2010). In the mathematical model described in this Dissertation, *H1* is similar to *h* which is a holding cost per unit, and *RP* is similar to *q* which represents units being held in a warehouse.

The holding cost equation in the general model could be calculated in a different way. Holding cost (*H1*) could consist of: cost of capital, rent, utilities, insurance, wages, taxes, etc. *H1* could also consist of fixed cost and variable cost; fixed cost such as utilities, insurance and rent cost could separated from *H1*. The variable cost depends on the number of units. So, another equation for total holding cost is:

$$\sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T}(RP_{zit}\ H1_{zit}) + FC$$

Equation 6.26

Where:

RP= number of returned products

H1= variable holding cost at shop

FC = fixed cost at shop warehouse

There would also be cost even without an inventory process, such as for rent cost or utilities costs called a mixed cost. An example could be electricity. Electricity usage may increase with production but if nothing is produced a factory still may require a certain amount of power just to maintain itself. Therefore, for this equation a constant variable can be included:

$$\sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T}(RP_{zit}\ H1_{zit}) + FC + c$$

Equation 6.27

Where:

RP = number of returned products

H1= variable holding cost at shop

FC = fixed cost at shop warehouse

c = constant to cover basic cost

In the mathematical model in the Excel spreadsheet, the constant *FC* and *c* was represent by an offset.

6.7.2 Sorting cost at shop

The sorting cost at a shop was calculated by multiplying returned units *RP* with the sorting cost *BC1* for each unit.

$$RP_{zit}\ BC1_{zit}$$

Equation 6.28

For this equation, similar to the previous equation, *BC1* consisted of fixed, variable and mixed cost. A labour cost could be calculated as a fixed cost or mixed cost. If the company considered recovery process time as important then labour cost could be calculated as a mixed cost where returned product cost would increase due to labour overtime. Therefore the equation for sorting cost at a shop could be:

$$\sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{zit}\ BC1_{zit} + LC + \ (LC * or * p)$$

Equation 6.29

Where

BC1 = sorting cost at a shop

LC = labour cost

or = overtime rate

p = percentage of overtime in period of time

This equation could also include a fixed cost separately:

$$\sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{zit}\ BC1_{zit} + FC + \ (LC * or * p)$$

Equation 6.30

Where:

BC1 = variable sorting cost at a shop

FC = fixed cost

LC = labour cost

or = overtime rate

p = percentage of overtime in a period of time

In the mathematical model in the Excel spreadsheet, *FC+(LC*or*p)* was represented by an offset.

6.7.3 Transportation cost at shop for un-obsolete products

Transportation cost for un-obsolete products from shop to recovery centre was calculated by multiplying the number of un-obsolete product units *RU* by transportation cost *T1* for each unit:

$$RU_{zrit}\, T1_{zrit}$$

Equation 6.31

This represented transportation cost in the simplest way. Transportation cost, *T1* could be calculated based on units, batches or vehicles. If the company used batches as a unit, transportation cost could be calculated per batch. If vehicle maximum capacity was used as a transportation unit, transportation cost could be calculated per vehicle.

Transportation cost included the maintenance cost for transport. This maintenance cost was a fixed cost that needed to be included. An equation for transportation cost could therefore be:

$$\sum_{z=1}^{Z}\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RU_{zrit}\, T1_{zrit} + FC$$

Equation 6.32

Where:

T1 = variable cost of transportation of un-obsolete products from shop to recovery centre

RU = number of un-obsolete products (could be per unit, per batch or per vehicle)

FC = fixed cost

6.7.4 Transportation cost for obsolete products

Transportation cost for obsolete products from shop to landfill was calculated by multiplying the number of obsolete units *RO* by the transportation cost *T2* for each unit:

$$RO_{zlit}\, T2_{zlit}$$

Equation 6.33

Section 6.7.3 shows a different equation for un-obsolete products which can be used here again. For the case of obsolete products, landfill cost could also be included as a mixed cost. This could happen if the company dealt with most end-of-life products as their returned product, where a company owned or rented landfill with waste processing. Waste processing cost could be added to the equation. A constant variable cost that occurred can also be added:

$$\sum_{z=1}^{Z}\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T} RO_{zlit}T2_{zlit} \ + FC + (WC * Q3_{zlit}) + c$$

Equation 6.34

Where:

RO = number of obsolete products (could be per unit, per batch or per vehicle)

T2 = variable transportation of obsolete products form shop to landfill

FC = fixed cost

WC = waste processing cost

Q3 = number of obsolete products (could be per unit, per batch or per vehicle)c = constant variable cost

6.7.5 Holding cost at collection point

Holding cost at a collection point was calculated by multiplying the number of un-obsolete units *RU* (from shop) by holding cost *H2* for each unit:

$$RU_{yit}H2_{yit}$$

Equation 6.35

Refer to equations 6.27 and 6.28 at section 6.7.1 for alternative equations.

6.7.6 Sorting cost at collection points

Sorting cost at a collection point was calculated by multiplying the number of un-obsolete units *RU* with sorting *BC2* cost for each unit:

$$RU_{yit}BC2_{yit}$$

Equation 6.36

Refer to equations 6.30 and 6.31 at section 6.7.2 for alternative equations.

6.7.7 Refurbishment cost at collection points

Refurbishment cost at a collection point was calculated by multiplying resalable units *RR* with refurbishment cost *RC* for each unit:

$$RR_{rit}RC_{rit}$$

Equation 6.37

In this process, resalable products usually were by direct resale. The main process for refurbishment was repackaging. Similar to sorting cost (refer to equation 6.30), the type of product affected how important this process was. If the product had a short lifecycle, it would be better to sell the product as soon as possible. This action could add an overtime cost when labour was needed. The equation could develop into:

$$\sum_{y=1}^{Y}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}RC_{rit} + FC + (LC * p)$$

Equation 6.38

Where

RR = number of resalable products

RC = refurbishment cost

FC = fixed cost

LC = labour cost

p = percentage of overtime in a period of time

In the mathematical model in the Excel spreadsheet, *FC+(LC*p)* was represented by an offset.

6.7.8 Transportation cost for direct resalable products

Transportation cost for resalable products from shop to second market was calculated by multiplying the number of direct resalable product units *RD* with transportation cost *T3* for each unit:

$$RD_{yoit}\ T3_{yoit}$$

Equation 6.39

Refer to equation 6.32 at section 6.7.3 for an alternative equation.

6.7.9 Transportation cost for non direct resalable products

Total cost for transportation cost for non direct resalable product from shop to recovery centre was calculated by multiplying non direct resalable units *RND* with transportation cost *T4* for each unit:

$$RND_{yrit}\, T4_{yrit}$$

Equation 6.40

Refer to equation 6.35 at section 6.7.3 for an alternative equation.

6.7.10 Holding cost at recovery centre

Holding cost at a recovery centre was calculated by multiplying non direct resalable units *RND* (from collection point) by holding cost *H3* for each unit:

$$RND_{rit}H3_{rit}$$

Equation 6.41

Refer to equations 6.27 and 6.28 at section 6.7.1 for alternative equations.

6.7.11 Sorting cost at recovery centres

Sorting cost at a recovery centre was calculated by multiplying non direct resalable units *RND* (from a collection point) by sorting cost *BC3* for each unit:

$$RND_{rit}BC3_{rit}$$

Equation 6.42

Refer to Section 6.6.2 for an alternative equation.

6.7.12 Disassembly cost at recovery centres

Disassembly cost at a recovery centre was calculated by multiplying non direct resalable units *RUS* (from a collection point) by disassembly cost *DC* for each unit:

$$RUS_{rit}DC_{rit}$$

Equation 6.43

Disassembly processes can take place at more than one stage, so an alternative equation for this process is:

$$\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RUS_{rit}(DC1 + DC2 + \cdots + DCn)_{rit} \; + \; FC$$

Equation 6.44

Where

RUS = number of un-resalable products

DC1 = disassembly stage 1 cost

DC2 = disassembly stage 2 cost

DCn = disassembly stage n cost

FC = fixed cost

6.7.13 Refurbishment cost at recovery centres

Refurbishment cost for useful parts at a recovery centre was calculated by multiplying the number of useful parts *RUP* by refurbishment cost *RC2* for each unit:

$$RUP_{rit}RC2_{rit}$$

Equation 6.45

In this process, an equation could be divided into the number of type of parts with their own refurbishment costs. Fixed cost could also be spread between types of parts. Therefore an alternative equation for this process is:

$$\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T}(RUP1_{rit}RC1_{rit}) + \cdots + (RUPn_{rit}RCn_{rit}) + FC$$

Equation 6.46

Where

RUP1 = number of useful parts type 1

RUPn = number of useful parts type n

RC1 = refurbishment cost for part type 1

RCn = refurbishment cost for part type n

FC = fixed cost

n = 1,…,n

6.7.14 Refurbishment cost at a recovery centres

Refurbishment cost for resalable products at a recovery centre was calculated by multiplying resalable units *RR* with refurbishment cost *RC3* for each unit.

$$RR_{rit}RC3_{rit}$$

Equation 6.47

Refurbishment processes can take several stages. In this process, there are additional parts that might be used in order to make products eligible for resale. Another equation for this process is:

$$\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}\,(RC1_{rit} + \cdots + RCn_{rit}) + FC + (NP1 * NC1) + \cdots (NPn * NCn)$$

Equation 6.48

Where

RR = number of resalable products

RC1 = refurbishment cost for stage 1

RCn = refurbishment cost for stage n

FC = fixed cost

NP1 = number of unit parts type 1 that need to be brought

NPn = number of unit parts type n that need to be brought

$NC1$ = purchasing cost for parts type 1

NCn = purchasing cost for parts type n

n = 1,…,n

6.7.15 Testing cost for resalable products at a recovery centre

Testing cost for resalable products at a recovery centre was calculated by multiplying the number of resalable units *RR* with the testing cost *TC1* for each unit:

$$RR_{rit}TC1_{rit}$$

Equation 6.49

Refer to Sections 6.6.2 and 6.6.13 for alternative equations.

6.7.16 Testing cost for useful parts at a recovery centre

Testing cost for useful parts at a recovery centre was calculated by multiplying the number of useful parts *RUP* by the testing *TC2* cost for each unit:

$$RUP_{rit}TC2_{rit}$$

Equation 6.50

Refer to Section 6.6.2 for an alternative equation.

6.7.17 Repackaging cost at a recovery centre

Repackaging costs for resalable products at a recovery centre were calculated by multiplying the number of resalable units *RR* with the re-packaging *KC* cost for each unit:

$$RR_{rit}KC_{rit}$$

Equation 6.51

Refer to Section 6.6.7 for an alternative equation.

6.7.18 Scrapping cost at a recovery centre

Scrapping cost for un-useful products at a recovery centre was calculated by multiplying the number of un-useful units *RNP* with scrapping cost *SC* for each unit:

$$RNP_{rit}SC_{rit}$$

Equation 6.52

If a company is mostly dealing with end-of-life products and the scrapping process done by a third party, the equation could be a fixed cost. An alternative equation is:

$$\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} SC_{rit}$$

Equation 6.53

Where

SC = scrapping cost

6.7.19 Transportation cost for waste at recovery centres

Waste transportation cost from recovery centre to landfill was calculated by multiplying the number of waste units *RJ* with transportation cost *T5* for each unit.

$$RJ_{rlit}T5_{rlit}$$

Equation 6.54

Refer to Section 6.6.4 for an alternative equation.

6.7.20 Raw material transportation cost from recovery centre to manufacture plant

Raw material transportation cost from a recovery centre to a manufacturing plant was calculated by multiplying the number of raw material units *RW1* with transportation cost *T6* for each unit:

$$RW1_{rmit}T6_{rmit}$$

Equation 6.55

Refer to Section 6.6.3 for an alternative equation.

6.7.21 Raw material transportation cost from recovery centre to second market

Raw material transportation cost from recovery centre to second market was calculated by multiplying the number of raw material units *RW2* with the transportation cost *T7* for each unit:

$$RW2_{roit}T7_{roit}$$

Equation 6.56

Refer to Section 6.6.3 for an alternative equation.

6.7.22 Resalable transportation cost from recovery centre to second market

Resalable products transportation cost from recovery centre to second market was calculated by multiplying the number of resalable product units *RR* with transportation cost *T8* for each unit:

$$RR_{roit}T8_{roit}$$

Equation 6.57

Refer to Section 6.6.3 for an alternative equation.

6.7.23 Useful parts transportation cost from recovery centre to manufacture plant

Useful parts transportation cost from recovery centre to manufacturing plant was calculated by multiplying the number of useful parts *RUP* with transportation cost *T9* for each unit:

$$RUP_{rmit}T9_{rmit}$$

Equation 6.58

Refer to Section 6.6.3 for an alternative equation.

6.7.24 Parts purchasing cost at a manufacture plant

Parts (from supplier) purchasing cost at a manufacture plant was calculated by multiply parts *PU1* with purchasing cost *NC1* for each unit:

$$PU1_{sit}NC1_{sit}$$

Equation 6.59

The equation could be more detailed in terms of types of parts and types of supplier. Parts could be brought from different suppliers to minimise cost. An alternative equation for this process is:

$$\sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{t=1}^{T}(PU1_{sit}NC1_{sit}) + (PU2_{sit}NC2_{sit}) + \cdots + (PUn_{sit}NCn_{sit})$$

Equation 6.60

Where

PU1 = number of unit part 1

PU2 = number of unit part 2

PUn = number of unit part n

NC1 = purchasing cost for part 1

NC2 = purchasing cost for part 2

NCn = purchasing cost for part 3

6.7.25 Raw materials purchasing cost at manufacture plants

Raw materials (from supplier) purchasing cost at a manufacture plant was calculated by multiplying number of units *PU2* with purchasing cost *NC2* for each unit:

$$PU2_{sit}NC2_{sit}$$

Equation 6.61

Refer to Section 6.6.24 for an alternative equation.

6.7.26 Raw materials holding cost at manufacture plant

Raw material holding cost at a manufacturing plant was calculated by multiplying raw material units *PU3* with holding cost *H4* for each unit:

$$PU3_{mit}H4_{mit}$$

Equation 6.62

Refer to Section 6.6.1 for an alternative equation.

6.7.27 Parts holding cost at a manufacture plant

Parts holding cost at a manufacturing plant was calculated by multiplying units *PU4* with holding cost *H5* for each unit:

$$PU4_{mit}H5_{mit}$$

Equation 6.63

Refer to Section 6.6.1 for an alternative equation.

6.7.28 Production cost at a manufacture plant

Production cost at a manufacturing plant was calculated by multiplying the number of products being produced *PU5* with production cost *PC* for each unit:

$$PU5_{mit}PC_{rit}$$

Equation 6.64

The manufacturing cost per (good) product was computed by dividing the sum of total direct manufacturing cost and total cost for all reworked units by the yield (Adam et al., 1981). This manufacturing cost consisted of fixed, variable and mixed cost.

6.7.29 Final product holding cost at a manufacture plant

Total cost for final product holding cost at a manufacturing plant was calculated by multiplying final units *PU6* with holding cost *H6* for each unit:

$$PU6_{mit}H6_{mit}$$

Equation 6.65

Refer to Section 6.6.1 for an alternative equation.

6.7.30 Transportation cost for final product from manufacturing plant to distribution

Final transportation cost from manufacturing plant to distributor was calculated by multiplying the number of final units *PU7* with transportation cost *T10* for each unit:

$$PU7_{mxit}T10_{mxit}$$

Equation 6.66

Refer to Section 6.6.3 for an alternative equation.

6.8 Company E

The company was based on a case study by Tonanont (2009). The company focused on carpet manufacturing and recycling as the main activities. Returned carpet from customers (either individual or organisation) were sent to a recovery centre and received in a recovery centre warehouse. In the recovery centre, returned carpets were processed based on the condition of the products. Mechanical and chemical processes converted the carpet into raw materials. The conversion process is referred to as a disassembly process and refurbishment process, where nylon polymer in used carpet was converted to monomer units which could be used as raw material in carpet manufacture. This process was called depolymerisation. There were three main types of materials related to carpet manufacturing: yarn, which is nylon;

chemical products such as polypropylene and polyester; and finally, the package (Tonanont, 2009).

In model E, a warehouse in the recovery centre received all returned carpets from the customer. Products were disassembled and processed until they became raw materials ready to be shipped to manufacturing plants. This action took place at the Recovery Centre.

Returned products underwent stages of disassembly. The first stage was usually carpet size reduction, followed by chemical separation of carpet components. Separated nylon was processed to be used as raw material (Wang, 2006). Figure 6.7 shows the level of disassembly processes in a recovery centre. Useful materials were refurbished for reuse at a manufacturing plant. Other parts were sent to landfill. All raw materials from the recovery centre were sent to a manufacturing plant to be used as raw material in the production process.

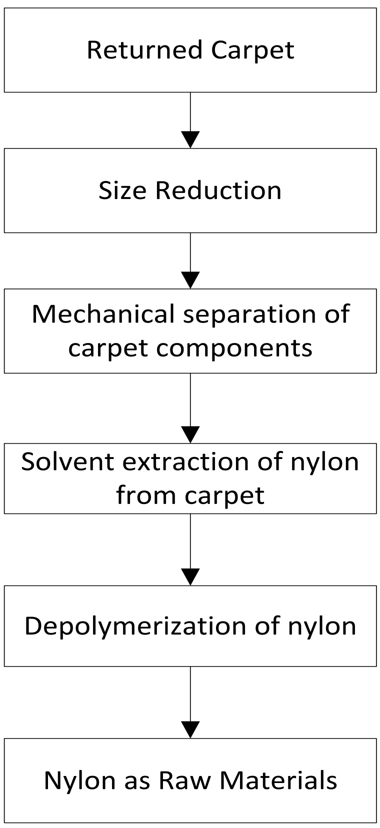

Figure 6.3 Level of disassembly process (Wang, 2006)

At the manufacturing plant, the additional material from returned products was used together with new materials to make new products that were stored and then shipped to distributors for sale.

The objective of the company was to minimise cost (Tonanont, 2009). A mathematical model was created based on the case study. The mathematical model is the sum of all the costs associated with the process.

$$\begin{aligned}
&\text{Total cost} \\
&= \text{Total holding cost at recovery centre} + \text{Total disassembly cost} \\
&+ \text{Total refurbishment cost } + \text{Total transportation cost from recovery centre to landfill} \\
&+ \text{Total transportation cost from recovery centre to manufacturing plant for raw material} \\
&+ \text{Total holding cost for raw materials at manufacturing plant} \\
&+ \text{Total purcashing cost for raw materials} + \text{Total production cost} \\
&+ \text{Total holding cost of final product} + \text{Total transportation cost to distributor}
\end{aligned}$$

$$\begin{aligned}
&Total\ Cost \\
&= \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{rit}H1_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{rit}DC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RF_{rit}RC_{rit} \\
&+ \sum_{r=1}^{R}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} RM_{rmit}\, T1_{rmit} + \sum_{r=1}^{R}\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T} RL_{rlit}\, T2_{rlit} \\
&+ \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} RW_{mit}\, H2_{mit} + \sum_{m=1}^{M}\sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{t=1}^{T} RN_{msit}\, NC_{msit} \\
&+ \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU1_{mit}PC_{mit} + \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU2_{mit}H3_{mit} \\
&+ \sum_{m=1}^{M}\sum_{d=1}^{D}\sum_{i=1}^{I}\sum_{t=1}^{T} PU3_{mdit}\, T3_{mdit}
\end{aligned}$$

Equation 6.67

Where:

R = number of recovery centres

M = number of manufacturing plants

L = number of landfill sites

S = number of suppliers

D = number of distributor

I = number of types of products

T = number of periods of time

H1 = holding cost for returned products at the recovery centre warehouse and

DC = disassembly cost.

RC = refurbishment cost.

T1 = transportation cost to manufacture

T2 = transportation cost to landfill

T3 = transportation cost from manufacture plant to distributor

H2 = holding cost for parts at the manufacturing plant warehouse and

NC = new part cost from a supplier

PC = production cost and

H3 = new product holding cost at manufacture plant warehouse

RP = number of units of returned products and

RF = number of units that being refurbished

RM = number of units sent to the manufacture plant and

RL = number of units sent to landfill

RW = amount of raw materials at the manufacturing plant warehouse.

RN = number of new parts from suppliers and

PU1 = number of final products

PU2 = number of new products at the manufacture plant warehouse

PU3 =number of units transported to distributors

The model could be used to investigate cost, subject to the capacity of the recovery centre warehouse; manufacture plant warehouse; recovery centre labour available; manufacture production capacity; and demand of new products.

A mathematical model was produced to describe each of the frameworks described in Chapter 5. The mathematical models can show reverse supply chain system performance and they can be explored to improve the systems.

From this mathematical from Model E, it was seen that the new general mathematical model covered all returned products activities in Model E. Based on this verification, the general model was verified along with the mathematical equations.

In the next Chapter the performance measurement for returned products using cost as a parameter is explained and tested. The mathematical equations for each model were used to measure the performance of their reverse supply chain in each company.

Chapter 7 Performance Measurement

Performance of the models is investigated in this Chapter by considering different inputs to the reverse supply chain (RSC) for each company. Based on the mathematical models described in Chapter 6 and generated data, a total cost for the whole system is produced for each model.

Each specific model of a company was derived from the general model. Total cost was counted based on the mathematical model and that was also derived from the general model. High number of returned product was compared to low number of returned product to see how returned products affected the whole system cost. Secondary data was use due to a lack of data, companies would not allow their real data to be published.

7.1 Model A

Spreadsheets were created from mathematical model A to accommodate processes in Company A. See Appendix A.01 for an Excel calculation spreadsheet.

Because Model A considered both forward supply chains and RSCs, demand for new products was considered first and then returned products were added. The graph of demand shown in Figure 7.1 was based on a “Current Market Outlook Boeing report for Europe” (see appendix A.03) (Boeing, 2014). There was a demand for 7310 new airplanes between 2015 to 2034 as shown in Table 7.1, extracted from the report for Europe.

Table 7.1 Europe an new airplanes demand markets (Boeing, 2014)

	New air planes	Share by size (%)
Large widebody	40	1
Medium widebody	510	7
Small widebody	910	12
Single aisle	5,770	79
Regional jet	80	1

Total	**7,310**	

A random number generator was used to produce demand for new products from the data shown in Table 7.1. This number was based on demand for new airplanes (single aisle type). From 2015 to 2034 there were 5770 single aisle airplanes. In order to create an approximate total of 5770 aeroplanes the lowest demand was experimentally set to 16 per month and the highest number of products demanded was set to 35. The demand is shown in Figure 7.1.

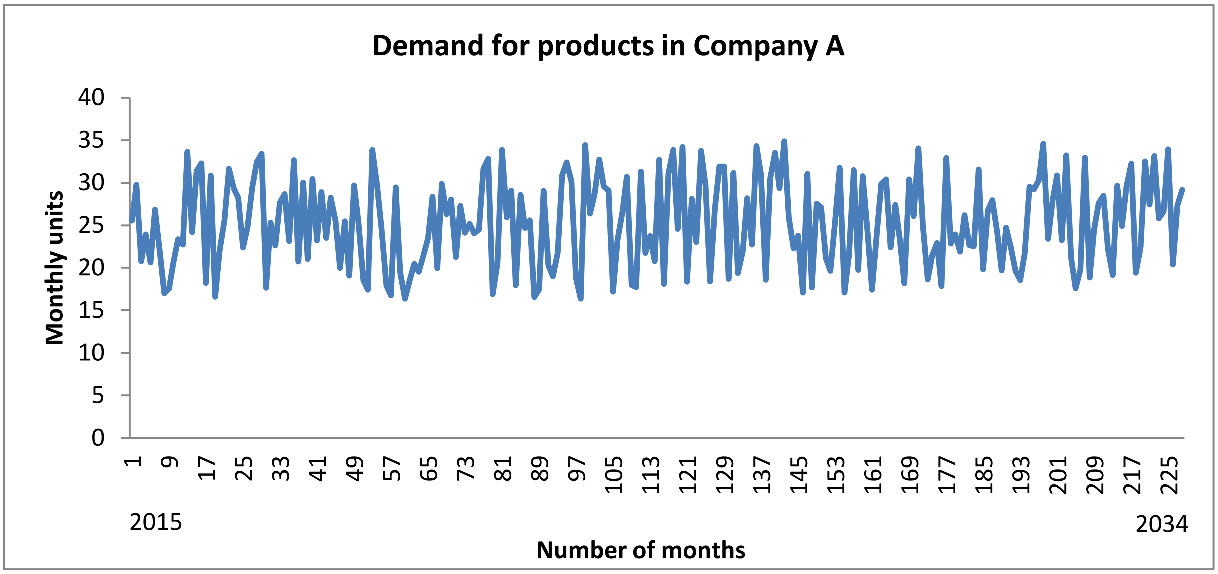

Figure 7.1 Demand for new products in Company A created using a random number generator

It was difficult to extract information from this data as it was noisy so the data was grouped into larger sets as a first step in data analysis. That filtered and smoothed the data in order to extract information more easily. A number of periods of time was calculated using:

$$\text{number (k) of classes, } k = 1 + 3.3 \log N$$

Equation 7.1 (Brkić, 1991)

where N is the number of data sets.

Nine classes (periods of time) were created in order to summarise and group the data. There were 25 months in each of the new groups and Figure 7.2 shows the filtered group demand for new products in Company A that was used to represent demand for products in Model A.

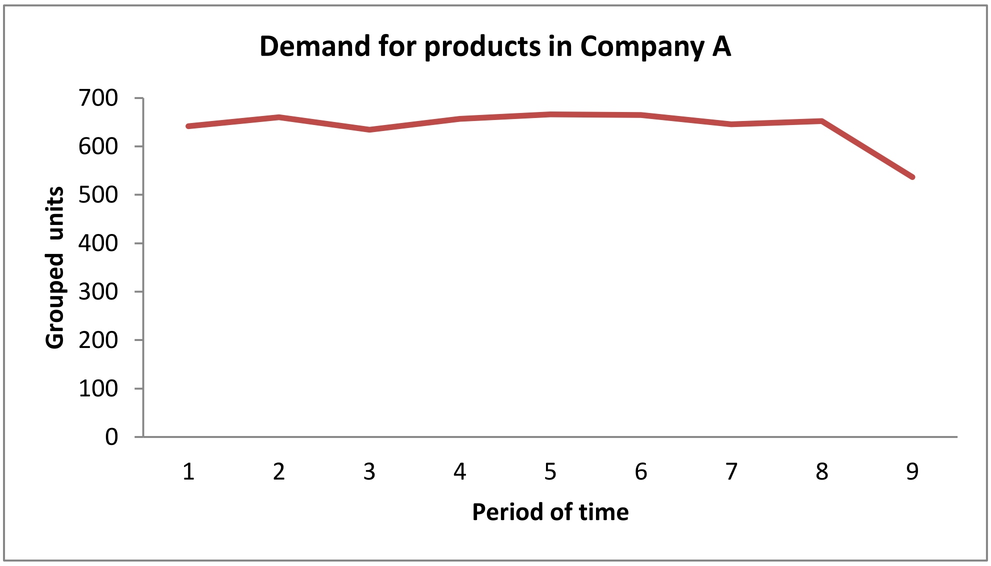

Figure 7.2 Grouped demand for new products in Company A

Returned units in Company A were entered into the spreadsheet representing the mathematical model based on demand in Company A. The number of returned products was set to 60% of demand for each period of time. Figure 7.3 shows returned products based on the number of demanded products.

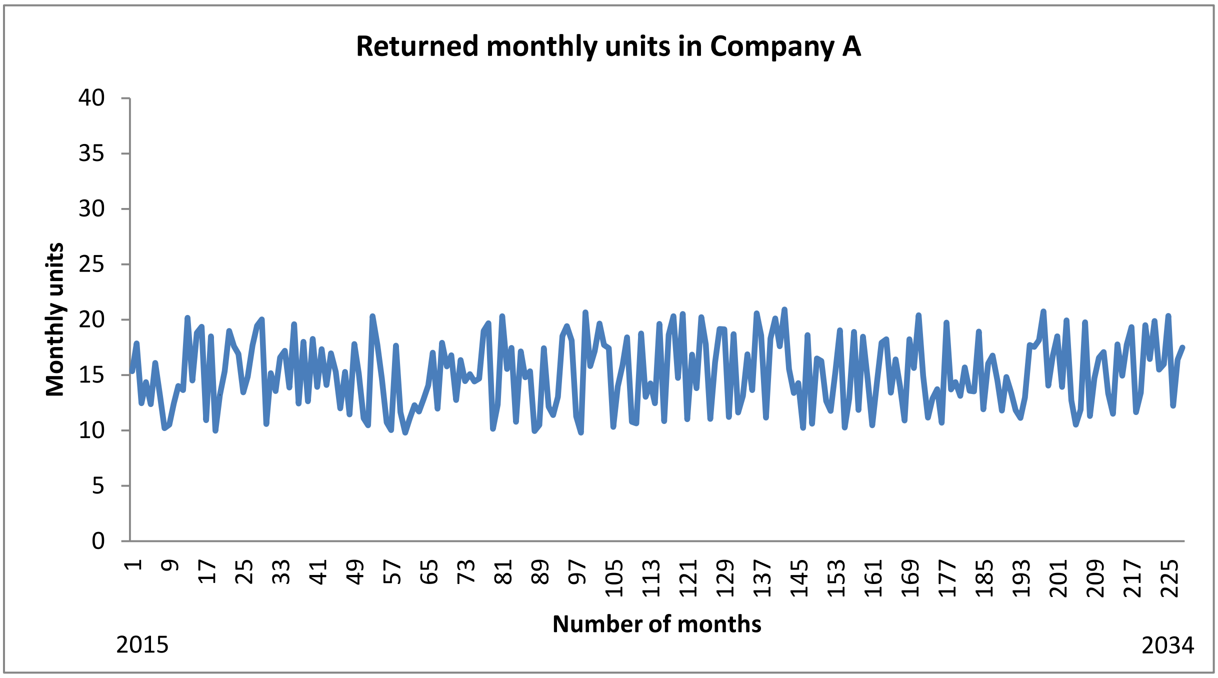

Figure 7.3 Returned monthly units in Company A (based on 60% of demand)

Returned product data was also noisy and needed to be filtered, smoothed and grouped. The number of months was represented in the model as a period of time. Figure 7.4 shows grouped data for returned products in Company A.

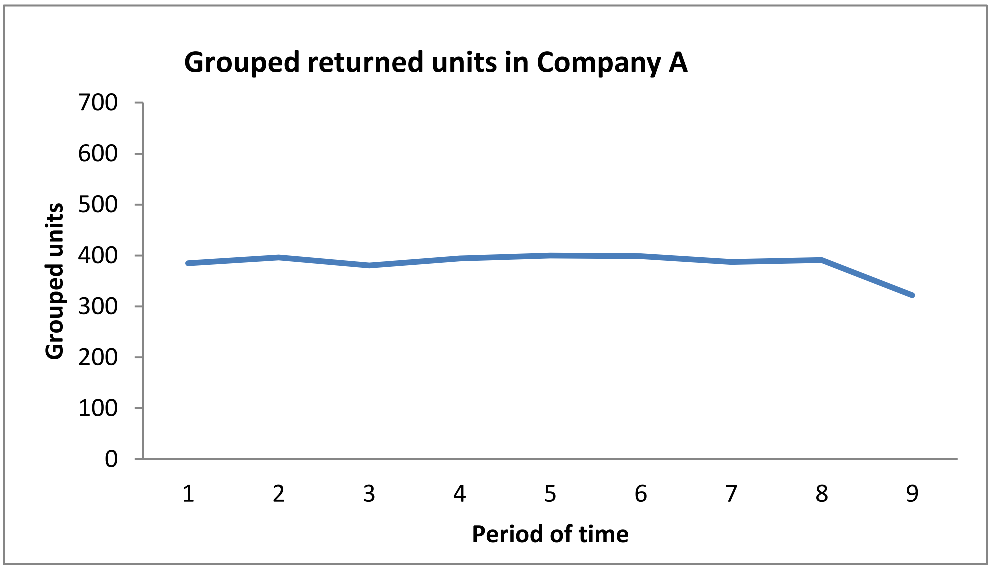

Figure 7.4 Grouped returned units in Company A

To investigate how returned products affected the company, the mathematical model was run in two ways. The first run was carried with low returned products and the second with high returned products. A comparison could then be made to investigate how reverse supply chain performance in the company was affected and could be measured. Therefore, the low return number was set in to 10% of the high returned number. This extreme data was to make differences on the comparison graph visible and easier to understand. This set of percentage of high return products and low returned products was applied in other companies in this Dissertation.

7.1.1 Total cost in Recovery Centre

In the Recovery Centre (RC), total cost was calculated from the holding cost for returned products that arrived in the RC warehouse, added to disassembly cost and refurbishment cost for returned products, and testing cost for reusable parts, as well as scrapping cost for un-reusable parts. Holding cost for reusable parts and raw material was also added. Finally landfill cost was added to total cost in the RC. Total cost was based on equation 6.3 from Chapter 6:

$$Recovery\ Centre\ Total\ Cost$$

$$= \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{rit}H1_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{rit}DC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RF_{rit}FC_{rit}$$
$$+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RF_{rit}TC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RS_{rit}SC_{rit} + \sum_{r=1}^{R}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} RM_{rmit}\,T1_{rmit}$$
$$+ \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RSM_{roit}\,T2_{roit} + \sum_{r=1}^{R}\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T} RL_{rlit}\,T3_{rlit}$$

Equation 6.3

Where

$$\text{Total holding cost} = \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{rit}H1_{rit}$$

$$\text{Total disassembly cost} = \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{rit}DC_{rit}$$

$$\text{Total refurbishment cost} = \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RF_{rit}FC_{rit}$$

$$\text{Total testing cost} = \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RF_{rit}TC_{rit}$$

$$\text{Total scrapping cost} = \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RS_{rit}SC_{rit}$$

$$\text{Total transportation cost to manufacture plant} = \sum_{r=1}^{R}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} RM_{rmit}\, T1_{rmit}$$

$$\text{Total transportation cost to second market} = \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RSM_{roit}\, T2_{roit}$$

$$\text{Total transportation cost to landfill} = \sum_{r=1}^{R}\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T} RL_{rlit}\, T3_{rlit}$$

Part of a worksheet for Model A is shown in Figure 7.5. In Figure 7.5, column one is the time period and column two is the number of units returned in that period. Column three shows the holding cost of the returned units and column four shows the number of products to be disassembled. Column five shows the cost associated with assembling the product. Column six shows the reusable parts extracted from returned products and column seven shows the number of parts that could not be reuse.

1	2	3	4	5	6	7
Period	Unit Returned					
		Holding cost for Retuned Product		Disassembly cost	Unit Dissambled	
		holding cost x returned unit	Returned prodcut to be dissasembled	dis cost x returned unit	Reuseable part	Other
0	0	0	0	0	0	0
1	15	153	0	0	0	0
2	18	179	15	307	100	50
3	12	125	18	357	120	60
4	14	144	12	249	80	40
5	12	124	14	287	100	50
6	16	161	12	248	80	40
7	13	131	16	322	110	50
8	10	102	13	263	90	40
9	11	105	10	204	70	40

Figure 7.5 Part of the worksheet screenshot for Model A at the Recovery Centre

Total cost in the RC is presented in Figure 7.6.

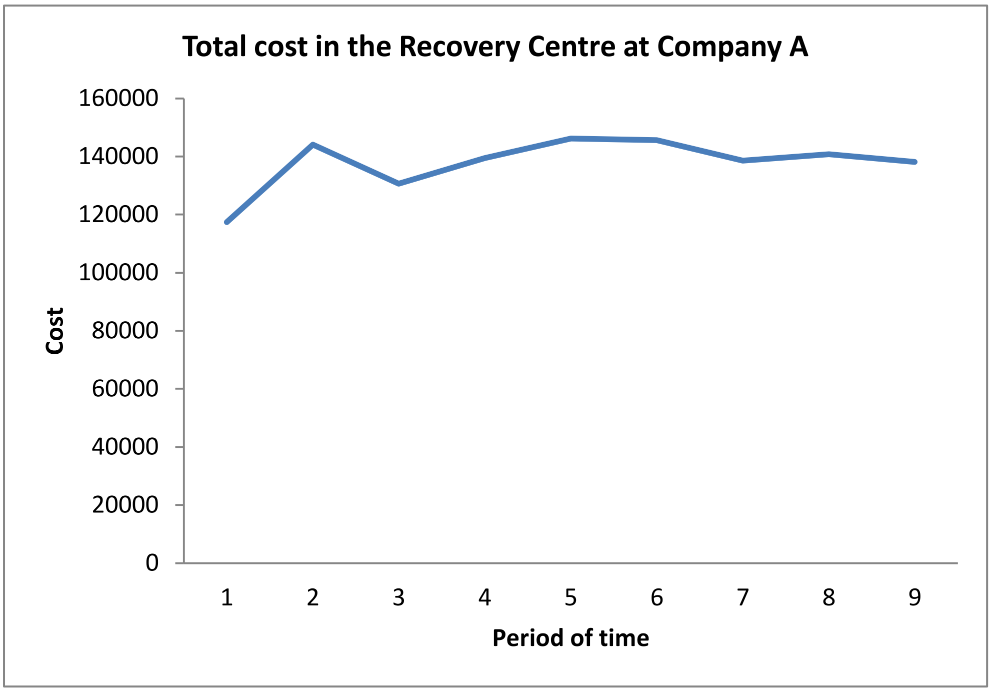

Figure 7.6 Total cost at recovery centre in Company A

7.1.2 Total cost in the Manufacturing Plant

In the Manufacturing Plant (MP), total cost consisted of the purchasing cost for parts and raw materials added to holding costs for both parts and final products, and production cost and transportation cost. Purchasing cost for parts was based on the parts needed minus reusable parts from the RC sent to the MP. Transportation cost in Model A was based on regular batches; the same number of units were assumed to be loaded in every batch. Total cost was based on equation 6.4 from Chapter 6:

$$Total\ Cost\ at\ Manufacturing\ Plant$$
$$= \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU1_{mit}\ H2_{mit} + \sum_{m=1}^{M}\sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{t=1}^{T} PU2_{msit}\ NC_{msit}$$
$$+ \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU3_{mit}\ PC_{mit} + \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU3_{mit}\ H3_{mit}$$
$$+ \sum_{m=1}^{M}\sum_{d=1}^{D}\sum_{i=1}^{I}\sum_{t=1}^{T} PU4_{mdit}\ T4_{mdit}$$

Equation 6.4

Where

Total holding cost of raw material at manufacture plant $= \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU1_{mit}\ H2_{mit}$

Total purcashing cost $= \sum_{m=1}^{M}\sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{t=1}^{T} PU2_{msit}\ NC_{msit}$

Total production cost $= \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU3_{mit}\ PC_{mit}$

Total holding cost of final product $= \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU3_{mit}\ H3_{mit}$

Total transportation cost to distributor $= \sum_{m=1}^{M}\sum_{d=1}^{D}\sum_{i=1}^{I}\sum_{t=1}^{T} PU4_{mdit}\ T4_{mdit}$

Figure 7.7 shows part of a worksheet in MP for Model A. In Figure 7.7, column one is the time period and column two is the number of units demanded in that period. Column three shows the number of parts that were needed to fulfil demand. Column four shows the number of reusable parts from RC and column five shows the number of the parts that needed to be bought from a supplier. Column six shows the number of parts from the supplier and column seven shows the purchasing cost.

1	2	3	4	5	6	7
Period	Demand	Part Needed	Reusable Part from Recovery	Part need to be brought	Parts from Supplier	Part purchase cost
						part cost x unit part
0	0	0	0	0	0	0
1	26	0	0	0	0	0
2	30	383	0	383	383	38345
3	21	446	0	446	446	44627
4	24	311	0	311	311	31131
5	21	359	0	359	359	35906
6	27	310	0	310	310	30954

Figure 7.7 Part of worksheet screenshots for Model A in a Manufacturing Plant

Figure 7.8 shows a graph of total cost in the MP

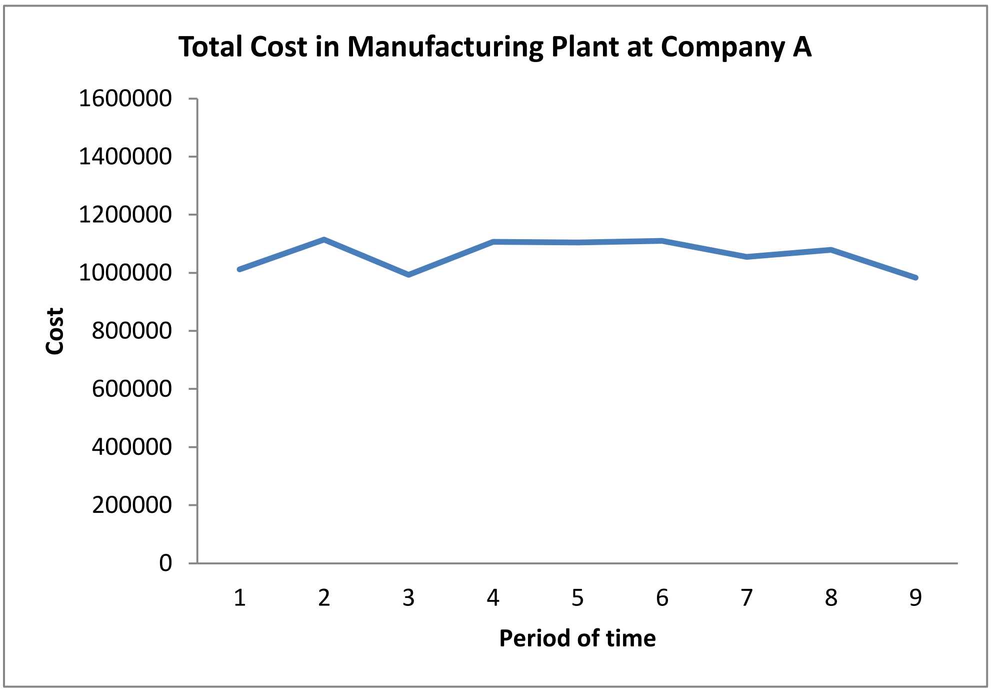

Figure 7.8 Total cost at manufacturing plant in Company A

7.1.3 Total cost of whole system

A graph of total cost for the whole system in Company A with returned products is shown in Figure 7.9. Total cost was based on Equation 6.5.

$$Total\ Cost$$
$$= \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{rit}H1_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{rit}DC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RF_{rit}FC_{rit}$$
$$+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RF_{rit}TC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RS_{rit}SC_{rit} + \sum_{r=1}^{R}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} RM_{rmit}\, T1_{rmit}$$
$$+ \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RSM_{roit}\, T2_{roit} + \sum_{r=1}^{R}\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T} RL_{rlit}\, T3_{rlit}$$
$$+ \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU1_{mit}\, H2_{mit} + \sum_{m=1}^{M}\sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{t=1}^{T} PU2_{msit}\, NC_{msit}$$
$$+ \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU3_{mit}\, PC_{mit} + \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU3_{mit}\, H3_{mit}$$
$$+ \sum_{m=1}^{M}\sum_{d=1}^{D}\sum_{i=1}^{I}\sum_{t=1}^{T} PU4_{mdit}\, T4_{mdit}$$

Equation 6.5

So that total:

$Total\ Cost$

= Total holding cost at recovery centre warehouse

+ Total disassembly cost at recovery centre

+ Total refurbishment cost at recovery centre + Total testing cost at recovery centre

+ Total scrapping cost at recovery centre

+ Total transportation cost from recovery centre to manufacture plant

+ Total transportation cost from recovery centre to second market

+ Total transportation cost from recovery centre to landfill

+ Total holding cost of raw material at manufacture plant + Total purcashing cost

+ Total production cost + Total holding cost of final product at manufacture plant

+ Transportation cost from manufacture plant to distributor

Where total cost for the whole company was the total cost at RC added to the total cost at the MP. An explanation of the equation can be found in Chapter 6.

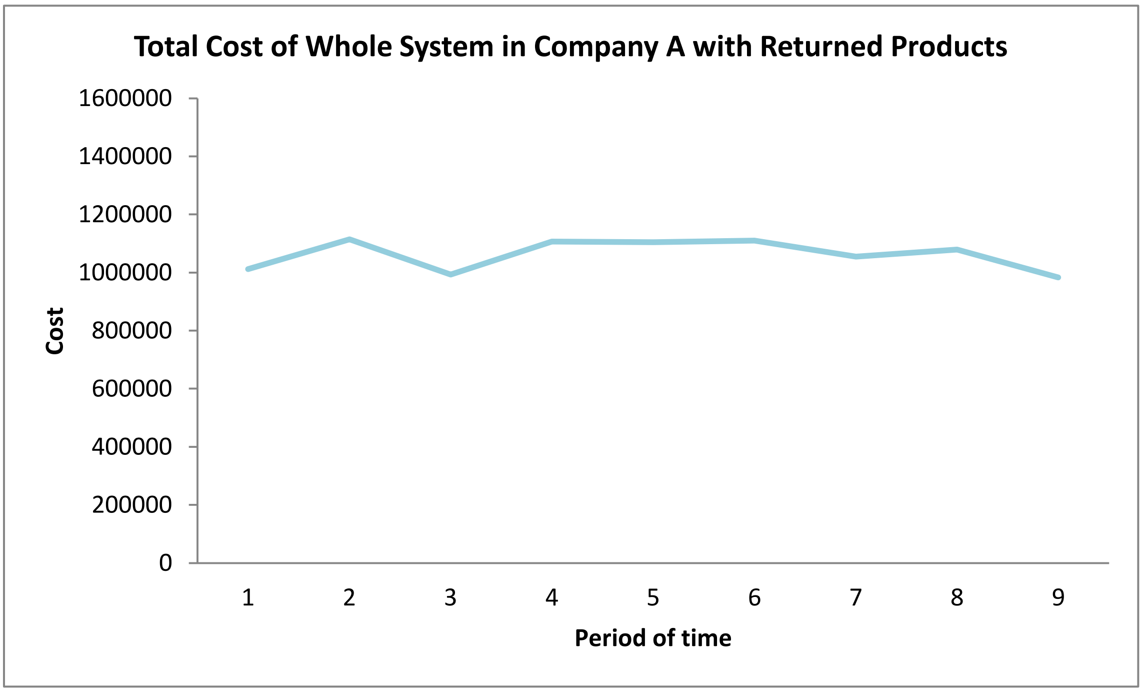

Figure 7.9 Total cost of whole system in Company A with returned products

See Appendix A.02 for details of the total cost for the whole system in Company A with a low number of returned products. Low number of returned products was 10% of the high number of returned products as shown in Figure 7.10.

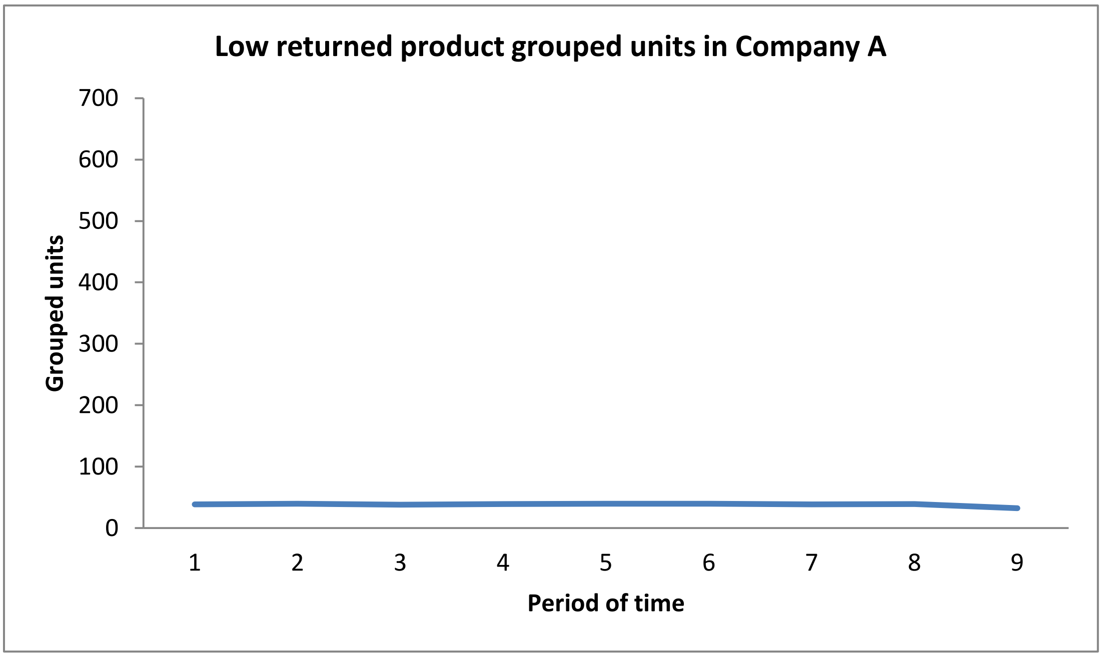

Figure 7.10 Low returned product grouped units in Company A

Figure 7.11 shows the total cost of the whole system when there was a low number of returned products. Both were calculated based on the total cost summation in Company A.

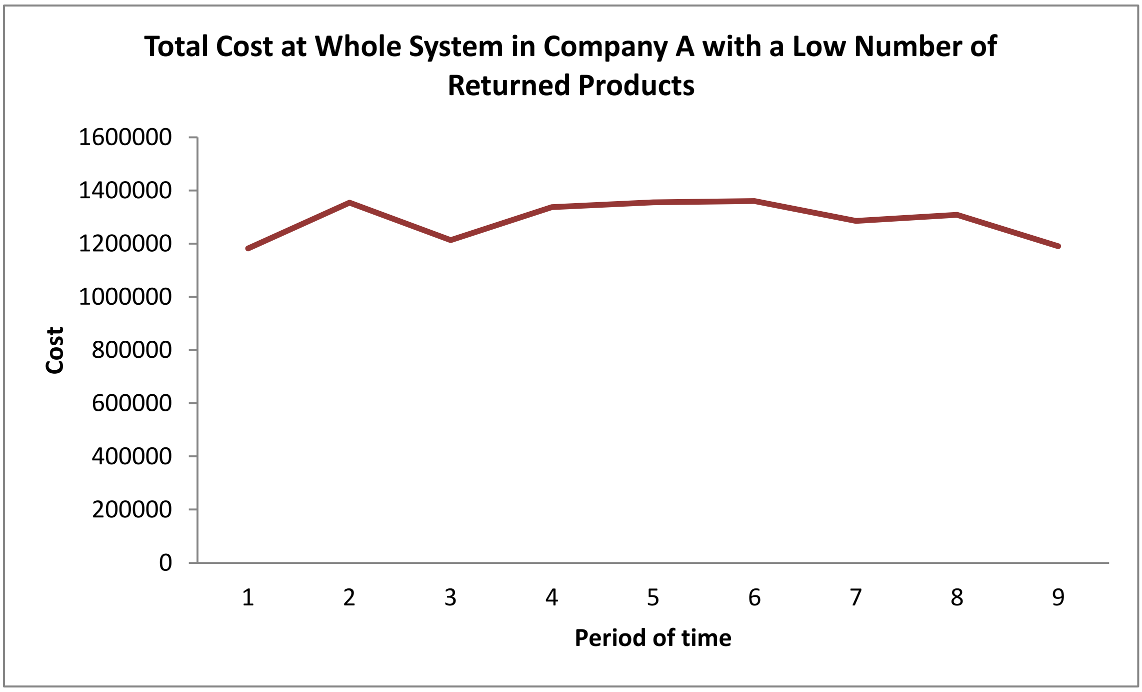

Figure 7.11 Total cost of whole system in company A with a low number of returned products

A comparison of the total cost with high number of returned products and with a low number of products is shown in Figure 7.12. A company could use this data to calculate how returned products affected their company.

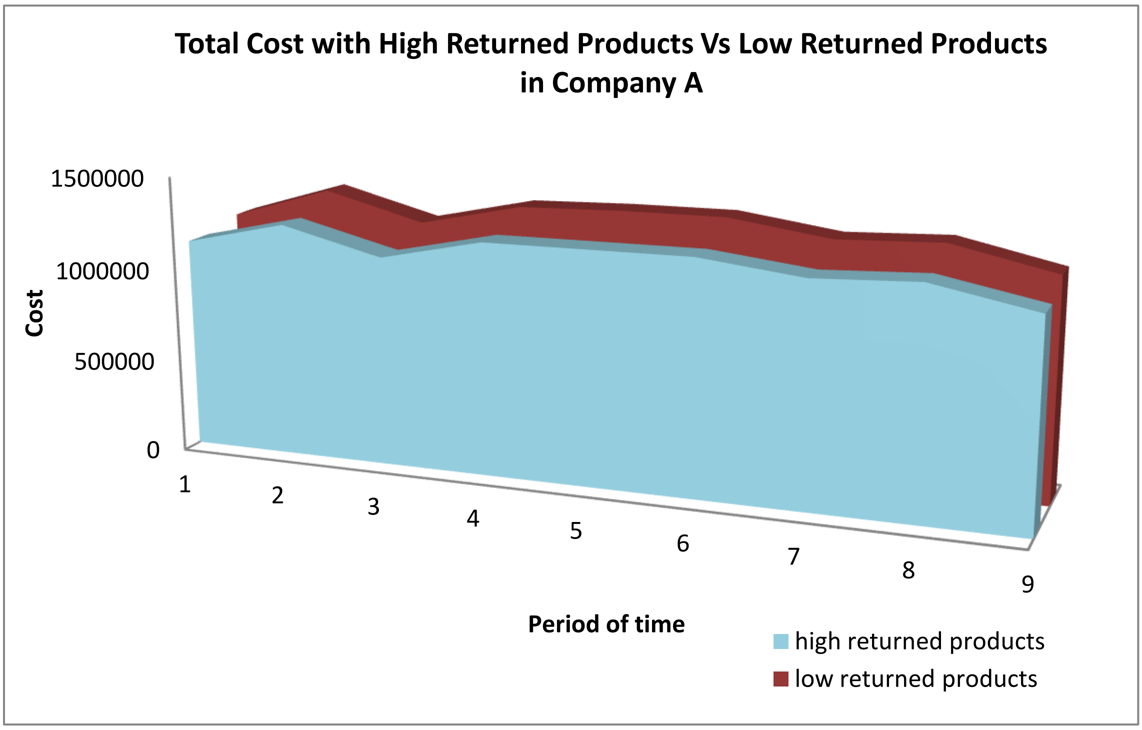

Figure 7.12 Total Cost with high returned products vs low returned products

The graph suggests that:

- Returned products and recovery processes could lower the total cost.
- The small difference in the graph shows that the company had high fixed costs or high production costs.
- Even though the cost reduction is small, it could add profit.

This is the first time that an attempt to measure performance with a reverse supply chain in the aircraft industry has been published.

7.2 Model B

Company B was different. It dealt with end of life products. There was no manufacturing process. All reusable parts and raw materials were sold to second markets from the Recovery Centre (RC). Other disposal was sent to landfill.

A random number generator was used to create a profile of returned products. The mean of the data was set to 100 and 228 was selected as the number of data sets to be produced because that number had been used previously for Company A. That made it easier to compare Company A and Company B. Figure 7.13 shows the set of data produced by the random number generator for returned products. In the same way as for Model A, this model was grouped to be able to extract information from the data.

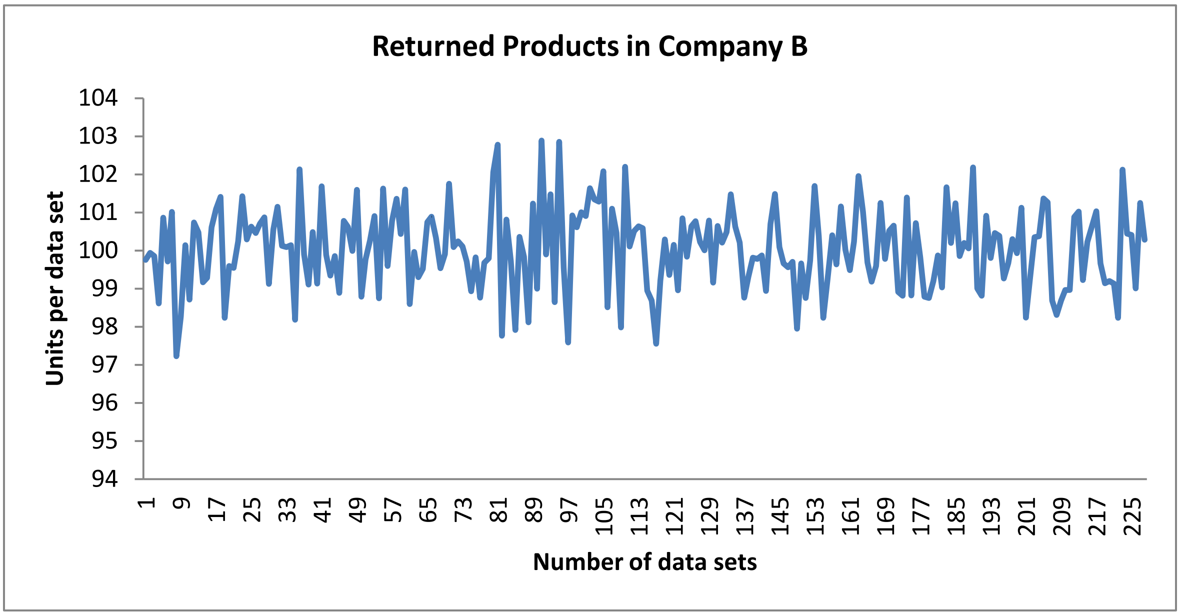

Figure 7.13 Returned products in Company B (created using a random number generator)

Figure 7.14 shows returned products for Company B in each grouped period of time.

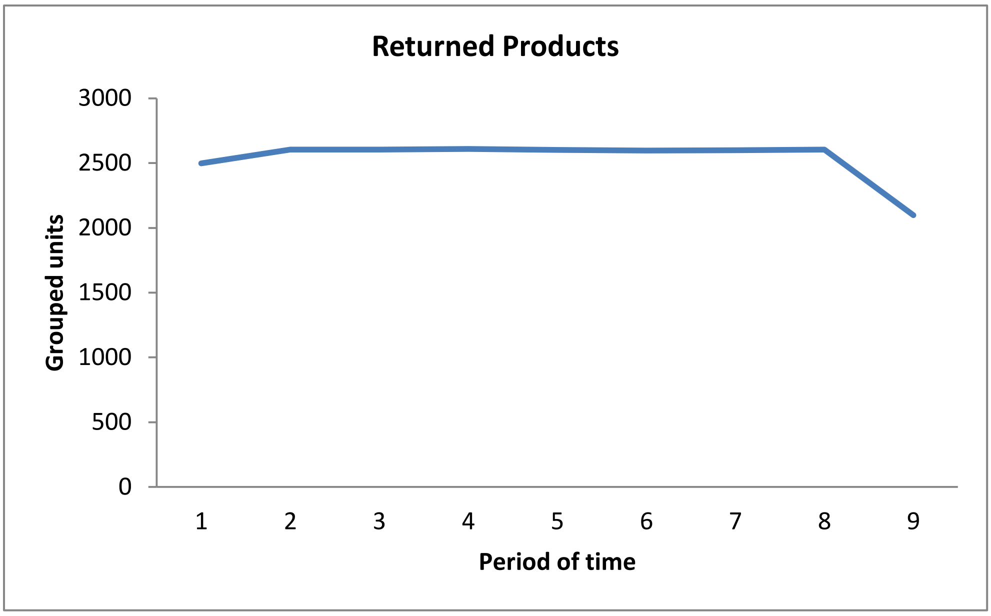

Figure 7.14 Grouped returned products at Company B

There was no manufacturing process in this model so the total cost for the whole system was equal to total cost at the RC. Total cost at the RC was the sum of holding cost, sorting cost, disassembly cost, refurbishment cost, testing cost, scrapping cost and transportation cost to second market and landfill. See Appendix B for an excel calculation spreadsheet. Total cost for the whole system was calculated based on equation 6.7 below, reproduced from Chapter 6:

$$
\begin{aligned}
Total\ cost \\
&= \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{rit}H1_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RB_{rit}BC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RF_{rit}DC_{rit} \\
&+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RF_{rit}FC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RF_{rit}TC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RS_{rit}SC_{rit} \\
&+ \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RSM_{roit}\, T1_{roit} + \sum_{r=1}^{R}\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T} RL_{rlit}\, T2_{rlit}
\end{aligned}
$$

Equation 6.7

Where:

$$\text{Total holding cost} = \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{rit}H1_{rit}$$

$$\text{Total sorting cost} = \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RB_{rit}BC_{rit}$$

$$\text{Total disassembly cost} = \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RF_{rit}DC_{rit}$$

$$\text{Total refurbishment cost} = \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RF_{rit}FC_{rit}$$

$$\text{Total testing cost} = \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RF_{rit}TC_{rit}$$

$$\text{Total scrapping cost} = \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RS_{rit}SC_{rit}$$

$$\text{Total transportation cost to second market} = \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RSM_{roit}\, T1_{roit}$$

$$\text{Total transportation cost to landfill} = \sum_{r=1}^{R}\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T} RL_{rlit}\, T2_{rlit}$$

Part of a worksheet for Model B is shown in Figure 7.15. In Figure 7.15, column one is the time period and column two is the number of units returned in that period. Column three shows the holding cost for each returned unit and column four shows total holding cost in the warehouse. Column five shows the number of units that will be sorted and the cost associated with it is shown in column six. Column seven shows the total sorting cost. Column eight shows the number of products to be disassembled and column nine shows the cost associated with assembling the product. Column ten shows the total disassembly cost.

1	2	3	4	5	6	7	8	9	10
Period	Unit Returned	Warehouse		Sorting			Disassembly		
		Holding Cost	Total Cost	Unit	sorting cost	total cost	Unit	Cost	Total Cost
0	0	10	0	0	15	0	0	20	0
1	100	10	998	0	15	1496	0	20	0
2	100	10	999	100	15	1499	90	20	1796
3	100	10	999	100	15	1498	90	20	1799
4	99	10	986	100	15	1479	90	20	1797
5	101	10	1009	99	15	1513	89	20	1775
6	100	10	997	101	15	1496	91	20	1816
7	101	10	1010	100	15	1515	90	20	1795
8	97	10	972	101	15	1458	91	20	1818
9	98	10	983	97	15	1474	88	20	1750
10	100	10	1001	98	15	1502	88	20	1769

Figure 7.15 Part of worksheet screenshots for Model B

Figure 7.16 shows a graph for the total cost of the whole system in Model B.

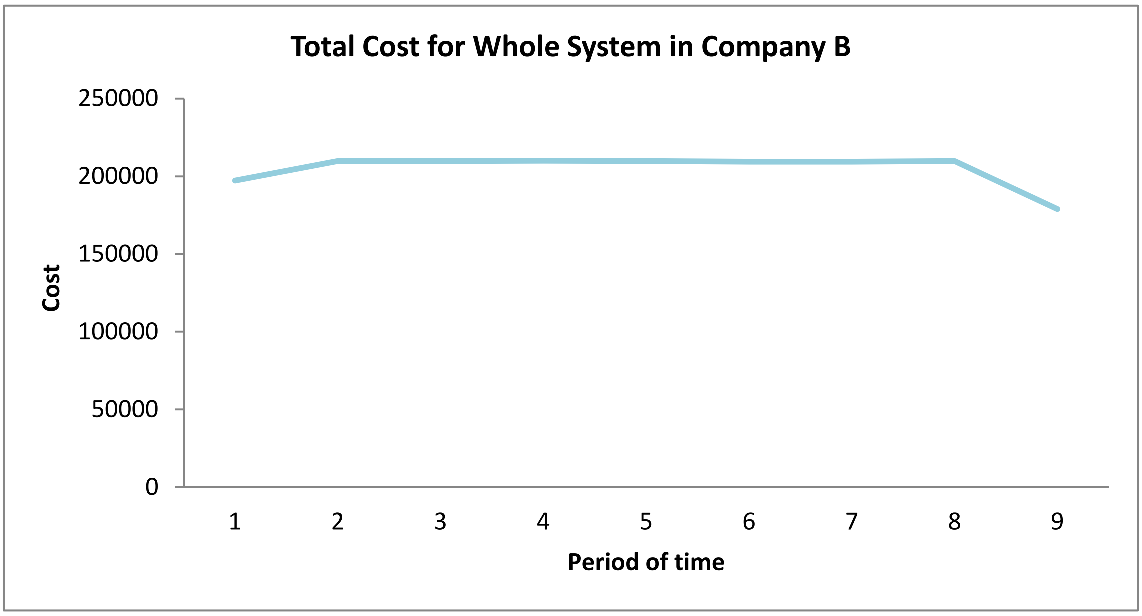

Figure 7.16 Total cost of whole system for Model B

To compare how returned products affected the system, the model was run with a low number of returned products and with a high number of returned products. High number of returned products was a set of data that was generated using a random number generator, and low number of returned products was 10% of the high number of returned products. In this model, landfill was the end of disposal place and needed to be paid as a fixed cost. Figure 7.17 shows a graph for the total cost in Company B with low returned products.

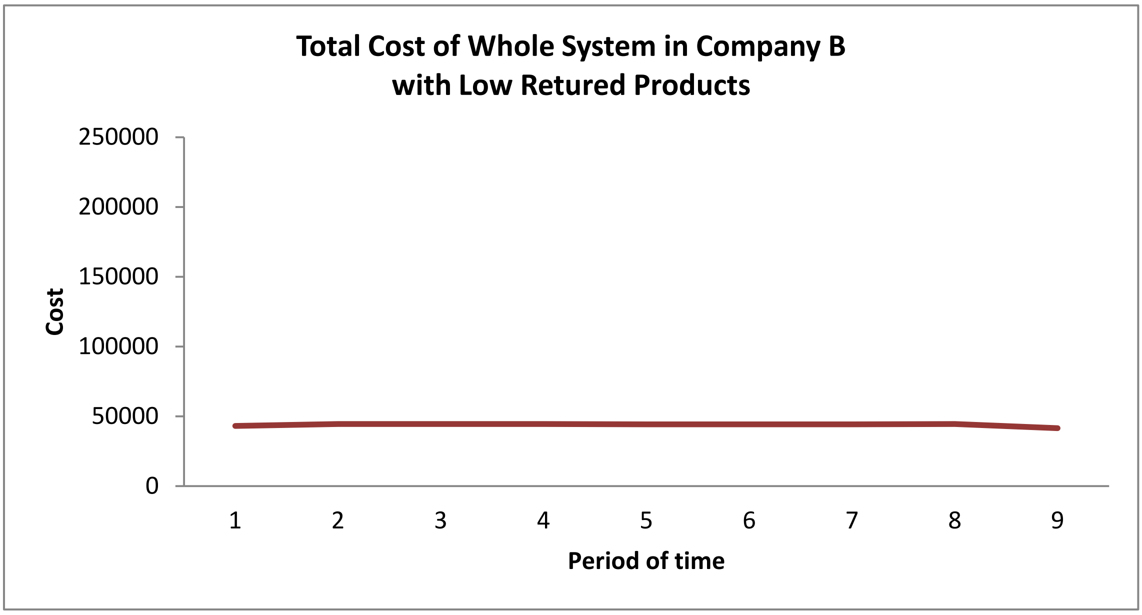

Figure 7.17 Total cost of whole system with low returned products for Model B

Figure 7.18 shows a comparison of a lower number of returned products with a higher number of returned products.

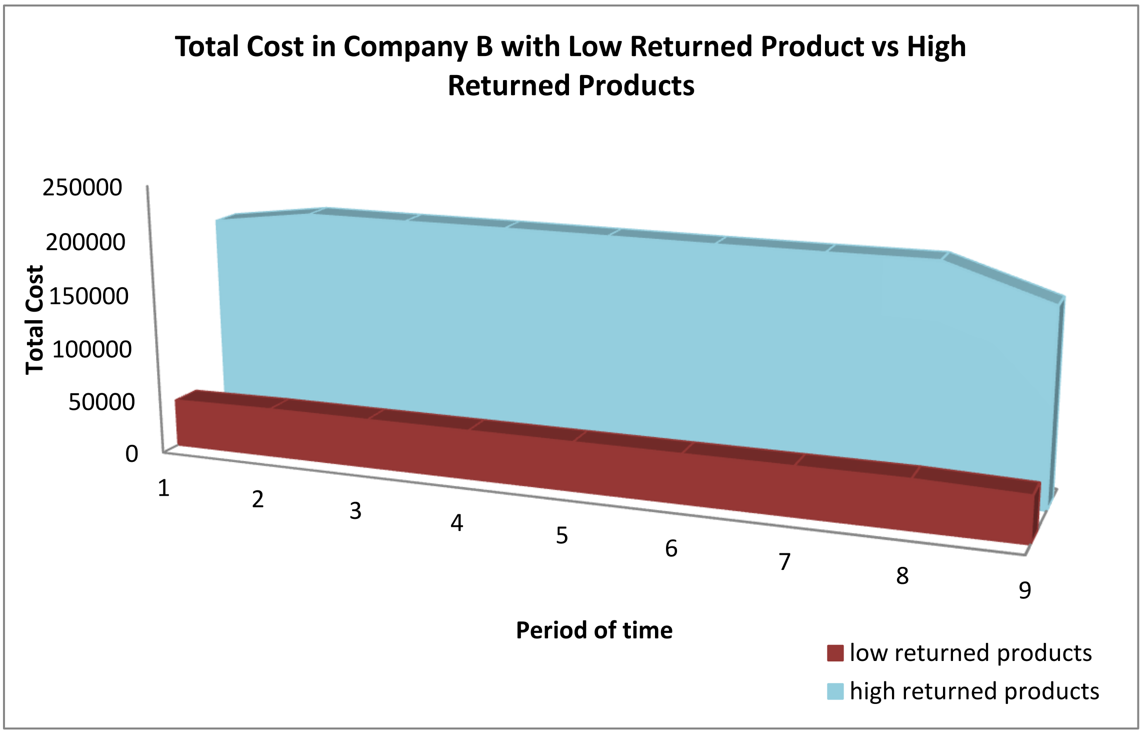

Figure 7.18 Low Returned Products vs High Returned Products in Model B

Figure 7.18 suggests that an increase in the number of returned products would add more cost to the system. However, that did not mean a returned product was not important. This company was dealing with end of life cycle products and/or was bound by environmental regulations to be responsible for their/other company end of life products.

The returned products were still important to the company, and minimising cost for the whole process could still be an objective of the company. In this model, landfill cost and refurbishment cost need to be investigated further. Optimising landfill rather than cost might be considered.

7.3 Model C

An Excel program was produced to represent the model of Company C. Demand for Company C was based on personal computer shipment data that was included in a press release by IDC Research Inc (IDC, 2016). Table 7.2 shows personal computer shipment for five top vendors.

Table 7.2 Top 5 Vendors: Europe, the Middle East, and Africa (EMEA) Personal Computer Shipments 2Q15 (Preliminary) (000 Units) (IDC, 2016)

Vendor	2Q14 Shipments	2Q15 Shipments	2Q14 Share	2Q15 Share	2Q15/2Q14 Growth
HP	4,735	3,921	21.6%	22.8%	-17.2%
Lenovo	3,947	3,366	18.0%	19.6%	-14.7%
Dell	2,277	2,011	10.4%	11.7%	-11.7%
ASUS	2,057	1,624	9.4%	9.4%	-21.1%
Acer Group	2,534	1,464	11.5%	8.5%	-42.2%
Others	6,388	4,822	29.1%	28.0%	-24.5%
Total	**21,938**	**17,207**	**100.0%**	**100.0%**	**-21.6%**

Source: *IDC EMEA Quarterly PC Tracker*, Preliminary Results, 2Q15, July 2015

Personal Computer = desktops and notebooks

Based on Table 7.2 there were 21,938,000 units being shipped to Europe, Middle East and Africa in 2014. This number was used as a base for the demand. In order to create an approximation that added to 21,938,000 the lowest demand was experimentally set to 25,000 per month and the highest number of products demanded was set to 150,000. Figure 7.19 shows the set of data produced by the random number generator for demanded products.

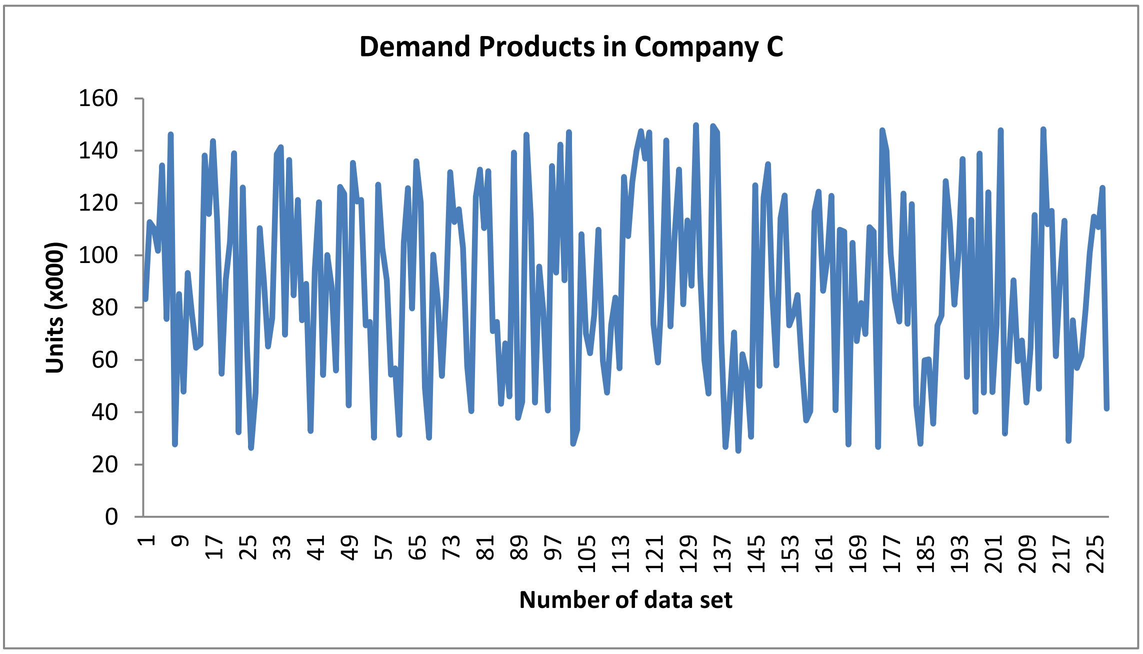

Figure 7.19 Demanded products in Company C using random generator number

In the same way as for Model A and B, this model was grouped to filter and smooth the data to be able to extract information from the data. Figure 7.20 shows demanded products for Company C in each grouped period of time.

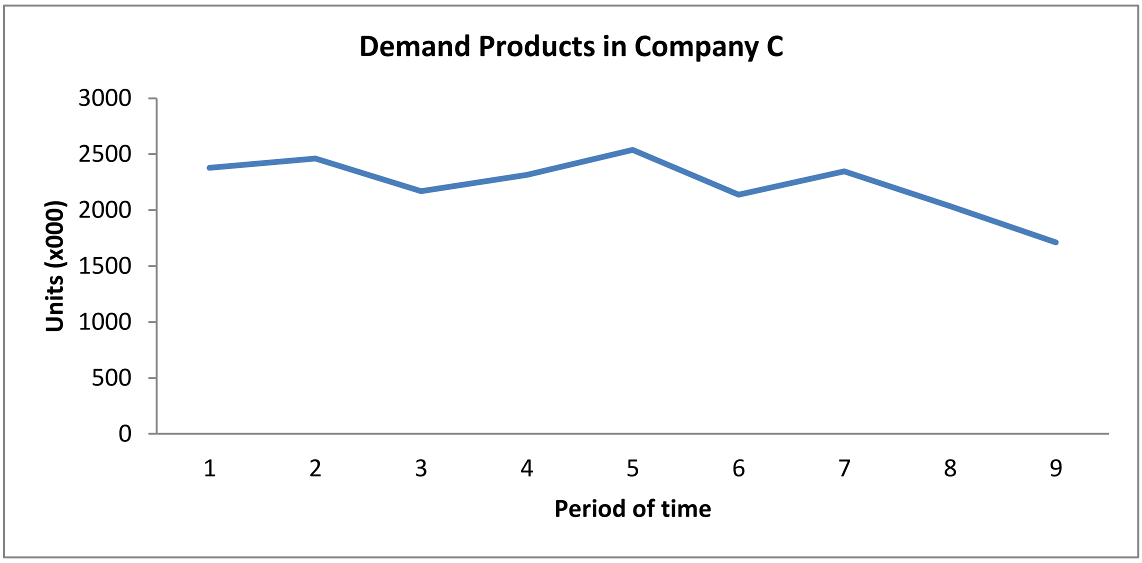

Figure 7.20 Grouped demanded units for Company C

Returned units in Company C were entered into the spreadsheet based on demand in Company C. The number of returned products was set to 90% of demand for each period of time. Figure 7.21 shows returned products based on the number of demanded products.

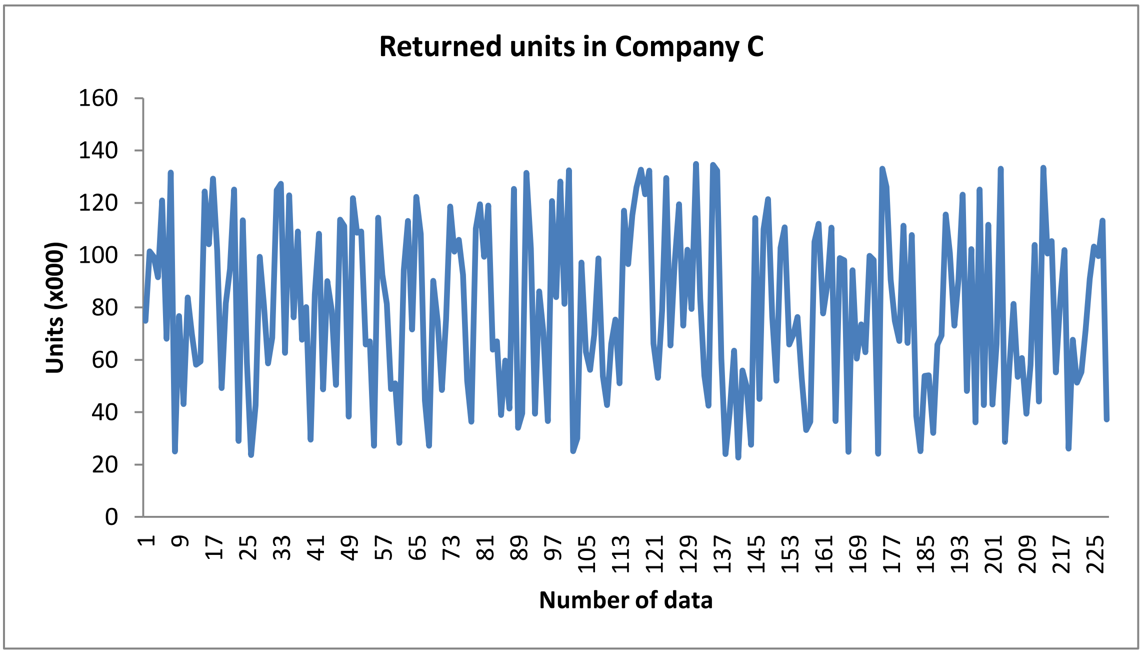

Figure 7.21 Returned units in Company C created using a random number generator

Returned product data also needed to be grouped. Figure 7.22 shows grouped data for returned products in Company C.

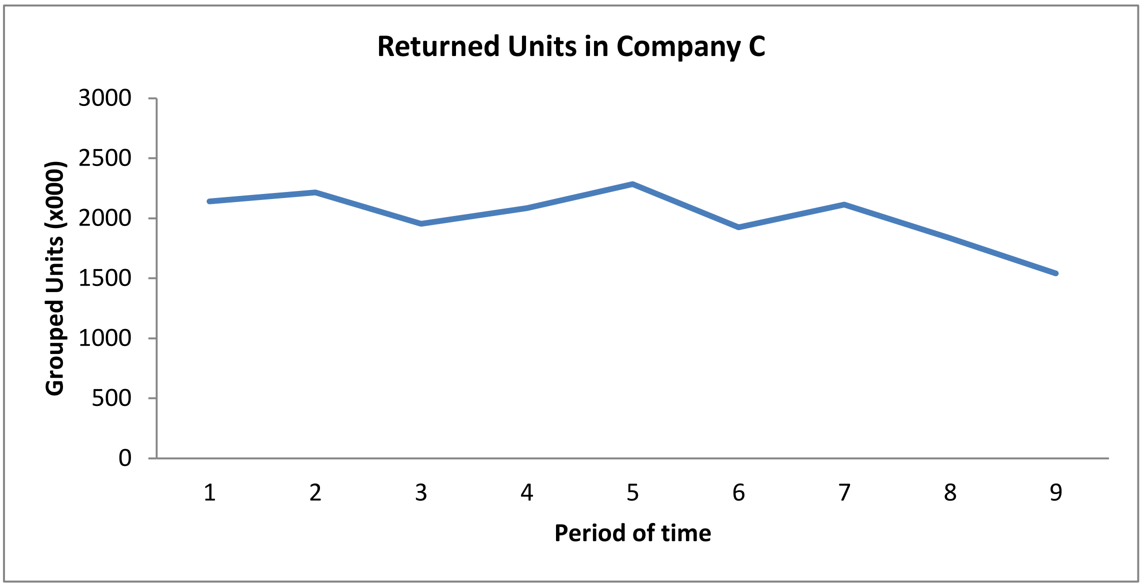

Figure 7.22 Grouped returned units for Company C

The demand was applied to the mathematical model to see how the cost was affected by returned products. The model was tested with a low number of returned products and a high number of returned products. The low number of returned products was 10% of the high number of returned products. Total cost for the whole system in Company C was based on equation 6.14 from Chapter 6:

$$
\begin{aligned}
&Total\ cost\ for\ Company\ C \\
&= \sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{zit}\, BC1_{rit} + \sum_{z=1}^{Z}\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RU_{zrit}\, T1_{zrit} \\
&+ \sum_{z=1}^{Z}\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T} RO_{zlit}\, T2_{zlit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RC_{rit}H1_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RC_{rit}BC2_{rit} \\
&+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}RC1_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}TC1_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}KC_{rit} \\
&+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RD_{rit}DC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{rit}RC2_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RS_{8rit}SC_{rit} \\
&+ \sum_{r=1}^{R}\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T} RJ_{rlit}T3_{rlit} + \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{roit}T4_{roit} \\
&+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{rit}H2_{rit} + \sum_{r=1}^{R}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{rmit}T5_{rmit} \\
&+ \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RW1_{roit}T6_{roit} + \sum_{r=1}^{R}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} RW2_{rmit}T7_{rmit} \\
&+ \sum_{m=1}^{M}\sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{t=1}^{T} PU1_{msit}NC1_{msit} + \sum_{m=1}^{M}\sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{t=1}^{T} PU2_{msit}NC2_{msit} \\
&+ \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU3_{mit}H3_{mit} + \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU4_{mit}H4_{mit} \\
&+ \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU5_{mit}PC_{rit} + \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU6_{mit}H5_{mit} \\
&+ \sum_{m=1}^{M}\sum_{d=1}^{D}\sum_{i=1}^{I}\sum_{t=1}^{T} PU7_{mdit}T8_{mdit}
\end{aligned}
$$

Equation 6.14

Where:

Total sorting cost at collection points $= \sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{zit}\ BC1_{rit}$

Total transportation cost from collection point to landfill $= \sum_{z=1}^{Z}\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RU_{zrit}\ T1_{zrit}$

Total transportation cost from collection point to RCs $= \sum_{z=1}^{Z}\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T} RO_{zlit}\ T2_{zlit} +$

Total holding cost at recovery centre $= \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RC_{rit}H1_{rit}$

Total sorting cost at recovery centre $= \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RC_{rit}BC2_{rit}$

Total refurbisment cost for resalable product at RC $= \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}RC1_{rit}$

Total testing cost for resalable product at recovery centre $= \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}TC1_{rit}$

Total repackaging cost for resalable product at RC $= \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}KC_{rit}$

Total disassembly cost at recovery centre $= \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RD_{rit}DC_{rit}$

Total refurbishment cost for part at recovery centre $= \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{rit}RC2_{rit}$

Total scrapping cost at recovery centre $= \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RS_{8rit}SC_{rit}$

Total transportation cost of residue from RC to landfill $= \sum_{r=1}^{R}\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T} RJ_{rlit}T3_{rlit}$

Ttransportation cost of resalable products from RC to second markets

$$= \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{roit}T4_{roit}$$

Total holding cost for reusable parts at recovery centre $= \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{rit}H2_{rit}$

Transportation cost of reusable parts from RC to MP $= \sum_{r=1}^{R}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{rmit}T5_{rmit}$

Transportation cost of raw material from RC to second market

$$= \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RW1_{roit}T6_{roit}$$

Transportation cost of raw material from RC to MP $= \sum_{r=1}^{R}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} RW2_{rmit}T7_{rmit}$

Total purcashing cost for parts $= \sum_{m=1}^{M}\sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{t=1}^{T} PU1_{msit}NC1_{msit}$

Total purchasing cost for raw materials $= \sum_{m=1}^{M}\sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{t=1}^{T} PU2_{msit}NC2_{msit}$

Total holding cost of parts at manufacture plant $= \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU3_{mit}H3_{mit}$

Total holding cost of raw materials at manufacture plant $= \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU4_{mit}H4_{mit}$

Total production cost $= \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU5_{mit}PC_{rit}$

Total holding cost of final product $= \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU6_{mit}H5_{mit}$

Total transportation cost to distributor $= \sum_{m=1}^{M}\sum_{d=1}^{D}\sum_{i=1}^{I}\sum_{t=1}^{T} PU7_{mdit}T8_{mdit}$

Part of a worksheet for Model C is shown in Figure 7.23. In Figure 7.23, column one is the time period and column two is the number of units returned in that period. Column three shows the sorting cost for each returned unit and column four shows total sorting cost in the collection point. Column five shows the number of units that will be sent to the RC and the transportation cost associated with it is shown in column six. Column seven shows the total transportation cost to RC. Column eight shows the number of units sent to landfill and the transportation cost associated with it is shown in column nine. Column ten shows the total transportation cost to landfill. Column eleven shows the total cost for each period of time.

1	2	3	4	5	6	7	8	9	10	11
Period	Unit returned	Sorting		To Recycling Centre			To Landfill			Total Cost
		cost (£)	total (£)	unit	transport	total cost	unit	transport	total cost	
0	0	0.2	0	0	0.5	0	0	0.3	0	0
1	75	0.2	15	67	0.5	34	8	0.3	2	50
2	101	0.2	20	91	0.5	46	10	0.3	3	68
3	99	0.2	20	89	0.5	45	10	0.3	3	67
4	92	0.2	18	82	0.5	41	10	0.3	2	62
5	121	0.2	24	108	0.5	54	13	0.3	3	81
6	68	0.2	14	61	0.5	31	7	0.3	2	46
7	132	0.2	26	118	0.5	59	14	0.3	3	89

Figure 7.23 Part of worksheet screenshot for Model C at Collection Point

Total cost per period of time can be seen in Figure 7.24 for the high number of returned products and Figure 7.25 for the low number of returned products.

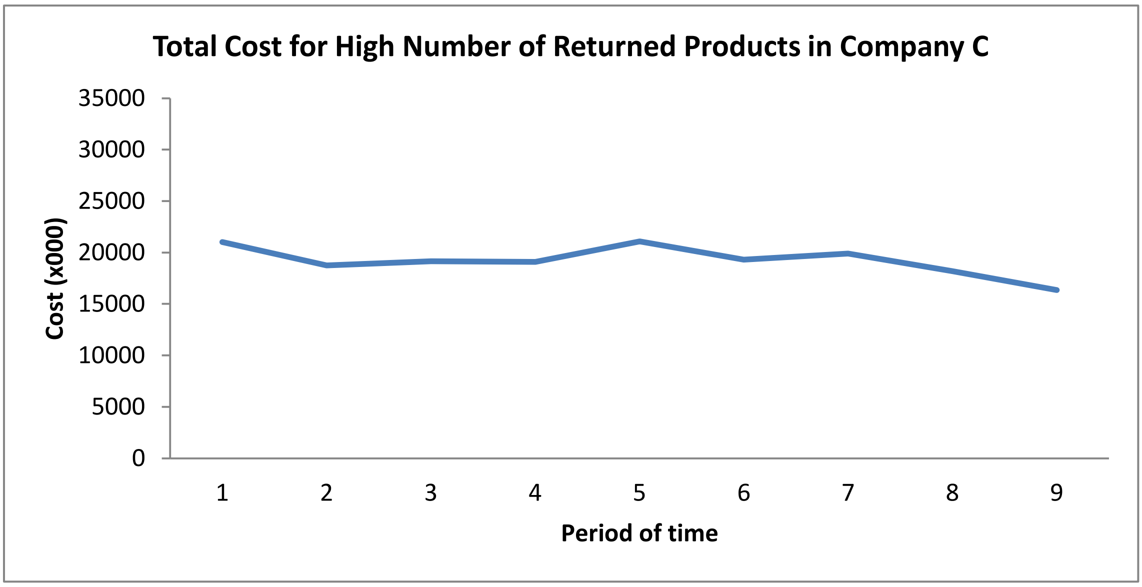

Figure 7.24 Total cost for a high number of returned products

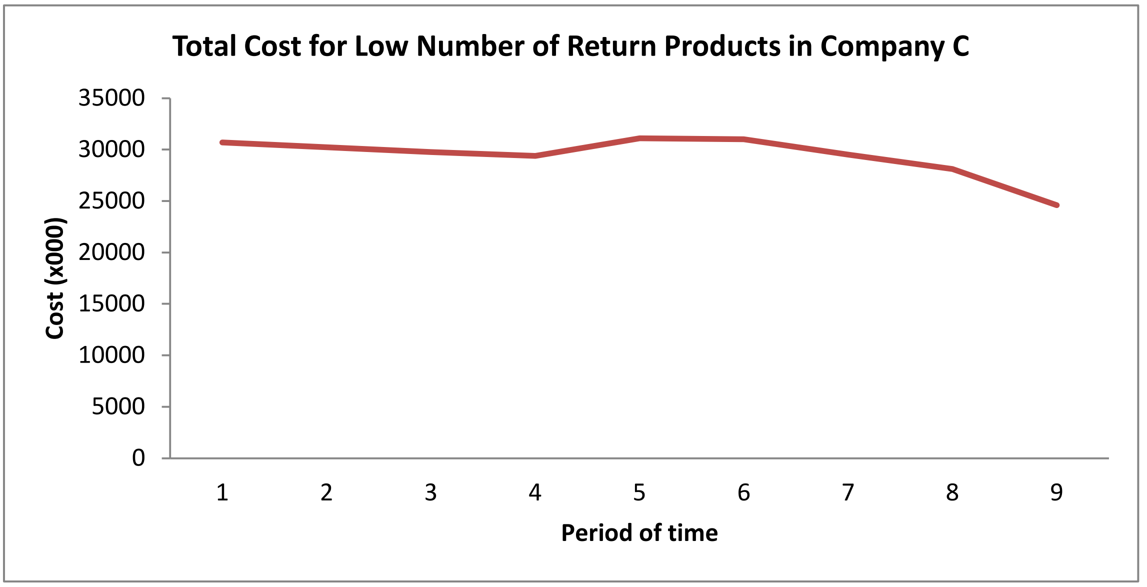

Figure 7.25 Total cost for low number of returned products

With the same demand, total cost was different for each. Returned products significantly affected total cost. The difference between a high number compared with a low number of returned products affected the total cost as shown in Figure 7.26.

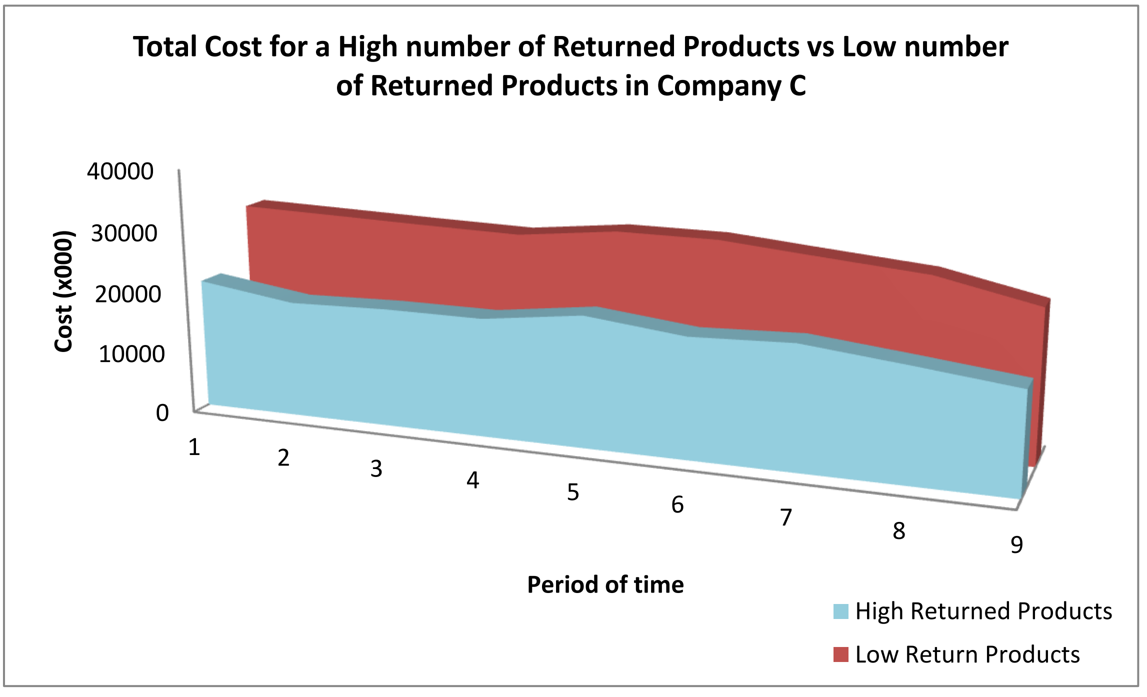

Figure 7.26 Total cost for high number of returned product vs low return in Company C

Cost for a low return product flow was lower than the cost for a high return product flow. Total cost for a low returned product flow was lower than for a high returned product flow. In future work an actual profit from selling the raw material from the scrapping process needs to be added to see how it affects RC costs. In addition, resalable products could be investigated.

Figure 7.25 shows that a high returned product flow lowered the total cost compared to a low returned product flow. With reusable parts and engines from the RC, new parts procurement would be reduced. That could lead to lower cost and more effective supply chain performance. The model needs some improvement, for example:

- Primary data could be improved.
- The model needs to know sale prices to second market and distributors to see how they affect profit.
- The part of the process that most affects total cost could be investigated.

This is the first time that an attempt to measure performance of RSCs in the computer hardware industry has been published. Most of the literature covering the computer industry focused on RSCs only mentions metrics and none of the references described how to measure performance. Most references only focused on a RC without considering the re-manufacturing process. In this research, simple, new mathematical models are presented that include re-manufacturing processes.

In the future, more could be explored, such as: which process in a RSC affects the systems performance the most and how to measure the performance of a RSC with environmental regulation as the objective.

7.4 Model D

Company D did not have a manufacturing process. In this company, returned products were divided based on where the supplier was as well as the value of the products. Returned product data was generated using a random number generator from Excel with a mean of 500, and 217 was selected as the numbers of sets of data. A graph of returned products is shown in Figure 7.27.

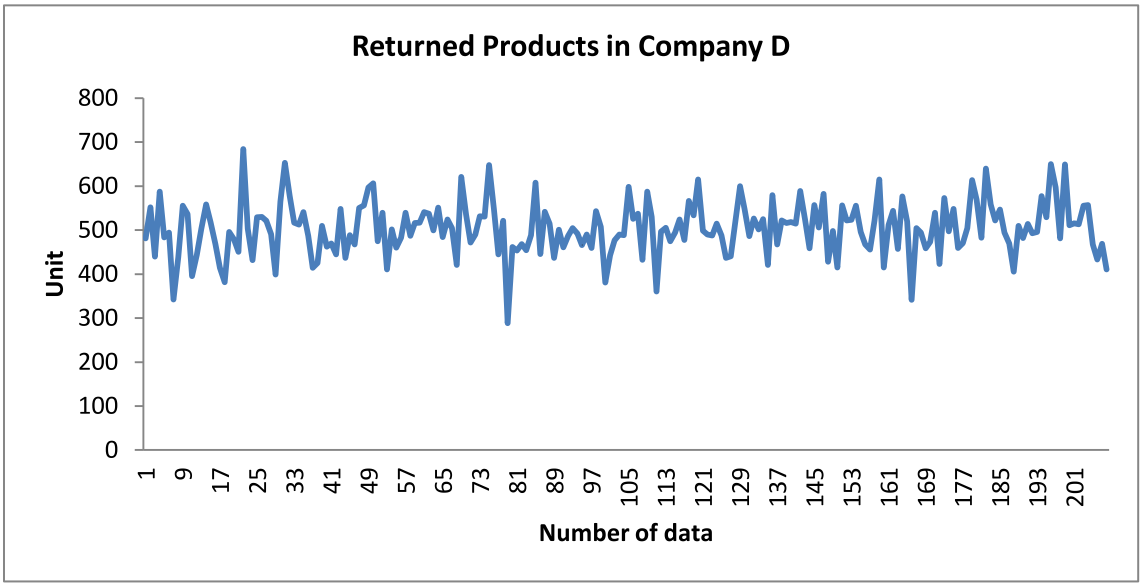

Figure 7.27 Returned units in Company D created using a random number generator

The data was grouped and the result is shows in Figure 7.28.

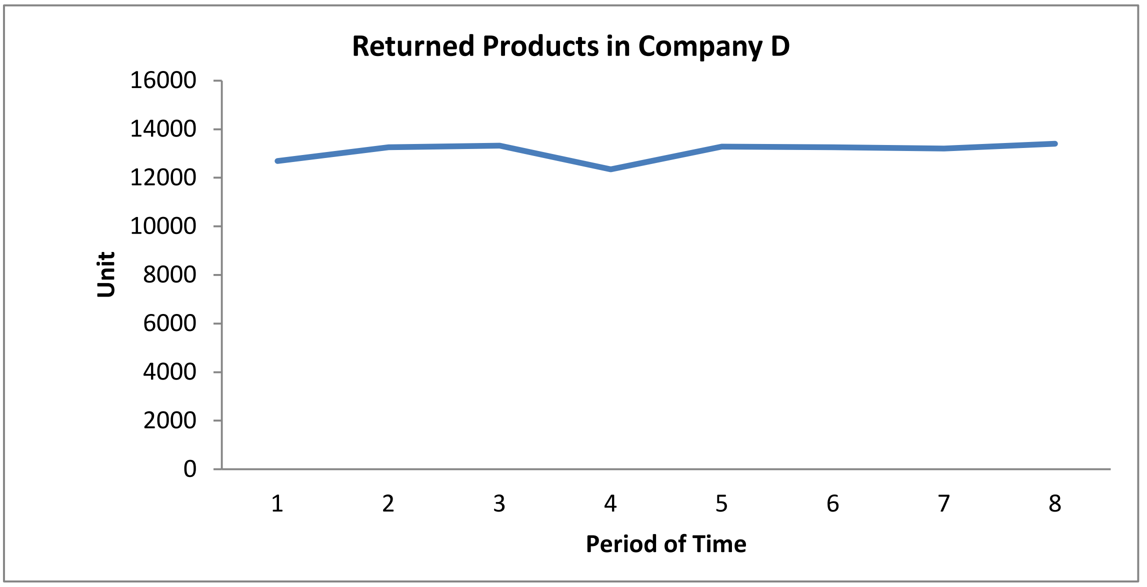

Figure 7.28 Grouped returned products in Company D

Total cost for the whole system was a summation of total cost at the collecting point and Recovery Centre (RC). Model D had two collecting points: a shop and a collection point (CP). Products from local suppliers were sent back once they arrived at a shop (where a customer usually returned the products directly). Therefore, total cost was a summation of sorting cost, holding cost and transportation cost to second markets in both places.

High value products were sorted into two types in the RC: resalable products and un-resalable products. Total cost in the RC was a summation of sorting cost for both types: disassembly cost for un-resalable products to get useful parts; and refurbishment and testing cost for both useful parts and resalable products. Scrapping cost was the cost of getting raw materials from other parts than useful parts. Re-packaging cost was needed in order to increase the value of resalable products. Transportation costs for parts, re-packaging products and raw materials to second market were added to the total cost for the whole system. The equation for total cost in Company D is described by equation 6.19 reproduced from Chapter 6:

$Total\ cost\ at\ company\ D$

$$= \sum_{y=1}^{Y}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{yit}BC1_{yit}$$

$$+ \sum_{s=1}^{Y}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RLS_{yoit}\,T1_{yoit} + \sum_{y=1}^{Y}\sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T} RFE_{yzit}\,T2_{yzit}$$

$$+ \sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T} REF_{zit}H1_{zit} + \sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T} REF_{zit}BC2_{zit}$$

$$+ \sum_{z=1}^{Z}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RLV_{zoit}\,T3_{zoit} + \sum_{z=1}^{Z}\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RHV_{zrit}\,T4_{zrit}$$

$$+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RHV_{rit}H2_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RHV_{rit}BC3_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}RC1_{rit}$$

$$+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RD_{rit}DC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{rit}RC2_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RS_{rit}SC_{rit}$$

$$+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}TC1_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{rit}TC2_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}KC_{rit}$$

$$+ \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{roit}\,T5_{roit} + \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{roit}\,T6_{roit}$$

$$+ \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RW_{roit}\,T7_{roit} + \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RJ_{roit}\,T8_{roit}$$

Equation 6.18

Where

$$\text{Total sorting cost at shop} = \sum_{y=1}^{Y}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{yit}BC1_{yit}$$

$$\text{Total transportation cost from shop to second market} = \sum_{y=1}^{Y}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RLS_{yoit}\,T1_{yoit}$$

$$\text{Total transportation cost from shop to collection point} = \sum_{y=1}^{Y}\sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T} RFE_{yzit}\,T2_{yzit}$$

Total holding cost at collection point = $\sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T} REF_{zit}H1_{zit}$

Total sorting cost at collection point = $\sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T} REF_{zit}BC2_{zit}$

Transportation cost from CP to 2nd market = $\sum_{z=1}^{Z}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RLV_{zoit}T3_{zoit}$

Total transportation cost from collection point to RC = $\sum_{z=1}^{Z}\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RHV_{zrit}T4_{zrit}$

Total holding cost at recovery centre = $\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RHV_{rit}H2_{rit}$

Total sorting cost at recovery centre = $\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RHV_{rit}BC3_{rit}$

Total refurbisment for resalable products = $\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}RC1_{rit}$

Total disassembly cost at recovery centre = $\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RD_{rit}DC_{rit}$

Total refurbisment for useful parts = $\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{rit}RC2_{rit}$

Total srapping cost = $\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RS_{rit}SC_{rit}$

Total testing cost for resalable products = $\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}TC1_{rit}$

Total testing cost for reusable parts = $\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{rit}TC2_{rit}$

Total repackaging cost for resalable products = $\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit}KC_{rit}$

Transportation cost for resalable products from RC to second market

$$= \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{roit}\, T5_{roit}$$

Transportation cost for useful parts from RC to second market

$$= \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{roit}\, T6_{roit}$$

Transportation cost for raw material from RC to second market

$$= \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RW_{roit}\, T7_{roit}$$

Transportation cost for disposal from RC to second market

$$= \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RJ_{roit}\, T8_{roit}$$

Part of a worksheet for Model D is shown in Figure 7.29. In Figure 7.29, column one is the time period and column two is the number of units returned in that period. Column three shows the sorting cost for each returned unit and column four shows total sorting cost in the shop. Column five shows the number of units that will be sent to second market and the transportation cost with associated with it shows in column six. Column seven shows the total transportation cost to the second market. Column eight shows the number of units that will be sent to collection point and the transportation cost with associated with it shows in column nine. Column ten shows the total transportation cost to the collection point.

1	2	3	4	5	6	7	8	9	10
Period	Unit Returned	Sorting		Transportation to second market			Transportation to Collecting point		
		Cost	Total Cost	Unit	Cost	Total Cost	unit	cost	total cost
0	0	2	0	0	1.5	0	0	2.5	0
1	481	2	962	48	1.5	72	433	2.5	1082
2	552	2	1104	55	1.5	83	497	2.5	1242
3	440	2	880	44	1.5	66	396	2.5	990
4	587	2	1174	59	1.5	88	528	2.5	1321
5	484	2	967	48	1.5	73	435	2.5	1088
6	494	2	989	49	1.5	74	445	2.5	1113
7	342	2	685	34	1.5	51	308	2.5	770
8	438	2	876	44	1.5	66	394	2.5	986

Figure 7.29 Worksheet screenshot for Model D at a Shop

Figure 7.30 shows the total cost of whole system representing Company D.

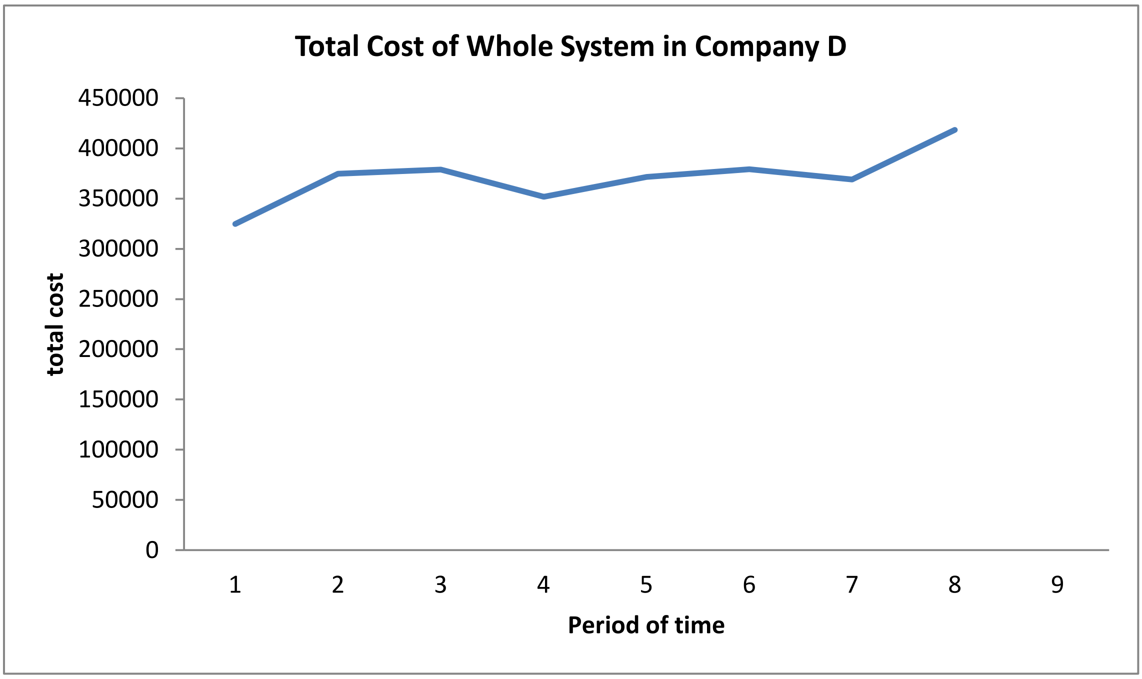

Figure 7.30 Total cost of whole system in Company D

To see how returned products affected the company, the total cost of the whole system with lower returned products was produced (see Appendix D for details). The low number of returned products was 10% of the number of high returned products. Figure 7.31 shows a comparison between both amounts of returned products.

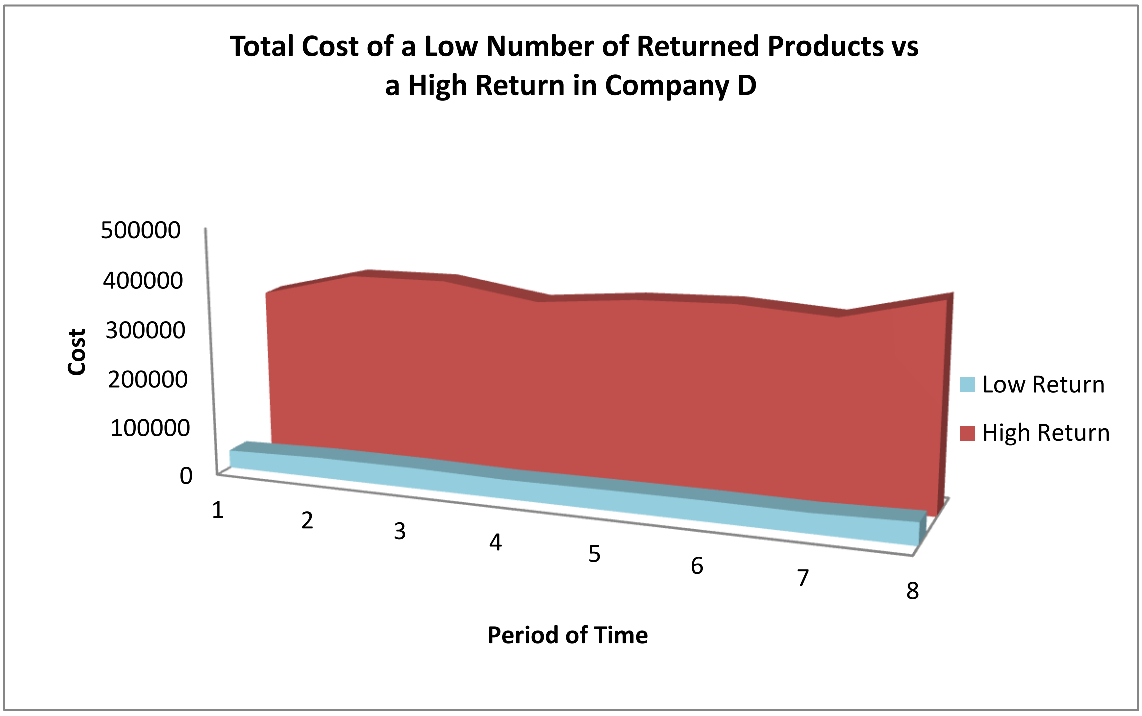

Figure 7.31 Total cost of a low number of returned product vs a high return in Company D

The selling price and profit for resalable products, parts and raw material was not included. The graph for company D is similar to company B. Models B and D do not have manufacturing processes. However, even though both models deal with returned products, they have different objectives. In Model B, the company was bound by environmental regulations, while company D wanted to make a profit. This model also lacked demand data for resalable products. In this model, the percentage of resalable units could be used as an important indicator of performance.

7.5 Model E

An Excel program was produced to represent the models of Company E. The number of returned products in Company E was generated using a random number generator in Excel. The number of data sets was set to 50. 20 was the lowest number of returned products and 100 was the highest number of returned products. Figure 7.32 shows a graph of returned products in Company E created using the random number generator.

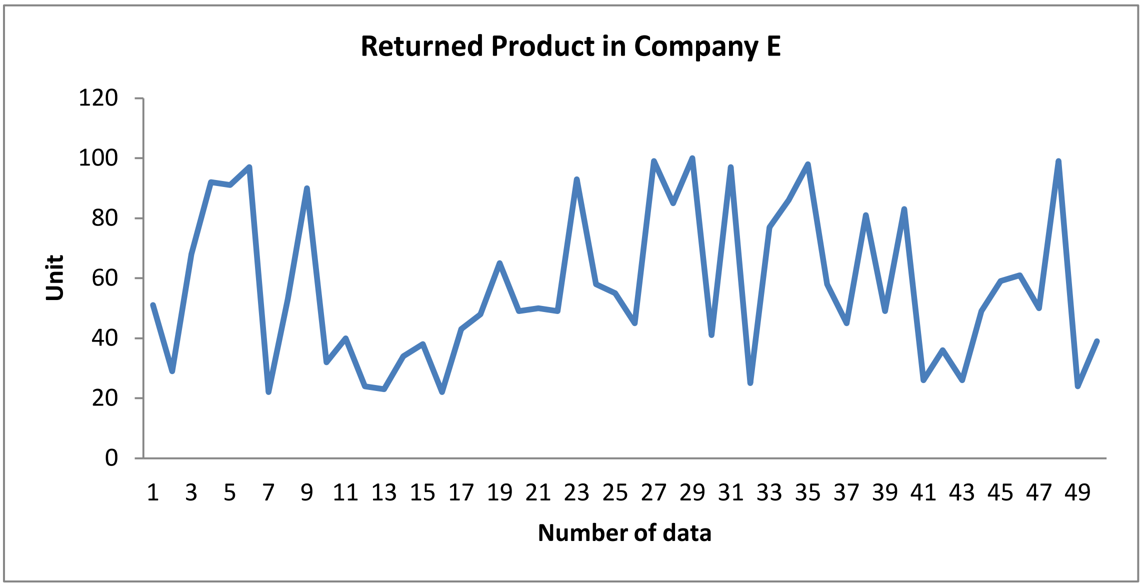

Figure 7.32 Returned units in Company E created using a random number generator

Figure 7.33 shows grouped returned product in Company E per period of time.

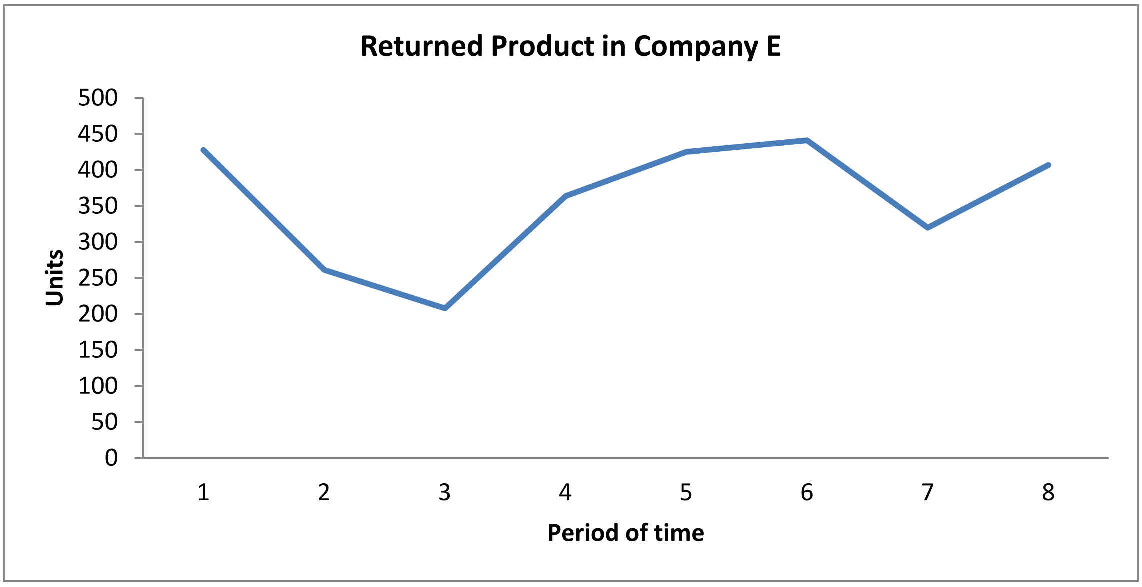

Figure 7.33 Returned products in Company E

Demand for the product was generated using a random number generator in Excel. With mean 50 and number of data sets set to 50, demand for products in Company E can be seen in Figure 7.34.

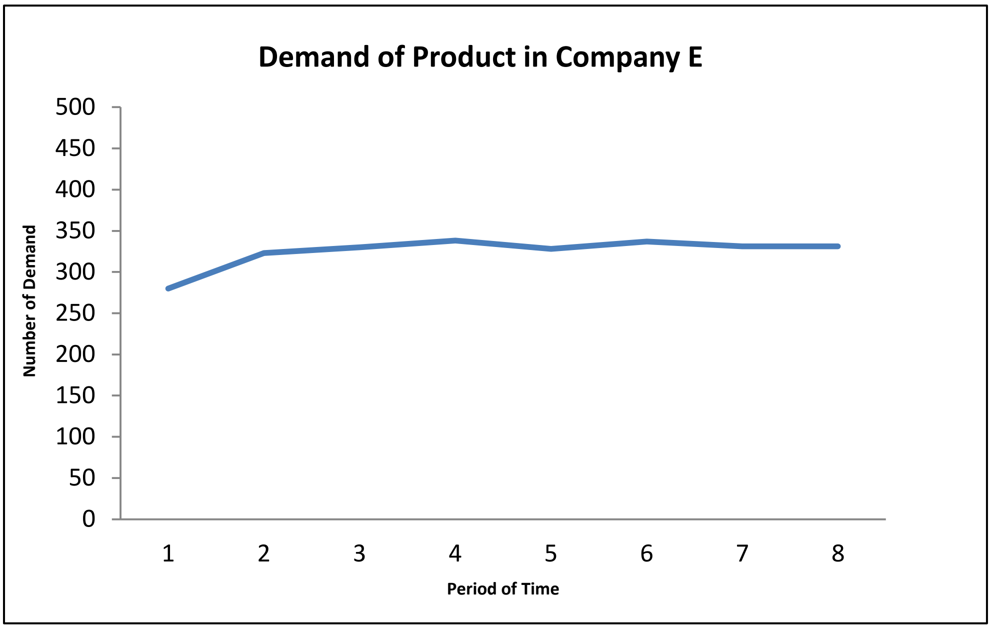

Figure 7.34 Demand of product in Company E

The demand was applied to the mathematical model to see how the cost was affected by returned products. The model was tested with a low number of returned products and a high number of returned products. The equation for total cost in Company E is equation 6.67 from Chapter 6:

$$
\begin{aligned}
&Total\ Cost \\
&= \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{rit}H1_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{rit}DC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RF_{rit}RC_{rit} \\
&+ \sum_{r=1}^{R}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} RM_{rmit}\,T1_{rmit} + \sum_{r=1}^{R}\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T} RL_{rlit}\,T2_{rlit} \\
&+ \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} RW_{mit}\,H2_{mit} + \sum_{m=1}^{M}\sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{t=1}^{T} RN_{msit}\,NC_{msit} + \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU1_{mit}PC_{mit} \\
&+ \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU2_{mit}H3_{mit} + \sum_{m=1}^{M}\sum_{d=1}^{D}\sum_{i=1}^{I}\sum_{t=1}^{T} PU3_{mdit}\,T3_{mdit}
\end{aligned}
$$

Equation 6.68

Where:

$$\text{Total cost } = \text{Total holding cost at recovery centre} = \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{rit}H1_{rit}$$

$$\text{Total disassembly cost} = \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{rit}DC_{rit}$$

$$\text{Total refurbishment cost} = \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RF_{rit}RC_{rit}$$

$$\text{Total transportation cost from RC to landfill } = \sum_{r=1}^{R}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} RM_{rmit}\, T1_{rmit}$$

$$\text{Total transportation cost from RC to MP for raw material} = \sum_{r=1}^{R}\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T} RL_{rlit}\, T2_{rlit}$$

$$\text{Total holding cost for raw materials at manufacturing plant} = \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} RW_{mit}\, H2_{mit}$$

$$\text{Total purcashing cost for raw materials} = \sum_{m=1}^{M}\sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{t=1}^{T} RN_{msit}\, NC_{msit}$$

$$\text{Total production cost} = \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU1_{mit}PC_{mit}$$

$$\text{Total holding cost of final product} = \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU2_{mit}H3_{mit}$$

$$\text{Total transportation cost to distributor} = \sum_{m=1}^{M}\sum_{d=1}^{D}\sum_{i=1}^{I}\sum_{t=1}^{T} PU3_{mdit}\, T3_{mdit}$$

Part of a worksheet for Model E is shown in Figure 7.35. In Figure 7.35, column one is the time period and column two is the number of units returned in that period. Column three shows the holding cost of the returned units and column four shows total cost for that. Column five shows the cost associated with assembling the product and column six shows the total cost for that. Column seven shows the number of units being refurbished and column eight shows the refurbishment cost. Column nine shows total cost for that. Column ten shows a number that represent the amount of nylon that was produced from refurbishment and column eleven shows a number that represent the amount of other material (other than nylon).

1	2	3	4	5	6	7	8	9	10	11
Period	Returned product	Warehouse		Disassembly process		Refurbish process			Raw Material Produced	
		cost	total cost	cost	total cost	unit	refurbish cost	total cost	nylon	other
1	0	0.1	0	0.5	0	0	1.5	0	0	0
2	51	0.1	5.1	0.5	0	0	1.5	0	0	0
3	29	0.1	2.9	0.5	25.5	0	1.5	0	0	0
4	68	0.1	6.8	0.5	14.5	45.9	1.5	68.85	0	0
5	92	0.1	9.2	0.5	34	26.1	1.5	39.15	41.31	4.59
6	91	0.1	9.1	0.5	46	61.2	1.5	91.8	23.49	2.61
7	97	0.1	9.7	0.5	45.5	82.8	1.5	124.2	55.08	6.12
8	22	0.1	2.2	0.5	48.5	81.9	1.5	122.85	74.52	8.28

Figure 7.35 Worksheet screenshot for Model E at Recovery Centre

Total cost per period of time can be seen in Figure 7.36 for the high number of returned products. In this graph total cost was high in the beginning period and slowly became lower due to the capacity of the disassembly process and batch production. Figure 7.37 for the low number of returned products.

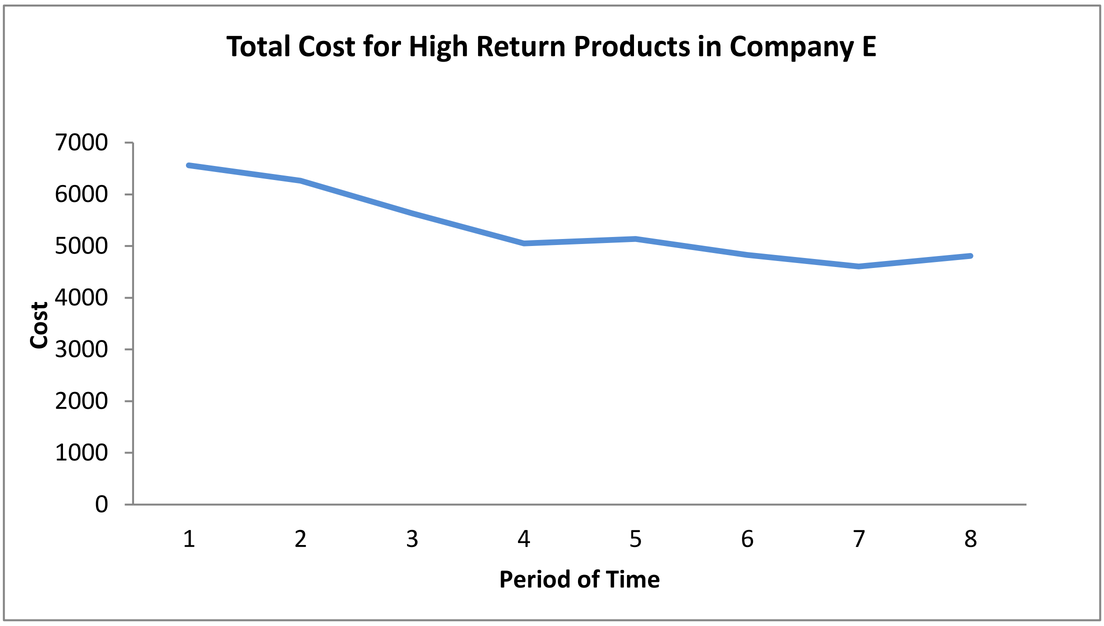

Figure 7.36 Total cost for a high number of returned products in Company E

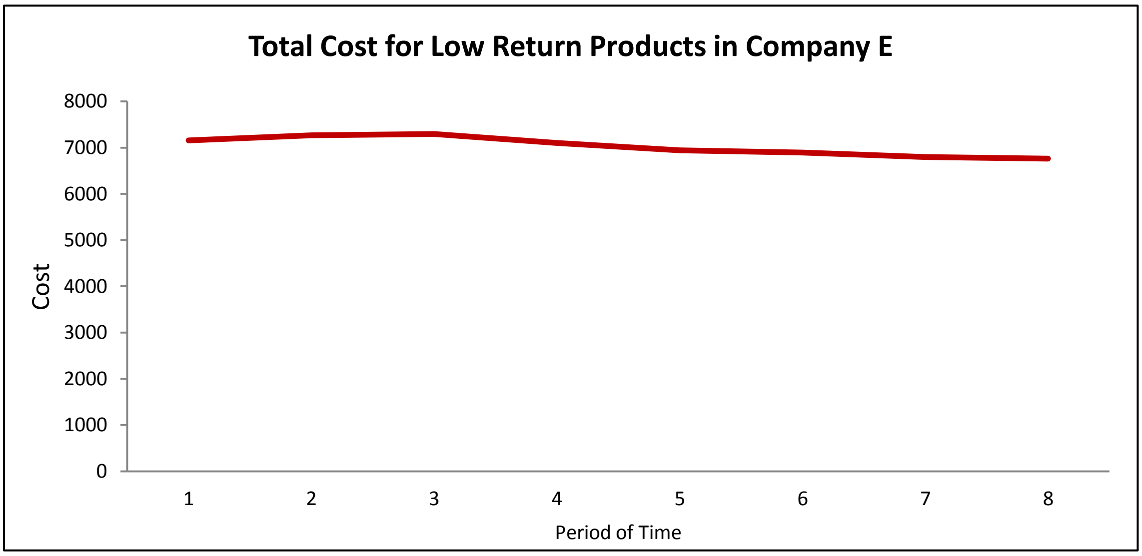

Figure 7.37 Total cost for a low number of returned products

With the same demand, total cost was different for each. Returned products significantly affected total cost. The difference between a high number of returns compared with a low number of returned products affected the total cost as shown in Figure 7.38.

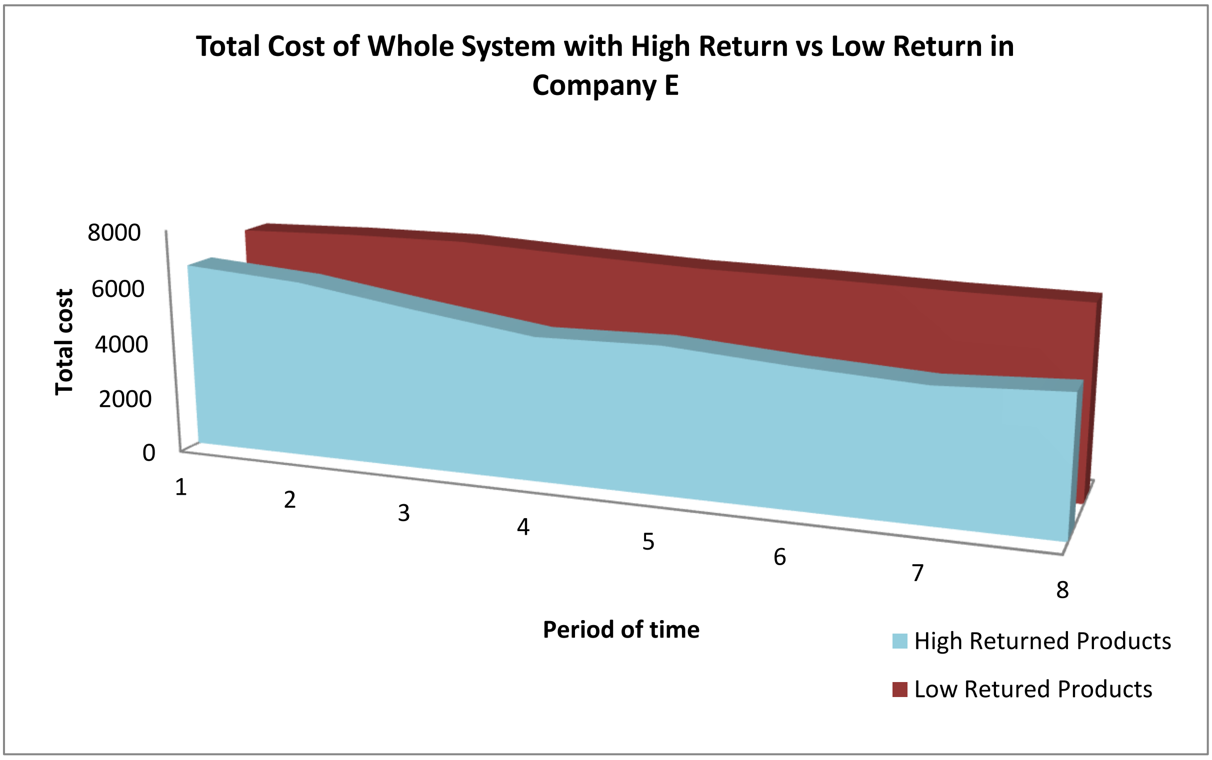

Figure 7.38 Total cost for high return vs low return product in Company E

Cost for a low return product flow was lower than the cost for a high return product flow. That is because there was no cost in the RC for a low return product flow.

In the RC, total cost for a low returned product flow was lower than for a high returned product flow. Therefore, in future work an actual profit from selling the raw material to a scrapping process could to be added to see how it affects RC costs, as well as how resalable products affect total cost.

The model could be improved, for example:

- Primary data could be improved.
- A real sale price to second market and distributors could be used to see how it affects profit.
- A more specific investigation could be carried out to identify which part of the process affects total cost the most.

This is the first time that an attempt to measure performance in a RSC of a carpet industry has been published. The simple mathematical model would allow a company to view their RSCs more easily as well as measure performance.

Most literature in the carpet industry focused on RSCs only mentions metrics and none of the references described how to measure performance. Most references only focused on a RC without considering the re-manufacturing process. In this Dissertation, new, simple mathematic models were presented.

In the future, more could be explored, such as: which process in the RSC affected the systems performance the most and how to measure the performance of a RSC with environmental regulation as the objective.

7.6 Type of Company

Comparing low returns and high returns in each company provided an overview of how RSC affected each company. That suggested six new general company types that could be used as RSC performance indicators. The following graphs describe six company types and could provide the first information to be used by a manager in a company.

Several comparisons between high numbers of returned products and low numbers of returned products were shown in this Chapter. The graphs showed how returned products affected the whole system in a company. Simplifying the graphs from these comparisons suggested six possible types of company:

- Sunny
- Cloudy High
- Cloudy Low
- Foggy
- Rainy High
- Rainy Low

These are described.

7.6.1. Sunny

Figure 7.39 shows a simplified comparison graph for Model C and Model E. In both models, a higher number of returned products lowered the whole system in the company. While a lower number of returned products increased the whole cost of the system. In this type a higher number of returned products tends to give a lower cost for whole system. The gap between total cost of the whole system for a higher number of returned products and a lower number of returned products is wide.

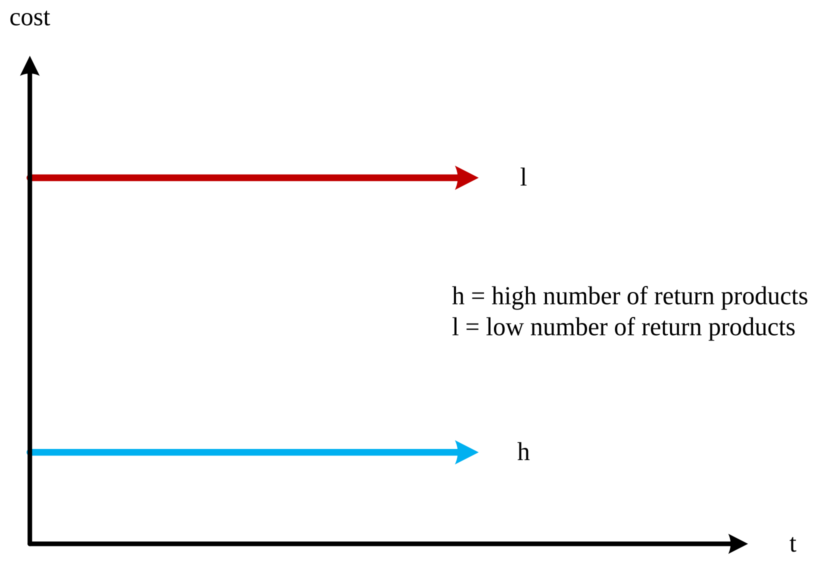

Figure 7.39 Comparison Graph in Company C and E (Sunny Graph)

From Figure 7.39:

- More returned products = less cost.
- Returned products can lower the cost.
- Reverse supply chain can make a profit for the company.

If a company had a Sunny Graph, returned products should be taken seriously as a new way to gain profit.

7.6.2. Cloudy

Figure 7.40 shows a simplified comparison graph of the whole system in Company A for returned products and without returned products. With a lower number of returned products the whole cost of the system was higher compared with a higher number of returned products but in both cases the cost were relatively high.

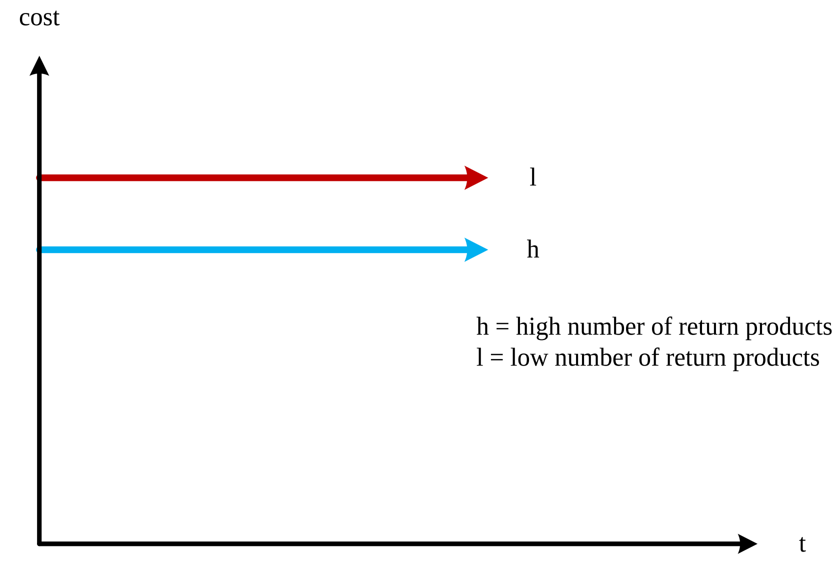

Figure 7.40 A Type A Company (Cloudy High Graph)

From Figure 7.40, for a Cloudy High company:

- More returned product = less cost.
- Returned product can lower the cost.
- High fixed cost.
- Since high fixed cost, usually the product needs high precision.

Another type of Cloudy Graph is shown in Figure 7.41 There is no company from among the case studies investigated during this research that represented a Cloudy Low company. In a Cloudy Low company, for a lower number of returned products the whole cost of the system would be higher compared with a higher number of returned products but both were in the range of low cost.

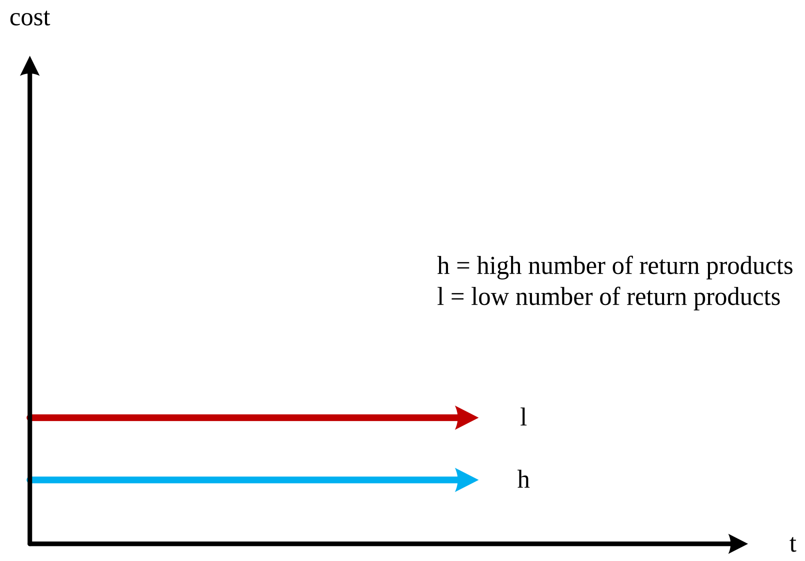

Figure 7.41 Graph E (Cloudy Low Graph)

From Figure 7.41, for a Cloudy Low company:

- More returned product = less cost.
- Returned product can lower the cost.
- Low fixed cost.

With a Cloudy Graph, a company should optimise their returned products.

7.6.3. Foggy

Figure 7.42 shows a comparison graph for models B and D. More returned products will increase cost. A lower number of returned products will reduce cost.

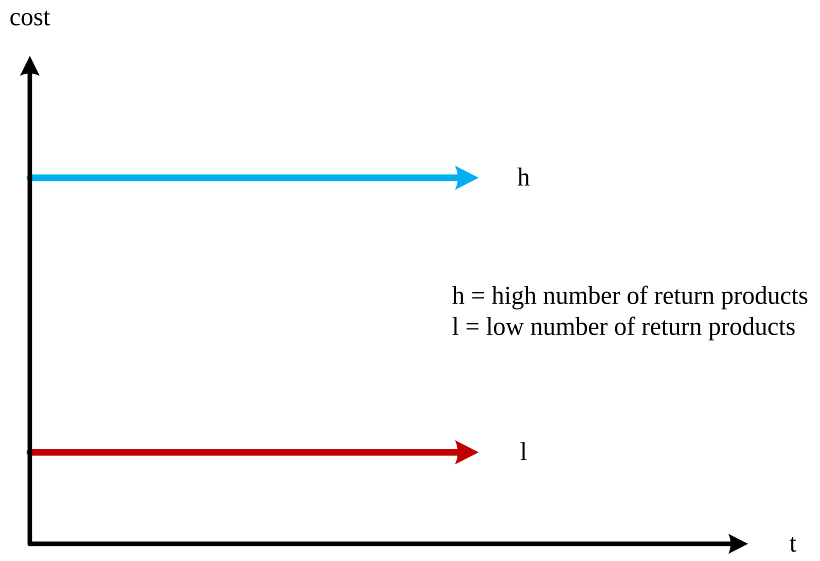

Figure 7.42 Comparison Graph between Total Cost in Company B and D (Foggy Graph)

From the graph based on Company B and D:

- More returned product = more cost.
- Returned products are not likely add profit to company.

However, more investigations would be needed if the company was:

- dealing with end-of-life products.
- bound by regulations.

If the company was dealing with end-of-life products or/and was bound to environmental regulations, the objective of the company could be to minimise cost. That could direct the pricing of products from the recovery centre to be sold in second market.

7.6.4. Rainy

A Rainy company incurs more cost when there are a higher number of returned products than when there is a lower number of returned products. Figure 7.43 shows a Rainy High Graph.

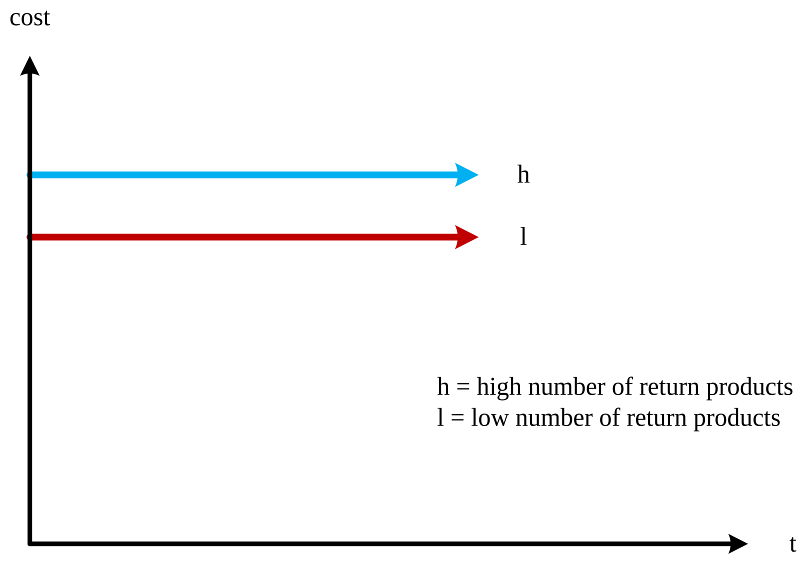

Figure 7.43 Type B Company (Rainy High Graph)

From Figure 7.43 for a Rainy High company:

- More returned product = more cost.
- Return product could add more cost.
- High fixed cost

Figure 7.44 shows Rainy Low Company. A Rainy Low Graph is the opposite of a Cloudy High Graph, there is no company from case studies in this research that represented a Rainy Low company. A Rainy Low company incurs more cost when there are a higher number of returned products than when there is a lower number of returned products. Similar to a Cloudy Low company, a Rainy Low company is in the lower cost area.

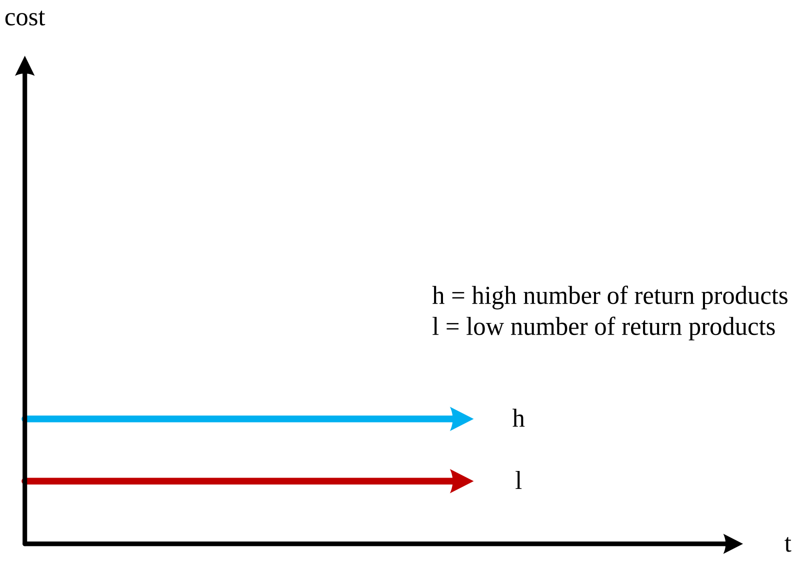

Figure 7.44 Graph F (Rainy Low Graph)

From Figure 7.44 for a Rainy Low company:

- More returned product = more cost.
- Return product could add more cost.
- Low fixed cost

7.7 Summary

In this Chapter, performance of the models was investigated by considering RSC system data in each company. Based on the mathematical model in Chapter 6 and generated data, a total cost for the whole system was produced for each model.

Several comparisons between high numbers of returned products and low numbers of returned products were presented in this Chapter. Based on the graphs produced a judgement of how returned products affect the whole system in a company could be made.

A simplified graph from these comparison graphs presented a first guide to how a company might be able to see the affect of returned products and start to measure their RSC performance. Based on comparison graphs, some general types of company are postulated from considering the different results described in this Chapter.

Chapter 8 Discussion, Conclusion and Future Work

Results from the research are discussed in this Chapter and novel claims are described. Results were explained in Chapters 5, 6 and 7 and summaries of the research results are revisited in this Chapter. The claims of originality within the research are:

- A new general model for RSC.
- A general mathematical model of the flow model.
- Both models can be adjusted for specific companies.
- Performance of both forward chain and RSC could be measured at the same time.
- Guidance graphs were produced for management to help them in decision making about RSC performance.
- Identification of six general company types.

Conclusions of this Dissertation are summarised and possible future work is suggested.

8.1 Discussion

8.1.1 General Model of a Reverse Supply Chain

A new General Model of a Reverse Supply Chain (RSC) was presented that included forward supply chains. The process of creating the general model was explained in Chapter 5 and reproduced in Figure 8.1.

This model was a first attempt to model the flow of returned products in a RSC that also considered forward flow. This model could be applied to many companies. This new general model was created using case studies for four companies and a fifth to verify the model. Company A and C represent large companies. Company B and D represent medium companies and Company E represents a small company.

This model was a simple and flexible model, which could be adjusted to fit a specific company by eliminating unnecessary processes or duplicating processes. The model was simple to use and could provide the management of a company with information about how to create a RSC system.

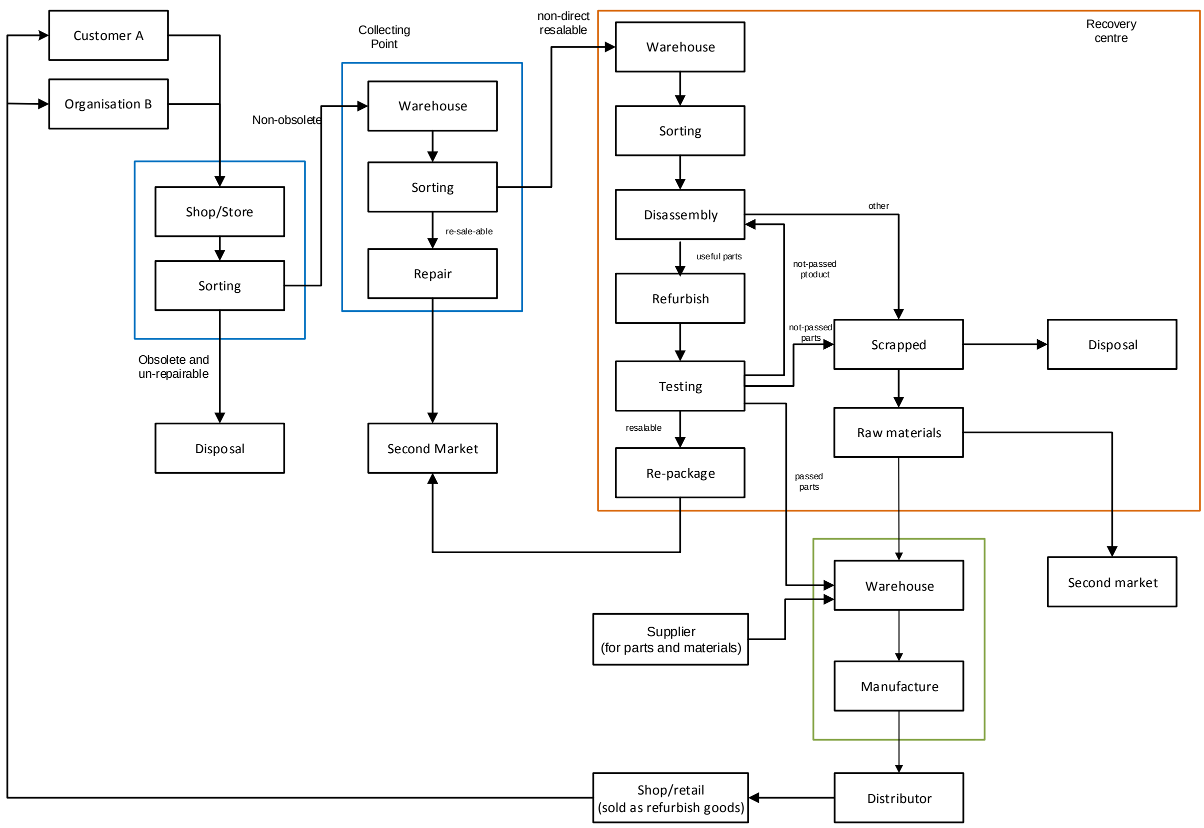

Figure 8.1 General Model for a Reverse Supply Chain (RSC)
(*Reproduced from Figure 5. 10*)

8.1.2 Mathematical model

Based on the new general model, a new mathematical model was created. Cost was used as a metric in measuring the performance in RSCs. The mathematical model was discussed and explained in Chapter 6 and published in Butar Butar *et al*. (2014) and Butar Butar et al. (2016).

The mathematical model was based on the new general model. Microsoft Excel was used as it was a common tool. Because the mathematical model was based on the new general model, it had a similar nature; simple yet flexible. It was easy to create graphs to view cost over time and to show system performance. A company could break down the mathematical model to see which activity or location affected their RSC system the most. If a company did not yet have a RSC flow, the model could be used for simulation so that the company could see how RSC could affect their company (for example either adding profit or not).

The equation for the mathematical model is reproduced from Chapter 6, Equation 6.24:

$Total\ cost\ for\ the\ General\ Model$

$$= \sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{zit}\, H1_{zit} + \sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{t=1}^{T} RP_{zit}\, BC1_{zit} + \sum_{z=1}^{Z}\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RU_{zrit}\, T1_{zrit}$$

$$+ \sum_{z=1}^{Z}\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T} RO_{zlit}\, T2_{zlit} + \sum_{y=1}^{Y}\sum_{i=1}^{I}\sum_{t=1}^{T} RU_{yit} H2_{yit} + \sum_{y=1}^{Y}\sum_{i=1}^{I}\sum_{t=1}^{T} RU_{yit} BC2_{yit}$$

$$+ \sum_{y=1}^{Y}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit} RC1_{rit} + \sum_{y=1}^{Y}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{yoit}\, T3_{yoit}$$

$$+ \sum_{y=1}^{Y}\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RD_{yrit}\, T4_{yrit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RND_{rit} H3_{rit}$$

$$+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RND_{rit} BC3_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RUS_{rit} DC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{rit} RC2_{rit}$$

$$+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit} RC3_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit} TC1_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{rit} TC2_{rit}$$

$$+ \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{rit} KC_{rit} + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} RNP_{rit} SC_{rit} + \sum_{r=1}^{R}\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{t=1}^{T} RJ_{rlit} T5_{rlit}$$

$$+ \sum_{r=1}^{R}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} RW1_{rmit} T6_{rmit} + \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RW2_{roit} T7_{roit}$$

$$+ \sum_{r=1}^{R}\sum_{o=1}^{O}\sum_{i=1}^{I}\sum_{t=1}^{T} RR_{roit} T8_{roit} + \sum_{r=1}^{R}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} RUP_{rmit} T9_{rmit}$$

$$+ \sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{t=1}^{T} PU1_{sit} NC1_{sit} + \sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{t=1}^{T} PU2_{sit} NC2_{sit}$$

$$+ \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU3_{mit} H4_{mit} + \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU4_{mit} H5_{mit}$$

$$+ \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU5_{mit} PC_{rit} + \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{t=1}^{T} PU6_{mit} H6_{mit}$$

$$+ \sum_{m=1}^{M}\sum_{x=1}^{X}\sum_{i=1}^{I}\sum_{t=1}^{T} PU7_{mxit} T10_{mxit}$$

8.1.3 Performance Measurement

After the mathematical model had been produced, various systems could be simulated. A comparison was made between having a low number of returned products compared with a high number of returned products. That could be used as information about whether returned products could add more profit or not. The graphs were based on the new models and new mathematical models. Chapter 7 explained how the graphs were produced.

As an example, Figure 8.2 shows the comparison between a high number of returned products and low number of returned products in Company A.

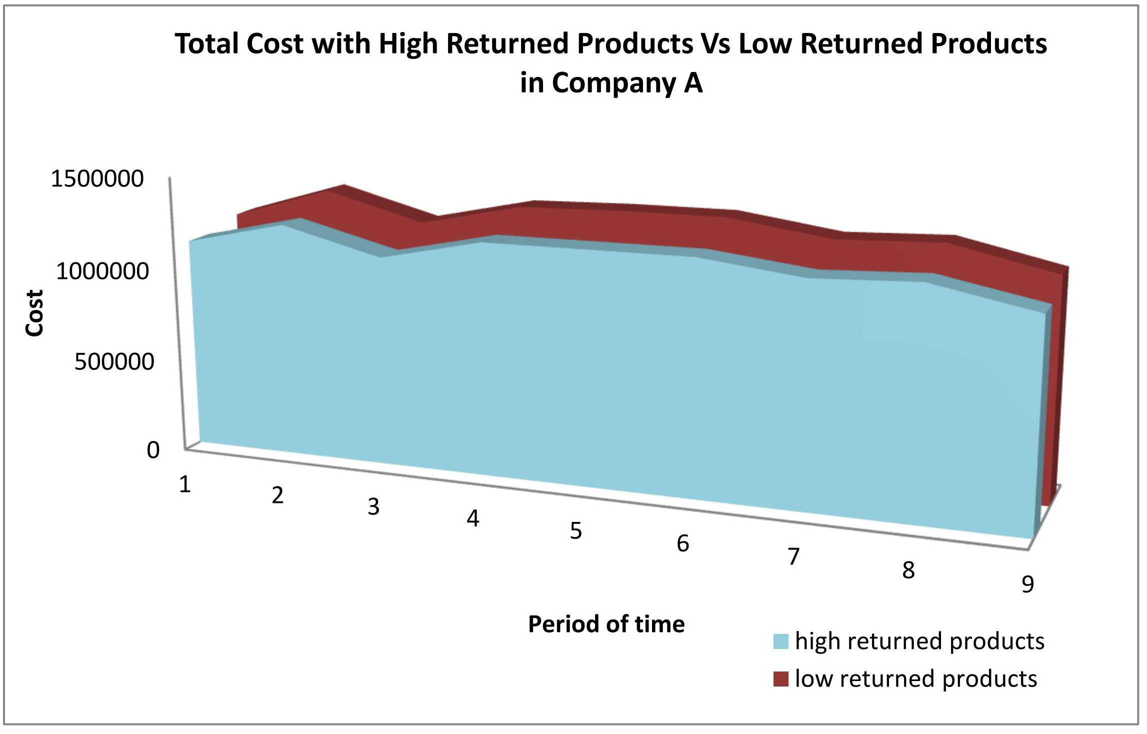

Figure 8.2 Total Cost with high returned products vs low returned products in Company A (*Reproduced from Figure 7.12*)

The graph in Figure 8.2 showed that a high number of returned products had a lower whole system cost compared to a low number of returned products. The difference between high returns and low returns was small. This could be because of high fixed costs in the company processes or there were not enough returned products to lower the cost.

This kind of graph could assist the company in deciding whether RSC could be a new way to increase profit or not. In this case, with more returned products, the total cost for whole system was lower, therefore the RSC system was a benefit to the company. Introducing returned products could be a new way to increase profit in this company.

Figure 8.3 shows a comparison between a high number of returned products and low number of returned products in Company B.

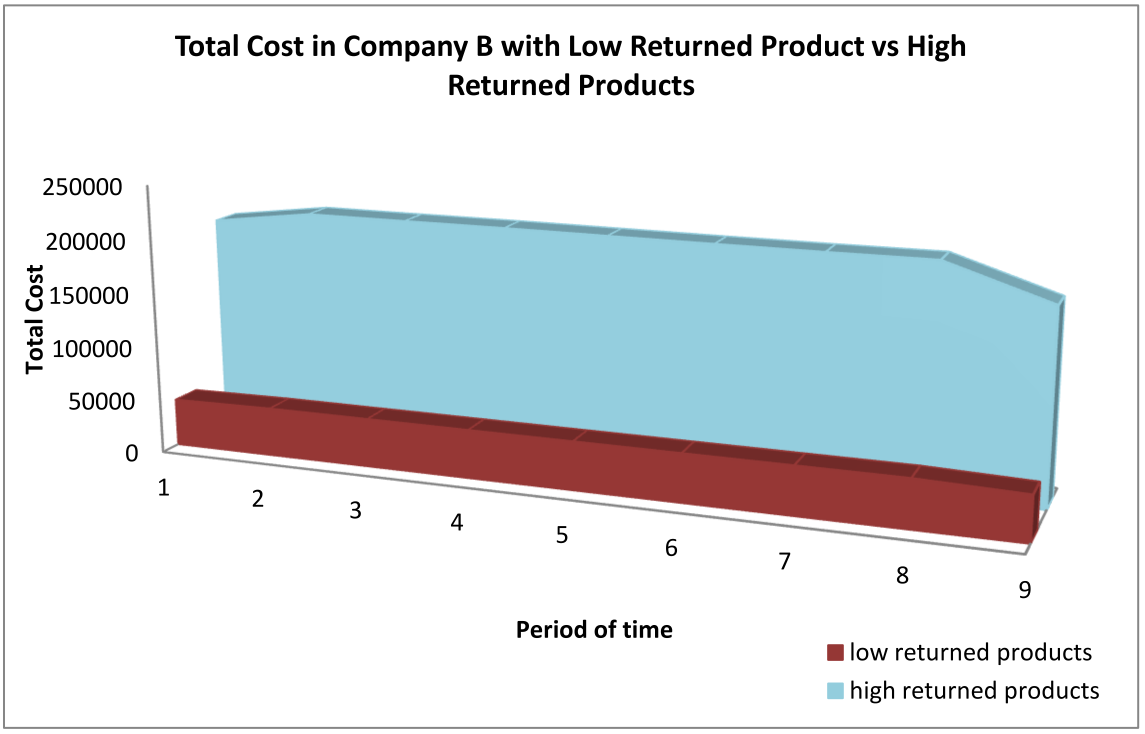

Figure 8.3 Low Returned Products vs High Returned Products in Company B
(*Reproduced from Figure 7.18*)

With low returned products the whole total cost was lower compared with a high number of returned products. Company B dealt with end-of-life products, so that the whole system cost followed the number of returned products. The higher the number of returned products, the higher the cost for the whole system.

The big difference for total cost between high number of returned product and low number of returned product was because there was not a manufacturing plant where the reusable parts and raw material could be reused.

In this case, the graph could provide the management with information to assist in lowering the cost when there was a high number of returned products. Making longer life products could be one option, useful parts and raw materials from a recovery centre could be sold to provide income. That would lead the company to decide on pricing to a secondary market.

Figure 8.4 shows the comparison between a high number of returned products and a low number of returned products in Company C.

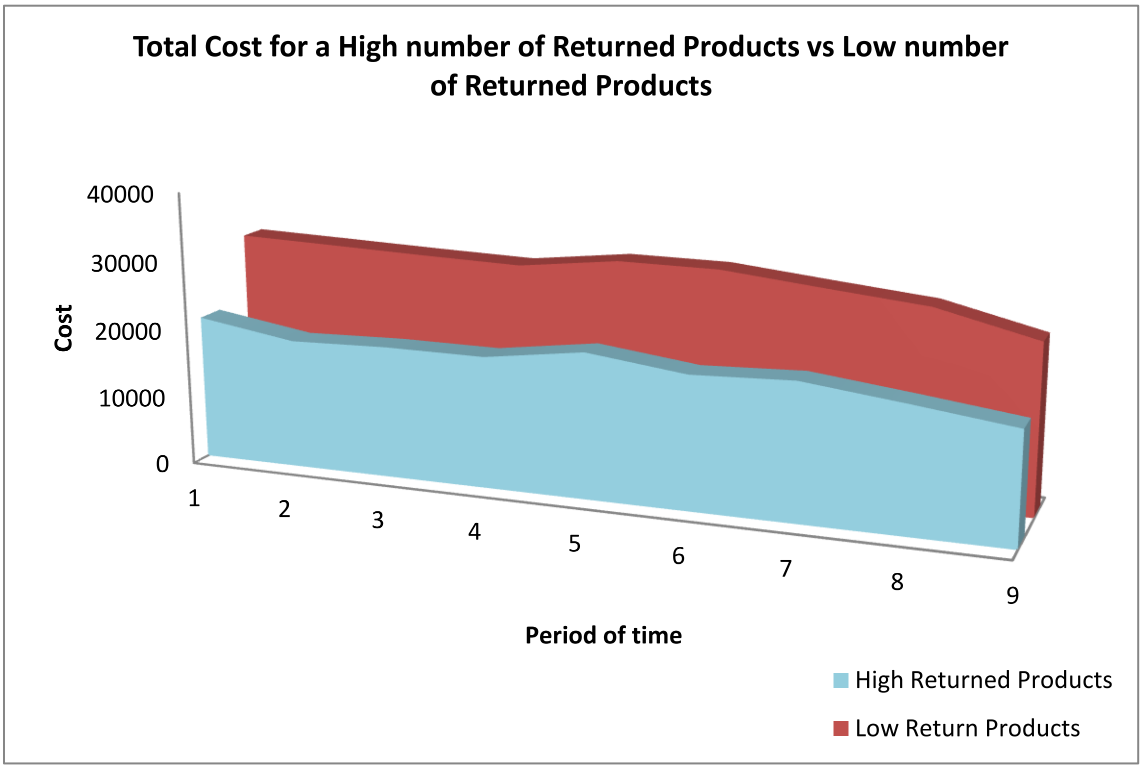

Figure 8.4 Total cost for high number of returned product vs low return in Company C (*Reproduced from Figure 7.26)*

In Company C, the difference between high returns and low returns was bigger compared to Company A. From this graph, a higher number of returned products led to a lower whole system cost compared with a lower number of returned products. Returned products could make a profit for the company and should be considered as a new way to gain more profit.

Furthermore, the company could start to pay more attention to their RSC system. The returned product flow could be investigated to optimise it. As well as monitoring the second market demand to make better judgments in terms of using reusable parts.

Figure 8.5 shows a comparison between a high number of returned products and low number of returned products in Company D.

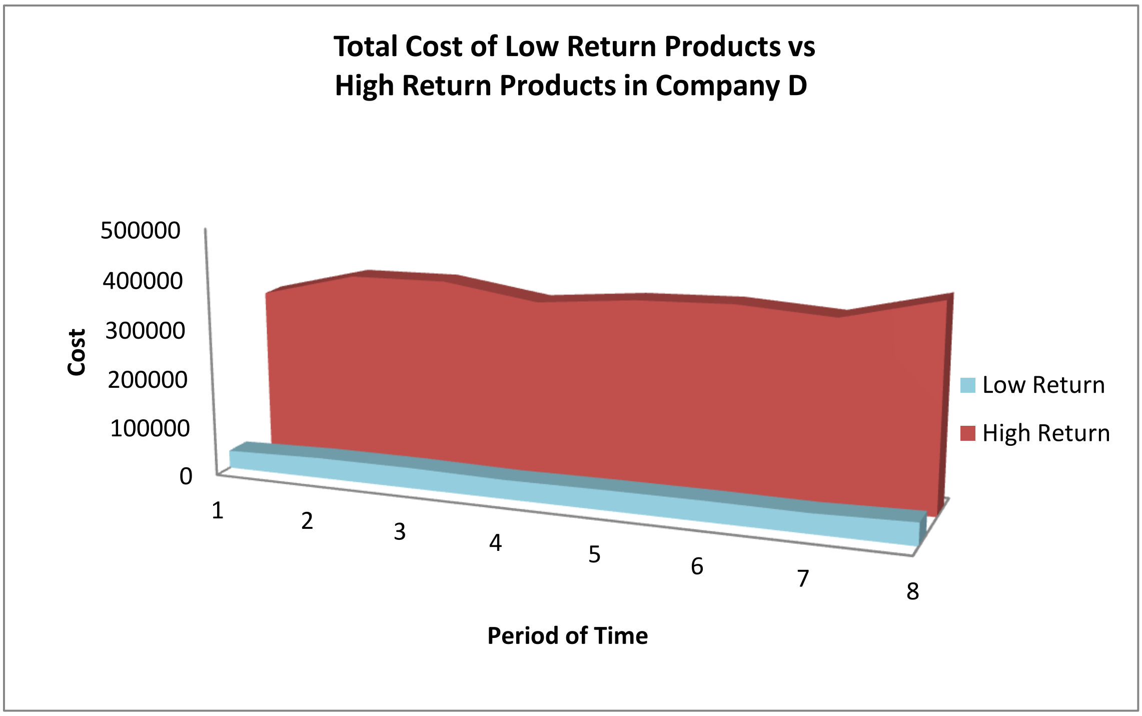

Figure 8.5 Total Cost of Low Return vs High Return in Company D
(*Reproduced from Figure 7.31*)

Figure 8.6 shows the comparison of a high number of returned products and a low returned products in Company E.

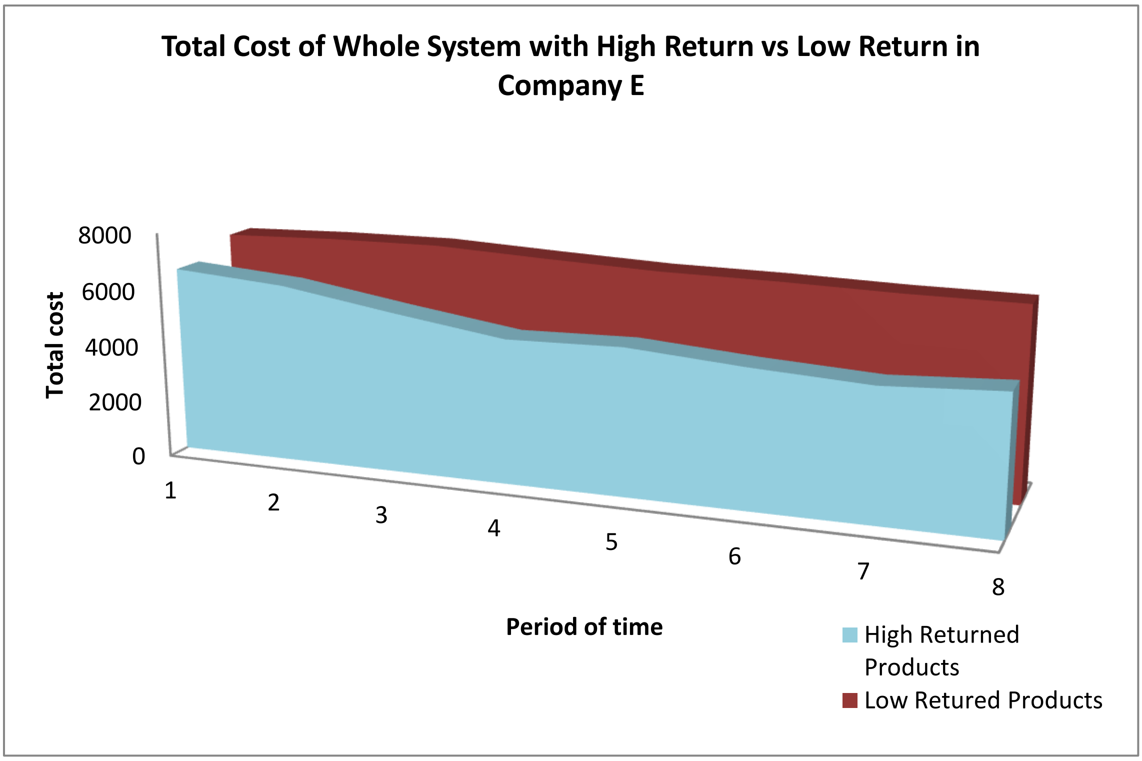

Figure 8.6 Total cost for high return vs low return product in Company E
(*Reproduced from Figure 7.38*)

8.2 Conclusion

The research described in this Dissertation investigated several industries with reverse supply chains (RSCs): aircraft manufacture, telecommunications, computer manufacture, general retail and carpet manufacture. From that investigation, a new general model that combined forward and reverse supply chains was created. From that model, a general mathematical model was created. From those general models, specific models (including mathematical models) can be created for specific companies. The new general model and the new mathematical model allowed performance of both forward and reverse supply chains to be measured at the same time. That allowed different modes of operation to be compared by testing with different data sets, especially high and low numbers of returns.

From an initial investigation of two case studies about an aeroplane company dealing with returned machines and a telecommunications company dealing with end of life products, a first initial model to describe their forward and RSCs was created. This was the first time that an attempt had been made to create a general model that could be used in more than one industry. Some detailed models had been created in the past for specific companies, and other more general models had been created to consider transportation, forward supply chains only or logistics, but at the start of the research, general models that included both the forward and RSCs did not exist.

A mathematical model was created to represent the first initial model and from that, two specific mathematical models were created to represent the two companies. The initial model was then tested against two other industries: computer manufacture and general retail. As a result of those tests, the model was modified to include shops and collecting points. That led to the creation of a general model of the forward and reverse supply chain. A general mathematical model was created to represent the general model and from that two specific mathematical models were created to represent the computer manufacture and general retail companies. The general model was then verified against another (fifth) industry, carpet manufacture. The model adequately described the fifth company.

The general model and the mathematical model allowed the performance of both the forward and RSC to be measured at the same time. By testing the models with sets of data containing a high number of returned products and a low number of returned products, companies were categorised according to the results. Six types of company were identified and were presented.

8.2.1 Review of The State of The Art

In this Section, the conclusions from Chapter 2, 3 and 4 are explained. This work included review of RSC, RSC framework and Performance Measurement (PM). Definitions and characteristics of RSCs were presented along with a detailed investigation into returned products, reverse distribution, product recovery, types of returns processing and disposition, and secondary markets.

The RSC was compared with forward supply chains and with green logistics. An investigation of closed loop supply chains was conducted, especially the process route in reverse and closed-loop supply chains.

That established that differences existed between the RSC and both forward supply chains and green logistics, and that a closed loop model would be required to represent companies with a RSC.

To create a general model of a RSC that included a forward supply chain, a framework was needed. Early work on RL frameworks explored, ways of structuring and explaining RLs. The components of RSCs were listed and were considered when making the models. This research focused on remanufacturing as a way for companies to gain more profit, and re-manufacturing was explained.

A gap in the research was identified in that no models had considered forward and RSCs. Proposing a general model became one of the aims of this Dissertation.

PM helps companies better understand the advantages and disadvantages of their strategies and provides an opportunity for improvement. Definitions of PM and classifications of PM were explored to provide a better understanding of PM. Some conceptual frameworks to help to design a PM system were presented as well as methods to design it.

A brief introduction about PM in forward supply chains was presented and PM in RSCs was also explored. PM is important in RSCs, however there was a lack of knowledge in the area and little literature.

This Dissertation makes a first attempt to create an easy way to look at RSC systems in companies. A model for returned product flow in a company was initially created, then a mathematical model was created with total cost used as a performance metric. This metric can give a company an idea about knowing how the whole RSC is operating within a company.

8.2.2 Model

Several industries were investigated to see how product returns flowed in each. From an initial investigation of two case studies about an aeroplane company dealing with returned machines and a telecommunications company dealing with end of life products, a first model to describe their forward chains and RSCs was created. A further two companies were investigated to explore their performance metrics in a RSC. That research included a general overview of each company as well as an interview with management about company objectives and policies.

The first four case studies were based on studies by Saibani (2010). Case study 5 (used as verification) was based on Tonanont (2009). Models were created to represent the case studies. The first models of RSCs were created based on the first two case studies. This first model was verified against two completely different companies (case studies 3 and 4). Case Study 3 was about computer companies dealing with returned laptops and Case Study 4 about retail companies dealing with returned merchandise. From an investigation of them, it was realised that returned products are also be received at shops or stores from customers. In the first model, the entire returned product arrived at the warehouse to undergo recovery processes and shops and stores were not considered.

By comparing the first model with the new case studies, it was observed that the first model did not cover all the processes. The first model was adjusted and named as a general model. The new model included all the processes for returned products in all the companies represented by the four case studies.

Based on the model of each company, a mathematical model was produced. A total cost for a whole system could then be generated that included forward and reverse flow in each company. That model could show how a company performed and mathematical modelling of total cost was a simple way to begin measuring performance in RSC.

8.2.3 Mathematical Model and Performance Measurement

The mathematical models described the total cost of all processes included in forward and reverse routing. The model could be used to investigate cost, subject to the capacity of the recovery centre warehouse; manufacture plant warehouse; recovery centre labour available; manufacture production capacity; and demand of new products.

Performance of the models was investigated by considering different inputs to the RSC for each company. Based on the mathematical model in Chapter 6 and generated data, a total cost for the whole system was produced for each model.

Several comparisons between high numbers of returned products and low numbers of returned products were presented. Based on the graphs produced a judgement about how returned products affected the whole system in a company could be made.

A simplified representation of these comparison graphs was presented as a first guide to how a company might be able to see the effect of returned products and start to measure their RSC performance.

8.2.4 Type of Company

Comparing low returns and high returns in each company provided an overview of how RSC affected each company. That suggested six new general company types that could be used as RSC performance indicators. The graphs showed how returned products affected the whole system in a company. Simplifying the graphs suggested six possible types of company that were named:

- Sunny.
- Cloudy High.
- Cloudy Low.
- Foggy.
- Rainy High.
- Rainy Low.

8.3 Limitations

There are limitation in this Dissertation:

- The danger of building a model using data of one type but applying it elsewhere.
- Secondary data were used instead of primary data due to company regulations.
- Warehouse had infinite capacity.
- Equation was simplified, for example there is no cost at warehouse when no inventory and the warehouse would have an over lead cost even if it was not used.

8.4 Future work

PM of the RSC with the general model and general mathematical model can help analysts, managers, or executives better understand their current operations and also provide a good opportunity for improving their current supply chain with alternative options that can be considered by conducting experiments.

Extending and adapting this methodology to more complicated network supply chains would be interesting. In addition a more complicated model to evaluate relative efficiency could be created and compared with this current model and different statistical experimental techniques could be considered.

This research has some limitations. First of all, the companies did not provide data. This was because of internal policies. Secondly there should be an improvement in measuring performance in companies dealing with end-of-life products. This would need more tools in order to measure their performance more accurately. Having cost as a measurement metric in this research limits the models as minimising cost is not always a main objective of a system. With end-of-life products the mathematical model could be different to cover regulation instead of minimum cost.

New models for forecasting and planning could be developed, models where the returns can be considered as part of the planning process. This model considered a RSC and forward supply chain in one system. However, this model could be more effective if planning and forecasting for return products could also be counted and considered.

The models can be investigated further to examine which processes in a RSC affect system performance the most. This model could be broken down, to see which processes affect the systems the most. With that new addition, managers could be able to optimise those processes.

The research concentrated on costs but investigations could also be made that consider other measures and objectives.

8.5 Summary

This Dissertation makes a contribution to the RSC literature and describes how to measure it. However, some improvements could be made to the model and mathematical model.

RSC remains an important subject to be explored to be able to deal with product waste and environmental regulations. The model of RSC needs to be explored for different companies and situations.

The outcome of this research, the New General Model and New Mathematical Model in this Dissertation could be used as start to create better models for measuring RSC systems. Types of company graphs could be used as first step in measuring RSC. For example, if the company produced a Sunny graph then RSC should be considered as a new way to gain profit. If it had a Cloudy graph (either high or low) the company needs to optimise their RSC system. The company with a Foggy graph needs more information to decide how to handle their RSC system. And if the graphs are Rainy (either low or high type), then returned products are not profitable, although environmental regulations might still bind a company.

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