Aerospace Manufacturing-Remanufacturing System Modeling and Optimization

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A Thesis

In the Department

Of

Mechanical and Industrial Engineering

Presented in Partial Fulfillment of the Requirements

For the Degree of Doctor of Philosophy at

Concordia University

Montreal, Quebec, Canada

April 2015

CONCORDIA UNIVERSITY
SCHOOL OF GRADUATE STUDIES

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Entitled: **Aerospace Manufacturing-Remanufacturing System Modeling and Optimization**

and submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY (Industrial Engineering)

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ABSTRACT

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In recent years, increasing environmental concerns, costs of raw materials, and stricter government regulations have resulted in companies striving to reduce their waste materials. An earlier approach adopted was the recycling of materials such as waste paper, glass and metals. However, recycled products typically lose a portion of their added values. Different waste reduction options such as direct reuse, repair, refurbishing, cannibalization, and remanufacturing were studied to overcome this drawback. Remanufacture recaptures the value added to materials when a product was first manufactured.

In the aerospace industry, where safety and performance are the overriding concerns and repairs are highly regulated, it could be perceived that remanufacturing has minimal appeal. However, the very low design tolerance of manufactured components results in a high percentage of defects. Due to the high price of raw materials, remanufacturing and components saving through “transforming” could be applied in imperfect production systems to reduce the amount of scrap materials. In this thesis, a general model is first proposed for a closed-loop supply chain network which includes the following processes: repairs, remanufacturing and transforming of selected defective components and end-of-life products, and cannibalization. A mixed integer linear programming formulation is developed to investigate the effect of various factors on profit, inventory carrying cost, and number of scrap components.

Uncertainty in demand and lead-time is one of the major issues in any manufacturing supply chain. Uncertainty is incorporated into an extended model through the scenario-analysis approach and outsourcing is considered as an option for remanufacturing of the customer owned components. Demand of final products is assumed to be deterministic. The defect rate of disassembled components, however, is considered to be variable which makes the demand for spares to be variable. The lead-time of in-house remanufacturing of the customer owned components is also considered to be variable. Sensitivity analysis is performed to investigate the effect of capacity, inventory carrying cost, outsourcing cost, lead-time, and defect rate variation on profit and amount of scraps. The inventory carrying cost variations have direct effect on the inventory turnover ratio. The maximum capacity of the outsourced company and process costs per unit have significant effect on the profitability. Maintaining a long-term relationship with third-party service providers, designing the components with a longer life cycle, and transforming and remanufacturing of defective components directly impact the profitability over the life cycle of a product.

ACKNOWLEDGEMENTS

First, I would like to thank my parents for their love, support, leading by example, and motivating me to achieve. It would not have been possible for me to reach where I am without many days and nights that they spent by my side helping me study and encouraging me to be curious and committed.

For believing in me from my first day at Concordia University and his continuous guidance and support throughout the years, I would like to thank Professor Mingyuan Chen. His patience, vast knowledge and experience in operations research and aerospace manufacturing enabled me to overcome many barriers throughout the research. I am very thankful for his understanding of my situation as a part-time, albeit dedicated, student. His flexibility and compassion allowed me to continue working full-time away from campus and he was incredibly accommodating of my schedule. Without his knowledgeable feedback and academic advice, my project would not have been possible.

I would like to express my sincere thanks to Dr. Liping Fang, Ryerson University, for his enthusiasm for new and challenging projects. His constant support and very helpful inputs eased the hardship that faced me throughout building the model and sensitivity analysis. I am grateful that I had the opportunity to work with and learn so much from him.

I would like to thank my friends Tom Najman and Richard Pellow for generously sharing their years of experience in aerospace industry and their inputs in building numerical examples. For his editorial assistance, I would like to thank Dr. Dean Langenfeld.

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CLSC	-	Closed-loop supply chain
EOL	-	End of life
EOQ	-	Economic order quantity
EPQ	-	Economic production quantity
KPI	-	Key performance indicator
MILP	-	Mixed integer linear program
MRO	-	Maintenance repair operations
MRP	-	Material requirement planning
OEM	-	Original equipment manufacturer
RL	-	Reverse logistics
RPS	-	Reverse production system
SC	-	Supply chain

CHAPTER 1

INTRODUCTION

1.1 Introduction

In recent years, increasing environmental concerns, the cost of raw materials, and government regulations directed towards the conservation of energy and natural resources, landfill reduction, pollution reduction, and creating new jobs and skills, have resulted in companies striving to reduce their waste materials (McConocha and Speh, 1991; Gray and Charter, 2006). The earlier approach to manage waste materials, introduced in the 1970's, was the recovery/recycling of materials such as waste paper, glass and metals. However, recycled products typically lose a portion of their added value and reuse may not be possible due to the impurity of the recovered materials. Also, additional and costly energy inputs are often required to convert recyclable materials back into raw materials. To overcome these deficiencies, different waste reduction options such as direct reuse, repair, refurbishing, cannibalization, and remanufacturing were studied (Thierry et al., 1995).

Direct reuse involves a used product being inspected and sent for use without changing any components. Repair involves only defective components being removed and/or corrected. Another option used for recovering the components is dismantling (or cannibalization), which is de-manufacturing a product to its components, inspecting the individual components, correcting them as necessary, and reusing them to manufacture new products or to service used ones. With reconditioning or refurbishment, a part will not be in "as new" condition, while with remanufacturing the product will regain its original "as new" condition after a detailed inspection and correction. Remanufacturing is "a process of recapturing the value added to the material when a product was first manufactured" (Gray and Charter, 2006). Synonyms for remanufacturing include:

- Second-life production,
- Repetitive manufacture,
- Asset recovery,
- Inverse manufacture,
- Renovation,
- Recharge (in laser toner cartridge),
- Rewinding (in electrical equipment), and
- Overhaul (in aerospace industry).

These terms may have different implications depending on the industry and context which they are used.

1.2 Drivers for Product Recovery

Remanufacture has received considerable attention due to the potential of full value recovery from the used products. Companies create different strategies to encourage customers to return products for remanufacturing. For example, up to 40% of part price is reimbursed by Caterpillar to dealers which return parts and engines depending on their conditions (Stahel, 1995). The benefits of remanufacturing were summarized in McConocha and Speh (1991) as: 1) labor, material and energy cost savings, 2) reduced production lead-times, 3) balanced production lines, 4) new market opportunities, and 5) a positive environmentally concerned corporate image. Gray and Charter (2006) added landfill reduction, pollution reduction, and creation of new jobs and skills to this list. According to Spengler et al. (1997) dismantling a building and reusing the components was 20% cheaper than conventional demolition and disposal. They presented the effect of government taxes and regulations as incentives for disposal reduction through reuse and remanufacturing.

In order for remanufacture to be successful, the following parameters are required: market demand for remanufactured products, technology to remanufacture, stable product technology, standard interchangeable parts, and a remanufacture cost that is lower than the cost of a new product (Lund, 1998). Guide (2000) provided a list of characteristics that made remanufacturing complex. The list included: 1) timing and volume of product returns, 2) yield estimation, 3) balancing demand with returns, and 4) managing reverse logistics. These characteristics affect different stages of the manufacturing/remanufacturing system with the most affected stages being scheduling and inventory control. Chung and Wee (2008) identified technology evolution, take-back ratio, and inventory holding costs as critical factors in the manufacturing/remanufacturing system. The primary goal of remanufacturing should be a product whose quality meets customers' expectations and exceeds that of competitors' products. Meeting customers' long-term requirements is essential for the survival of a company. Secondly, government and environmental regulations should be met in order to portray a positive image of the company in the society and to able the business to continue without undue government interference. Thirdly, processes should be improved and costs should be minimized to maintain profitability (Dowlatshahi, 2005).

Michaud and Llerena (2006) considered economies of scale, transaction costs, coordination of needs, and tacit knowledge as the major factors affecting remanufacturing profitability. The effects of remanufacturing unit costs, direct channel cost and customers' preferences in a multi-agent supply chain where a manufacturer sold both new and remanufactured products were studied by Jiang et al. (2010).

Subramoniam et al. (2010) developed a remanufacturing decision making framework (RDMF) where some of the strategic decision making factors were: design for remanufacturing, intellectual property, product life cycle, core management, and organizational alignment. They identified three reasons for remanufacturing failures: 1) high set-up cost of establishing reverse logistics networks, 2) high cost of quality assurance, and 3) the fact that product was not designed for remanufacturing. Jin et al. (2013) studied remanufacturing of modular products with substitution of low quality modules by high quality modules. They found that when the customer demand rate and return rate were equal, the cost would be minimized. Also, substitution became more desirable as the quantity of low quality and high quality returns got closer.

In Europe, remanufacturing is very popular because of higher landfill costs and more comprehensive government regulations. European companies extended remanufacturing to rugs, sands, automotive components, photocopiers, materials from building demolitions, cameras, and electronic equipment. Based on automotive industry statistics in Germany, in 2006, 85% of cars (in weight) were recycled and recovered. Only 15%

were subject to disposal. This amount is to be reduced to 5% in 2015 under that recovery process due to the use of composite materials in building cars (Lucas, 2001). The Netherlands, Germany, Greece and the United Kingdom are pioneers in remanufacturing studies and applications.

Remanufacturing is not very popular in developing countries due to weak legislation and lack of technical know-how. In the United States there are different reasons for the unpopularity of remanufacturing. First, labor is expensive and remanufacturing involves a great deal of labor interaction. In many cases, customers can buy a new product for less than a remanufactured one. Second, original equipment manufacturers have a mass production mentality and may not put enough emphasis on design for remanufacturing. Third, there may not be significant technical, environmental and quality data to convince customers (Subramoniam et al., 2009).

1.3 Closed –Loop Supply Chain Network

Traditionally, manufacturers were responsible for production of new products and supply of spare parts. As the landfill costs increase and government regulations put greater pressure on manufacturers to reduce their ecological footprints, this responsibility has been expanded over the life cycle of products. Guide and Van Wassenhove (2009) states “Closed-loop supply chains (CLSC) focus on taking back products from customers and recovering added value by reusing the entire product or some of its modules, components and parts”. Competitive pricing and flexible return policies have caused high return rates in retail industries where products can be returned within 30, 60, or 90 days after purchase. Return rates can be as high as 10% for major appliances. In the past, the cost of returns was absorbed by retailers. As new laws require transferring the ownership of returns from retailers to manufacturer, it becomes more important to develop a reverse supply chain to collect products and repair or remanufacture them to bring them to “as new” condition. Based on Savaskan et al. (2004), the retailer being closest to the customer, is a more effective agent for collecting used products compared to a manufacturer or a third party logistics provider. Differences between traditional supply chain and reverse supply chain of electronics are studied by Lu et al. (2000). Some of these differences are: greater variability of end-of-life products and demand for reprocessed products, lower acquisition cost but higher process cost, and different inventory holding cost components i.e. no shortage cost and/or obsolescence cost in reverse supply chain. In their article, an algorithm for designing a reverse supply chain was developed and five criteria for scheduling of recyclable products were identified: 1) material recovery revenue, 2) incoming product revenue, based on quantity and frequency of incoming products, 3) inventory space, 4) customer demand, based on material or recovered products that had high demand, and 5) material recovery revenue and inventory space which were a combination of 1) and 3). Srivastava (2008) developed a model to determine the most economical collecting centers and reworking facilities where customers returned products to a collection center for a resolution price. He concluded that distance, processing time and costs, and return rates were sensitive parameters in this model.

1.3.1 Closed-loop Supply Chain Network in Aerospace

In the aerospace industry, where safety and performance are the overriding concerns and repairs are highly regulated; the general opinion is that remanufacturing has minimal appeal. However, the very low design tolerance of manufactured components in aerospace results in a high percentage of defects. Due to the high price of raw materials and complex production processes, remanufacturing and component saving through "transforming" could be applied in imperfect production systems to reduce the amount of scrap materials. In some cases such as landing gear tires, remanufactured components may even have longer life cycles due to thicker retread rubber. By definition, an aviation product overhaul involves cleaning, carefully inspecting, and repairing or replacing components to meet service limits. It is recommended that components used in the overhauled product meet new limits. Many national and international authorities permit the replacement of a used component that meets only service limits into an overhauled product as a replacement. To ensure safety, when used components are installed more frequent inspections are required. Managing the aftermarket spare part/component inventory is sometimes difficult for the following reasons: 1) demand for service is uncertain and inconsistent, 2) when there is a high variety of final products, the number of spare parts increases, resulting in a high level of inventory, 3) there is a need for a short cycle time, and 4) repairs require cooperation between different parties (Amini et al., 2005).

Traditionally, components were manufactured and inspected before assembly started. Defective components would either be repaired and used as spares with a reduced price or disposed of. At service centers, where products were returned for overhaul or repair, components were disassembled and inspected. Damaged and end-of-life components would be repaired or sent for recycling. Figure 1.1 shows a simplified closed-loop supply chain network.

Evolution of technology, increases in costs of raw materials, introduction of new government regulations and increases in landfill taxes encourage companies to add new processes like cannibalization and remanufacturing to their network to maintain their profit margins.

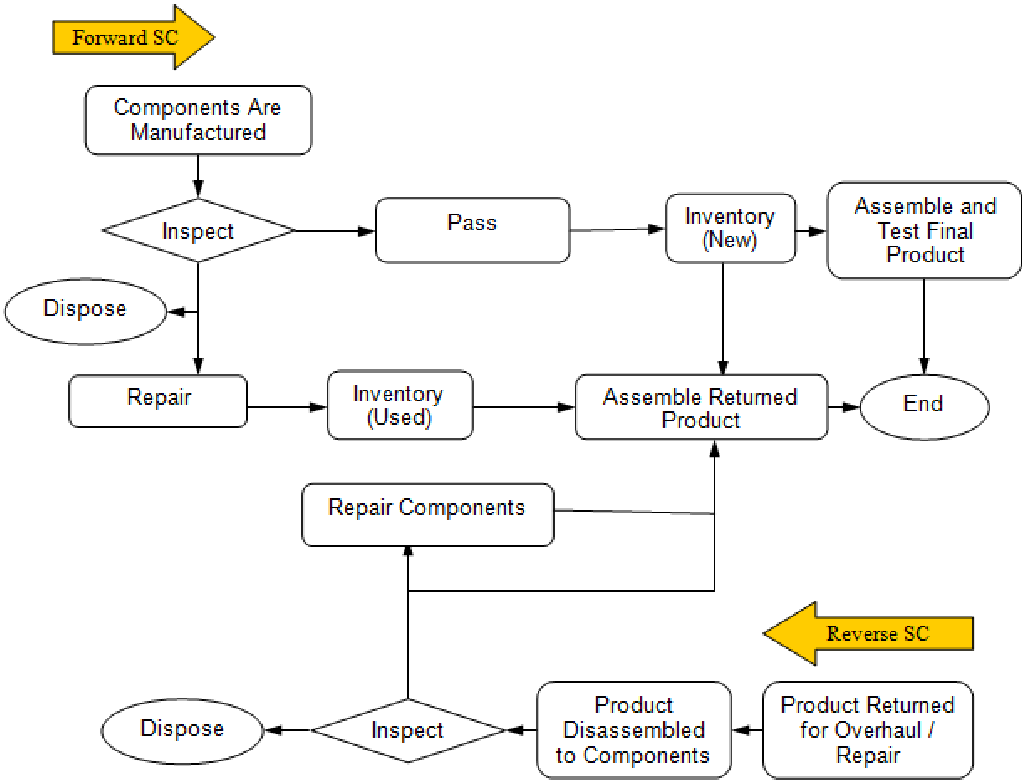

Figure 1.1: Traditional closed-loop supply chain network

Ijomah (2009) introduced a paradigm shift from a product sales model to a service business model where the company's needs are much more closely tied to the customers' needs. This model considers the following factors differently: product price, quantity of spares, reliability, customer expectation, source of profit, and incentive to overhaul. It also lists the differences between the new and old business models for aircraft engine life cycle costs. Aftermarket services encourage major aerospace manufacturers to reduce maintenance costs. For example, extending the life of defective components through remanufacturing, which may not have been profitable in the old business model, becomes a desirable alternative in the new business model.

Projections show that the global airline fleet will double by 2033. More than 60% of annual demand for used serviceable components is for engine parts/components and less than 5% is for airframe materials (Broderick, 2014). As demand for spares increases and airlines or aircraft owners put more pressure on aftermarket service providers to reduce their prices, new strategies and programs such as power-by-the-hour, partnership for success (Boeing) and forward-stocking are developed. Companies like Boeing and GE are increasing their share in aftermarket services and asking their suppliers to provide a much greater quantity of components with lower prices (Broderick, 2014).

The overall aim of this thesis is to demonstrate the effect of environmental impact reduction by introducing innovative processes in the closed-loop supply chain network where the amount of scrap material is decreased and profit is increased. A generic model is proposed for a closed-loop supply chain network in the aerospace industry. New processes are introduced to extend components life cycles. Uncertainty in demand for components is added to the model through scenario analysis. The effects of the variation of some parameters on key performance indicators are studied through sensitivity analysis.

1.4 Research Objectives

Based on a review of published articles and books, it was noticed that most studies consider remanufacturing only for used products that were returned from customers.

Also, studies on remanufacturing in the aerospace industry are limited. It is believed that there is a significant amount of material scrap from imperfect production systems and that applying remanufacturing principles can reduce these waste streams. Improving production processes by applying Six Sigma principles reduces the amount of defects, but it does not totally eliminate them. There are also cases where a component cannot be remanufactured but can be transformed to another component. In the aerospace industry, where many components have life cycles that must be respected, e.g. fan and compressor blades in engines; the inventory holding cost of used components can be very expensive. Remanufacturing of these components can increase inventory turnover.

The objectives of this research are to design a closed-loop supply chain network with new processes introduced to reduce disposal of defects, identify the most sensitive parameters, and compare the effectiveness of different key performance indicators to measure overall profitability. In order to represent a real-world scenario lead-times are considered more than one time period and production process has yield of less than one. A generic mathematical model is developed for the proposed network to study the effects of the added processes on profitability. Based on results, the model has been extended and uncertainty is added by introducing different scenarios for defect rate and lead-time.

Therefore, the objectives of this research can be summarized as follows:

1. Design a closed-loop supply chain network that includes production of new components and products as well as service of returned products.
2. Introduce new processes that can be used to reduce the number of components that are sent for disposal.

3. Incorporate uncertainty to the model by considering different scenarios for the defect rate of returned components and the lead-time of in-house remanufacturing using deterministic probability for each scenario.
4. Perform sensitivity analysis on scenario-based models to weigh the effect of different parameter changes on profit.

1.5 Research Approach

To achieve the aforementioned research objectives, the research approach consists of the following steps:

1. Review published work on closed-loop supply chain, remanufacturing, and imperfect production systems to explore approaches used by others in designing a system considering waste reduction.

2. Develop a generic mathematical programming model for an aerospace manufacturing company to represent:
    a. Forward flow which includes: manufacture, test, repair, remanufacture and transformation of components as well as the assembly and test of final products.
    b. Reverse flow which includes: disassembly of returned products, test of components, remanufacture and repair of defective components, or cannibalization of non-repairable components.
3. Test the mathematical model through a numerical example that is designed in a small version but is illustrative of an actual operation.

4. Use a commercial optimization solver to perform a sensitivity analysis on some input factors of the numerical example.
5. Based on the results of the sensitivity analyses extend the model and add uncertainty by introducing different scenarios for defect rate of disassembled components and lead-time of certain processes.
6. Test the second model through a numerical example with three different scenarios.
7. Perform sensitivity analysis to test the impact of some input factors of the numerical examples on profit, inventory level, and scraps using a commercial optimization solver.

1.6 Research Contribution and Publication/Submitted Paper

In this thesis, the traditional supply chain network in the aerospace industry is modified by introducing new processes to reduce the environmental impact and increase profit over the life cycle of products. These processes are remanufacturing of customer owned disassembled components and transforming of new but defective components. This is a deterministic model with lead-time more or less than one time period. Labor hours allocated to the production line at certain periods define the capacity limit.

Further, the model is modified and outsourcing of remanufacturing in the reverse flow is allowed. In order to incorporate uncertainty to the model, scenario-based analysis is used for the defect rate of the disassembly process and lead-time of remanufacturing. The two models and the results of their sensitivity analysis are compiled in the following papers.

1. Hashemi, V., Chen, M., Fang, L. (2014). Process Planning for Closed-loop Aerospace Manufacturing Supply Chain and Environmental Impact Reduction, Computers and Industrial Engineering, 75, 87- 95.
2. Hashemi, V., Chen, M., Fang, L. (2015) Modeling an Aerospace Manufacturing/Remanufacturing System with Demand Uncertainty, submitted to the International Journal of Production Economics

1.7 Organization of the Thesis

The remainder of this thesis is organized as follows. Chapter 2 categorizes and summarizes some of the relevant literature on the remanufacturing system, closed-loop supply chain, and imperfect production systems. In Chapter 3, we present the closed-loop supply chain network of interest and introduce a mixed integer programming model for a multi-product, multi-period, closed-loop supply chain aimed at aerospace manufacturing and remanufacturing applications. Chapter 3 is completed with a numerical example and a sensitivity analysis. Chapter 4 provides an extended version of the model presented in Chapter 3 based on the results of the sensitivity analysis. A scenario-based analysis is used to incorporate uncertainty into the model. Numerical examples are presented for both the deterministic and scenario-based models. In Chapter 5, the results of performing sensitivity analyses on some key parameters are presented and the implications of the findings in industry are discussed. Finally, Chapter 6 concludes the study with a summary, extensions, and directions for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In the last 20 years much research has been done on characteristics of reverse logistics and the applicability of remanufacturing in different industries all over the world. The number of articles has increased from 14 (between 1971 and 1995), to 99 (between 1996 and 2005), and then to 51 (between 2006 and 2008) (Pokharel and Mutha, 2009). Atasu et al. (2008), Rubio et al. (2008), Chanintrakul et al. (2009), and San et al. (2012) provided up-to-date and extensive reviews of the literature on reverse logistics structure, processes, and outputs.

In this chapter, the related literature is first classified into four categories: product related issues, capacity planning for reverse logistics and facility locations, business analysis and pricing strategy, and production planning and inventory control. Then, a review of the recent published works on remanufacturing is presented. These publications provide a general guideline for developing the conceptual and mathematical model for a reverse flow and closed-loop supply chain. We also provide a summary of papers on imperfect manufacturing systems since they provide insight on how these systems work and what can be done to reduce the amount of defects produced. The chapter ends with a review of different approaches made to incorporate uncertainty of demand in the forward flow and reverse flow.

Important aspects of product related issues are outlined as follows:

1. Product: Disassemble and remanufacture must be considered during the design phase of a product (Brass and Hammond, 1996) in order to have a successful remanufacture. Factors affecting the selection of economical products for remanufacture are discussed in Pochampally and Gupta (2003). Gungor and Gupta (1998) developed an algorithm for the disassembly of defective components. Gupta and Taleb (1994) developed a material requirement planning (MRP) model to determine the disassembly of products. Geyer et al. (2007) developed an economic model for components whose life cycles exceeded the product's life cycle and which could subsequently be used in different products. They concluded that production cost structure, collection rate, product life cycle and component durability should be coordinated to minimize the overall cost.

2. Capacity planning for reverse logistics and facility locations: Reverse logistics is the process of planning and controlling the efficient flow of used products from point of consumption to the point of origin for the purpose of recapturing their remaining values or minimizing their disposal costs. A quantitative model for a single product network, including manufacturing plants, distribution centers, collection centers and remanufacturing facilities, was developed by Fleischmann and Dekker (2001). Salema et al. (2007) extended the model by Fleischmann and Dekker (2001) for a capacitated, multi-product system considering uncertainty for demand and return flows. Kroon (1995) studied reverse logistics for collapsible plastic containers in The Netherlands. Schultmann et al. (2006) used a Tabu

search to find the locations of the most profitable dismantling facilities in reverse logistics for end-of-life vehicles in Germany. Zhang et al. (2011) and Wang and Di (2010) built a cost minimization model to find the best locations for facilities of a reverse logistics network. Georgiadis and Athanasiou (2010) studied a remanufacturing network for sequential entry into service of two products to investigate the effect of market interest on production capacity and inventory. Alshamrani et al. (2007) developed a dynamic logistics planning model to design a blood distribution network of the American Red Cross that included return of empty containers from customers to distribution centers. Hassanzadeh and Zhang (2011) considered a situation with three types of returns: 1) end-of-life, 2) end-of-use, and 3) commercial returns. They concluded that as capacity of a disassembly facility increased, profit increased to a maximum point and then it went flat.

3. Business analysis and pricing strategy: It is assumed that remanufactured products have the same quality as new products and should be sold at the same price. Although the cost of raw materials is less for remanufactured products compared to new products, extra processes such as disassembly and cleaning are required to remanufacture. The best price and remanufacturability level to maximize profit for a manufacturer who sells both manufactured and remanufactured products were studied in Debo et al. (2005). Kocabasoglu et al. (2007) investigated the balance between supply chain investment, risk propensity, and business uncertainty in forward and reverse supply chain. Lack of a good communication system between logistics, receiving, processing, and accounting

departments reduces visibility over inventory level throughout the reverse logistics (Lee and Lund, 2003). Krikke et al. (1998) and Teunter (2001) developed methods to calculate the value of assemblies and net profit. Baumgarten et al. (2003) suggested using barcodes on products and developing an online database of information on used products and their components between disassembly factory, end-customers, and retailers to efficiently market the disassembled products and schedule disassembly. Jayaraman (2006) studied the effect of buy-back on the quality of returns where acquisition cost was a function of cost of used product and logistics. Li et al. (2013) extended this work by considering stochastic acquisition and an imperfect remanufacturing process. They found that expediting remanufacturing improves acquisition price. Also, when the remanufacturing yield is random, acquisition price decreases. Substitutability of different products from different manufacturers was studied by Wang et al. (2008). In this study, rate of return was a function of investment on product recovery activities. Minner and Kiesmuller (2012) studied the effect of product life cycle and buy-back price in a single period closed-loop supply chain. Ferrer and Swaminathan (2010) studied a differentiated market and price between new and remanufactured products. They found that as remanufacturing cost decreases, price of remanufactured products decreases leading to higher sales and decrease in demand for new products. To respond to this decrease in demand for new products, companies may reduce the price of new products so they can have enough returned products in subsequent time periods.

4. Production planning and inventory control: In a closed-loop supply chain, where parts and components can either be provided by suppliers or obtained by disassembly of returned products, production planning and inventory control play key roles in managing raw material and inventory cost. Forecasting lead-time of returns and quality of the disassembled components is sometimes difficult. Most deterministic models in the literature are extensions of the economic order quantity (EOQ) model which includes backorders and capacity limits. On the other hand, stochastic models can be based on different assumptions or use simulation. Schrady (1967) extended the EOQ model to include inventory costs of returned products. Guide and Srivastava (1997) reviewed studies on the inventory of repairable items. The effect of manufacturing/remanufacturing lead-time variation on the cost of inventory with stochastic demand and return was studied by Inderfurth (1997) and Inderfurth and Van der Laan (2001). The latter study suggested considering lead-time of remanufacturing as a variable because as remanufacturing lead-time decreases, cost decreases to a certain level before it increases again due to high safety stock cost. Inderfurth and Minner (1998) studied a multi-stage supply chain network where demand follows a normal distribution and periodic review base-stock inventory management policy is used to optimize inventory for different service levels. Guide et al. (1997) used simulation to study different scheduling rules in a remanufacturing facility with exponential lead-time. They concluded that First Disassembled-First Remanufactured (FDFR) and reassembled based on due dates are easy to use and produce good results. Guide (1997) used a drum-buffer-rope policy in

remanufacturing systems to measure performance under different dispatching rules. According to Fleischmann et al. (2002) and Fleischmann and Kuik (2003), reorder quantity-reorder point and min-max inventory model could give optimal average cost of inventory where returns are stochastic. Kleber et al. (2002) considered a system where returned products had the same value and quality but could go through different remanufacturing processes to gain different values at the end of each process. Richter and Sombrutzki (2000) modified the Wagner-Whitin method for a manufacturing/remanufacturing system where return rate is high and the inventory holding cost of returns is low. The Silver-Meal heuristic is modified so that it can be used to solve the model. Golany et al. (2001) extended Richter and Sombrutzki's work by developing a minimization model where disposal could generate income if it was sold to a recycling company. Beltran and Krass (2002) studied the effect of zero inventory policy in a closed-loop network with deterministic demand. De Croix and Zipkin (2005) used a series system to study a closed-loop manufacturing system with stochastic demand and return where return was considered a past demand. The effect of batched returns was studied in a maximization model developed by Li et al. (2009). In this study returns were prioritized based on their residual life, demand for the remanufactured product, and high depreciation rate.

Most published work on product recovery through remanufacturing focus on end-of-life (EOL) products where customers do not see any value in keeping them or are willing to sell them to collectors for a low price. Also, not much research has been done in aerospace manufacturing where service times are quite long and the price of products and their components are quite high due to the expensive materials used in their production.

Major factors considered in the literature affecting the profit and cost of remanufacturing are: 1) facility capacity, 2) lead-times, 3) fixed, variable, backordering, and disposal costs, 4) single period versus multiple period horizons, 5) deterministic or stochastic returns, 6) deterministic or stochastic yields, and 7) independent or integrated forward and reverse supply chains.

2.2 Deterministic Models

Realff et al. (2000) studied reverse logistics design in the carpet industry using a robust optimization framework. A mixed integer linear programming (MILP) model was developed to find the number and size of collection and processing sites, the routes for transportation of products and raw materials, the mode of transportation, and the amount of material allocated to each end-user while maximizing net profit. The two main factors noticed which affected reverse production systems (RPS) were: average frequency of product retirement and complexity in product manufacturing. Frequency of product retirement increased as the quantity of components increased or the length of use decreased. The second factor encouraged preserving the added value through remanufacturing. Simple product structure with high value raw material encouraged material recycling.

An integrated system of manufacturing and remanufacturing with capacitated facilities was studied in Kim et al. (2006). A MILP model was developed to maximize profit considering the costs of inventory, set-up, disassembly, refurbishing, disposal, and idle time. The model calculated the quantity of products to be disassembled or sent to a subcontractor for renewal and the number of components (new and as-new) to be stored. They concluded that the profit increases as the capacity of each facility increases (one at a time) up to a certain level. After that level, increasing the capacity may not have an effect on profit.

Considering uncertainties in supply, quality, reprocessing times, and cost-benefit function of reprocessed items, Pochampally and Gupta (2003) proposed a three-phase mathematical programming approach to design a reverse supply chain network. The first model selected the most economical products among all products that could be collected for remanufacturing. A mixed integer mathematical programming model was developed to maximize profit. In this model, the reverse supply chain was independent of the forward supply chain, no fixed cost was included, product disposal was allowed, reprocessing costs were time-oriented, and yields were deterministic. Analytical Hierarchy Process (AHP) was used to identify potential facilities. The authors chose the following criteria to compare facilities: quality of output versus quality of input, throughput multiplied by supply of used product, and throughput multiplied by disassembly time. The last phase was designing the reverse transportation network to minimize transportation, reprocessing, inventory, and retrieval costs subject to volume limitation and cost of facilities.

Li et al. (2007) considered a capacitated batch manufacturing/remanufacturing system where the time horizon was finite, demand was deterministic, emergency subcontracting and substitution were allowed, and set-up costs were considered separate from production costs. A genetic algorithm was applied to find time periods with non-zero set-up costs.

Through dynamic programming the quantity of products produced by different processes were calculated.

Chung and Wee (2008) developed a mathematical programming model for an inventory deteriorating system that included reverse flows. Supply and return rates, deteriorating rate, greenness rate, and lead-times were considered deterministic. The model optimized the lot size for production, number of deliveries per cycle time, and number of life cycles before the part was disposed of or recycled. Some of the key assumptions included: shortages were not allowed, work-in-process or defects were not considered, deteriorated items were not replaced, and the deteriorating rate was constant per item. The authors concluded that as the deterioration rate increases, delivery time should be decreased, and as the return rate increases the total cost decreases. Also, as inventory holding cost increases, take-back rate and technology evolution should be increased in order to remain profitable.

Bulmus et al. (2013) studied a closed-loop system where products were produced at the first period and returned for remanufacturing at the second period. A profit maximization model was developed followed by sensitivity analysis on the cost of manufacturing and remanufacturing, return rate, market demand, and capacity cost. Based on the results, a reduction in remanufacturing costs increased manufacturing in the first period. Also, the effect of remanufacturing cost variation is much significant than remanufacturing capacity variation.

Teunter et al. (2008) extended the work done in Tang and Teunter (2006) by comparing two scenarios. In the first scenario, manufacturing and remanufacturing were done on the same production line. In the second, they were done in separate areas. A mixed integer programming model and an algorithm to find the best fixed cycle time were developed where demand, return, and manufacturing/remanufacturing rates were constant. The results of numerical examples showed that in the two-line scenario, cycle time was longer, but cost per hour was lower due to longer idle time. Also, since the system was more flexible, the cost of inventory was reduced. The authors concluded going from a one-line system to a two-line system could reduce cost per time.

A deterministic linear programming model for a manufacturing/remanufacturing system, where both products and their components were considered, was developed in Han et al. (2013). The model allowed returned products to be either directly reused or remanufactured. Market was considered segmented into customers buying only new products, customers buying only remanufactured products, and customers who were not sensitive to price differences. Sensitivity analysis was performed on the price of remanufactured products and the rate of return. It was noticed that an increase in the price of remanufactured products had less of an effect on profit change because the rate of return was constant. On the other hand, the model was more sensitive to a decrease in the price and an increase in the rate of return.

2.3 Stochastic Models

A reliability model to calculate the number of returned products, and their usable and failed components, in a stochastic environment was presented in Murayama et al. (2006). A product would reach the end-of-life stage because of component failure or loss of value. A third party company would receive products, remove reusable components and send them for processing. Next, the number of usable components was integrated into a material requirement planning (MRP) system, which would release purchase orders. Both disassembly and ordering lead-times were considered more than one time period.

Guide (1997) studied the performance of a remanufacturing system under a drum-buffer-rope policy using a simulation model. Mean flow time, mean lateness, mean percentage of parts expedited, mean percentage tardy, and mean throughput were the key performance indicators. Different dispatching rules were compared against each other: first in-first processed, shortest processing time, earliest due date, longest processing time, and global shortest processing time. It was concluded that at 75% equipment utilization, the performances of all dispatching rules were similar. However, at 82% utilization, early due date and first in-first processed had the best results. As utilization increased above 90% no dispatching policy performed well.

Toktay et al. (2000) modeled Kodak's single-use camera supply chain as a closed queuing network. Most production planning articles prior to this considered forward and reverse flows separately. In this paper, the reverse flow was considered a continuation of the forward flow. Bayesian statistics and survival analysis were used to estimate probability density of returned products. The model aimed at minimizing procurement cost, inventory holding cost, and lost sales cost while incorporating dynamic aggregate base-stock policy with updated information on the customer-use stage. A heuristic procedure was developed to solve the model and study the effects of length of product life, procurement delay, demand rate, and information structure.

Products that are environmentally friendly may be costly. Material design change could affect tolerance, processing time, energy consumption and overhead costs. Stuart et al.

(1999) studied trade-off of yield, reliability, and business-focused environmental impacts for an electronic assembly/disassembly company. A stochastic mixed integer programming model was developed to maximize profit over the life cycle of the product where set-up cost, fixed cost, energy consumption cost, and packaging cost were considered. The model calculated economic production quantity (EPQ), process and packaging waste quantities, and recycling capacity. It also determined the type of products to be produced through proper processes to minimize environmental impact.

Tang et al. (2007) considered a make-to-order system in an engine manufacturing company where disassembly lead-time and procurement lead-time were stochastic. At each time period, returned products were disassembled. Based on the quantity of remanufactured components and the demand for final products, manufacturing of new components would start. The two main costs included in the model were inventory cost of disassembled components and stock-out cost. Optimized processes and lead-times were determined for production systems with single-component product and two-component product.

A single-item product recovery system with stochastic demand and return was studied by Inderfurth (1997). All costs were considered variable while lead-times of manufacturing and remanufacturing were deterministic and less than one time period. Two assumptions were proposed in order to make recovery profitable: production cost was higher than remanufacturing cost minus disposal cost and product price was higher than remanufacturing cost minus disposal cost. Stochastic dynamic decision making was used to solve the problem and observe the impact of the relationship of manufacturing and remanufacturing lead-times in getting the optimal solution under two main scenarios: no stock of returned product was allowed over several periods; stocking was allowed over several periods.

Van der Laan et al. (1999) studied the effect of lead-time variations in manufacturing/remanufacturing systems under pull and push strategies. They used the following assumptions in developing the model: 1) periodic review policy, 2) stochastic lead-time, 3) stochastic demand and return, and 4) no fixed ordering cost. A Markovian chain was used to calculate the net inventory of serviceable and remanufacturable parts as well as backordering level. They concluded that manufacturing lead-time had a greater impact on system cost than remanufacturing lead-time. Greater remanufacturing lead-time and greater variability in the manufacturing lead-time might sometimes result in cost reduction. Also, when rate of return and demand were equal, costs were insensitive to changes in lead-time duration. When inventory holding cost of serviceable parts was greater than that of remanufacturable parts, pull strategy outperformed push strategy.

Inderfurth and Langella (2006) studied a remanufacturing system where yield of disassembled parts was stochastic and there were common components among products. The following four costs were used to define the objective function: core acquisition costs, separation costs, disposal costs, and subassembly procurement costs. Heuristic methods were developed for cases of products with single components and products with multiple components to minimize disassembly cost. A stochastically proportional yield model was used to estimate expected yield rate and design of experiments was performed to study the effects of disassembly profit, subassembly procurement symmetry, subassembly demand symmetry, and yield distribution.

Li et al. (2006) studied an uncapacitated multi-product, multi-period stochastic remanufacturing system with part substitution where no backlog/shortage or disposal was allowed. This was a downward substitution, meaning that product "*i*" could be replaced by product "*j*", but not vice versa. The lead-time of manufacturing and remanufacturing were assumed to be less than one time period. A dynamic programming model was used to find the optimal solution. It was observed that substitution reduced the total cost as well as the number of set-ups for manufacturing and remanufacturing.

Bayindir et al. (2007) explored the conditions that made remanufacturing profitable in a segmented market. A profit maximization model was presented where demands were stochastic and lead-times were less than one time period. They remarked that for remanufacturing to be financially feasible, either the cost of remanufacturing or the resource hours required for remanufacturing must be less than the corresponding manufacturing factors. However, the effect of capacity outweighed the cost.

Kim et al. (2013) presented a profit optimization model for a capacitated manufacturing/ remanufacturing system with random lead-time, demand, and return in order to investigate the effect of inventory holding cost on returns. They found that the model was more sensitive to disposal cost than remanufacturing cost and less sensitive to remanufacturing and disposal cost change. They concluded that inventory of returns should be controlled by disposal, not by remanufacturing. Also, comparing push and pull policies, pull gave better profit margin while push was easier to use and required less parameters for decision making.

Dynamic lot sizing, in an environment where demand and returns were stochastic and backlog was allowed with a penalty cost, was studied by Arshad Naeem et al. (2013). A cost minimization model was developed to compare the inventory holding cost of returns versus the inventory holding cost of remanufactured products. They reached three conclusions: 1) unit cost of manufacturing and remanufacturing had no impact on the optimal structure, 2) situations with rate of return greater than demand rate should be avoided, and 3) the number of time periods affected optimal policy, thus short-term policy might not optimize long-term policy.

A reverse supply chain with stochastic demand, returns, and processing time was studied by Silva Filho (2011), where remanufacturing of returns was more expensive than manufacturing new products but inventory holding cost of returns was cheaper. Two scenarios with different return rates, 20% and 100%, were considered. The author developed a heuristic approach to transform the stochastic model to a linear model. He concluded that even with the greater cost for remanufacturing compared to manufacturing, remanufacturing could reduce the total cost of the system.

2.4 Imperfect Production Systems

Schwaller (1988) extended the economic order quantity (EOQ) and economic production quantity (EPQ) models (with and without backorder) by adding defect and inspection costs. In this model, set-up and unit inspection costs were added to the total cost equation and optimal production quantity and backorder level were calculated.

Hayek and Salameh (2001) studied an imperfect production system where inventory holding costs of good products and defective products were different. There was a maximum limit on backorder level; set-up costs were considered, and production and rework rates were different. The model calculated the optimal backorder level and production quantity where demand, defect, and rework rates were deterministic.

An extended EPQ model was developed by Chiu et al. (2009) for a system with quality failure in production and rework processes where backlogging and random machine breakdowns were permitted. Mathematical modeling was used to deal with variable cycle length while production, demand, defect, and rework rates were considered deterministic. The model calculated optimal production batch and backorder level considering breakdowns follow a uniform or a poisson distribution.

Otake et al. (1999) studied the effect of investment on set-up time reduction where no shortage was allowed. Demands and prices were considered deterministic. Two scenarios were considered: only production batch quantity was variable; production batch quantity and capital investments were variable. It was observed that shorter set-up time affected production batch size and inventory level, which in turn reduced costs and increased profits.

Wahab and Jaber (2010) studied the effect of the learning curve on lot size quantity in an imperfect production system where no shortage was allowed. The unit inspection cost, inspection time, and selling price of defective items were considered in the model. The authors concluded that lot size should be larger when there was significant difference between the holding cost of good and defective parts.

El Saadany and Jaber (2008) explored an imperfect manufacturing system that also performed repairs. An EOQ model was developed for two facilities, the first one performed production and repair and the second one consumed the product. Used products could be stored in the second facility or be returned to the first one for repair or disposal. The developed model aimed at finding optimal batch size for production and recovery and included a warm-up period for systems when there is no repair. Also, different set-up costs are assigned to manufacturing of different products.

El Saadany and Jaber (2010) developed a deterministic model for multiple manufacturing and production cycles where the return rate was variable and buy-back price depended on the quality of returned products. Their model included one facility for manufacturing and repair and another for collecting used products.

2.5 Incorporation of Uncertainty into Deterministic Models

The literature shows that uncertainty associated with demand and return is one of the major issues in a closed-loop supply chain. There are several articles on employing stochastic programming and scenario-based approaches in a forward supply chain with variable demand, lead-time, and yield of processes. Mobasheri (1989) proposed guidelines to conduct scenario analysis. Zipkin (1986), Federgruen and Zipkin (1986), Kleywegt et al. (2001), and Delft and Vial (2004) developed different methods to solve stochastic models in supply chain management. Santoso et al. (2005) applied stopping rules presented by Kleywegt et al. (2001) to their model of forward supply chain where demand was stochastic.

A stochastic non-linear model was developed in Azaron et al. (2008). The authors expanded the model presented in Santoso et al. (2005) by making demand, supply, processing and transportation lead-time uncertain (stochastic). Their model minimizes investment and logistics costs as well as financial risk and variance of the total cost. Goal Attainment methodology was used to solve this model.

Gupta and Maranas (2003) developed a stochastic model for a forward supply chain that included a penalty cost for over-stocking and loss of sales. Monte Carlo simulation was used to solve the model where variance of cost, range of cost variation, and probability of exceeding a certain cost level were considered as key performance indicators. They concluded that implementing uncertainty could result in lower costs, which was consistent with the findings of Escudero et al. (1993).

The scenario-based approach is best described by Birge and Louveaux (2011) in their book entitled "Introduction to Stochastic Programming". Eppen et al. (1989) developed a model for General Motors to determine facility type, locations and capacities through scenario planning and risk analysis. Escudero et al. (1993) used this approach for capacity planning, production planning, and designing of reverse logistics. Salema et al. (2007) incorporated a scenario-based approach into the model developed by Fleischmann and Dekker (2001) for a capacitated, multi-product system where demand and return were stochastic.

CHAPTER 3

DETERMINISTIC MATHEMATICAL MODEL

3.1 Introduction

In this chapter, a closed-loop supply chain network for a manufacturing and assembly company in the aerospace industry is presented. The network presented attempts to capture most of the activities that are common in these types of companies and introduces two new processes that, to the best of the author's knowledge, have not been studied in the literature. A mixed integer programming model is developed to optimize the profit. This model provides decisions for the number of components to be: manufactured, kept as an inventory, repaired, remanufactured, and scrapped at each time period. Demand, returns, and lead-times are considered deterministic. A commercial mathematical programming solver was used to solve this model. Further, a numerical example is provided to illustrate the actual operation and perform a sensitivity analysis to investigate the impact of different costs and lead-time variation.

3.2 Problem Definition

An aerospace manufacturing company with different product families is studied in this thesis. The proposed closed-loop network aiming at reduction of environmental impact and increase of profit is presented in this section. Each product is made by assembling different components which are made of different parts. Usually there are common components among products within a family. We study a closed-loop supply chain where components are manufactured and inspected and depending on the severity of defects, they could be sent for repair type I, repair type II or disposal. The repairs types are defined as follows.

- Repair type I: applicable to minor defects like scratches or unclear name plates. These defective components are repaired and returned to “as good as new” condition.
- Repair type II: applicable to some major defects. These defective components are repaired and used only on products that come for repair and overhaul because of their reduced life cycle.

New components are pulled out of the inventory pool either to assemble new products, which eventually go through intensive test and certification by regulatory authorities before being delivered to customers, or to reassemble used products. At each overhaul or repair, the product is disassembled and components are cleaned and inspected. Components in good condition are put back into products, and defective components are classified as: repairable, non-repairable, or suitable to be cannibalized. Dismantled parts are stored in service centers and when there is demand for used components during overhaul, these parts will be assembled to produce used components with limited life cycles. Lead-times, inventory carrying costs, and profit margins are the major factors determining where defective components should be sent. Figure 3.1 shows current forward and reverse flows in a closed-loop supply chain network. The processes presented in this figure have been studied separately across different industries. The specified processes are evaluated in an aerospace manufacturing company.

It is difficult to forecast the demand for components that can only be sent through repair type II. Many manufacturing companies have applied or are in the process of applying Continuous Improvement tools such as Kaizen, 5S, TQM to the practical aspects of their businesses. Inventory turnover ratio, which is calculated by dividing sales by inventory cost, is one of the metrics used to measure profitability in Lean manufacturing. Keeping defective components that cannot be repaired to "as new" condition increases inventory carrying costs and consequently decreases inventory turnover ratio.

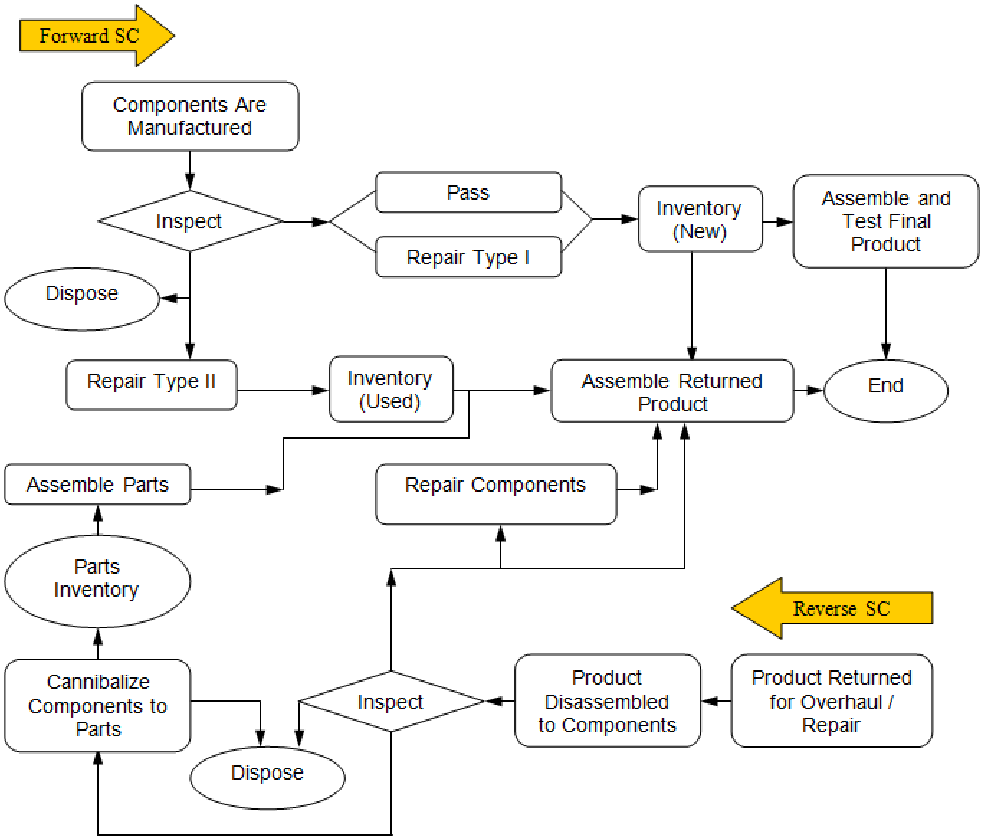

Figure 3.1: Current closed-loop supply chain network

In this chapter, a modified network is proposed as shown in Figure 3.2. New processes have been added to reduce the number of scraps and to increase profit over the product life cycle. Remanufacturing and transforming processes are considered for new defective components. Through transforming, a defective component is transformed to another "as good as new" component. Remanufacturing is also considered for repairable disassembled components as well as for those that are not repairable and their remanufacturing requires more time and is more costly. These components become the property of the company.

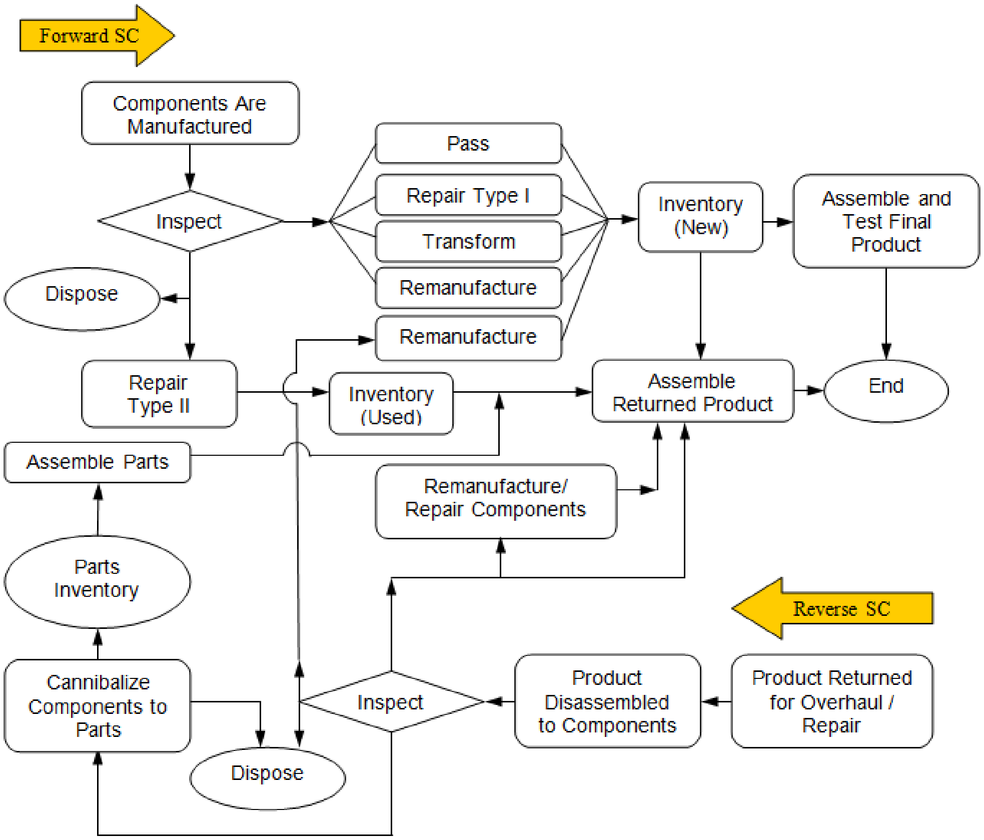

Figure 3.2: Recommended closed-loop supply chain network

3.3 Mathematical Model

In this section, we develop a mathematical model for the recommended closed-loop supply chain network as shown in Figure 3.2. The objective is to maximize the total profit, which is the total revenue minus the total cost. The total revenue is generated from the sales of final products, new and used spare components as well as repair and remanufacturing of customer owned components. The total cost is comprised of process cost of manufacturing, repairs, remanufacturing, transforming, cannibalization and their corresponding set-up costs as well as inventory carrying costs, shortage cost, and scraps costs. Inspection cost is considered part of the processing cost. Assembly cost, material handling cost, and new product packaging costs are included in the aggregated cost. Major constraints are for: set-up costs of each process; linking products, components, and parts; inventory level of components and parts; linking defects and processes; as well as production capacity.

The model gives priority to spare component demand, that is, at each period demand for new and used spare components is satisfied first. If there are not enough used components, new components will be required. It is only then that production of final products starts from assembling the remaining new components. The model allows for a backlog in assembly of new products. Inventory of new and used components is measured at the end of each period.

The capacity of the system, presented by labor hours in this model, is considered finite, i.e. no over-time or temporary staffs are allowed. During peak season more manpower is allocated to the service of returned products; most new component production should occur prior to these periods. Upper bound and lower bound limits are determined for certain processes to prevent the model of routing defective components solely through the processes with the highest profit margin.

The considered manufacturing process is associated with a certain defect rate. However, repair, transforming, and remanufacturing are considered to be without defect since defective components for these processes will be removed after inspection. Deterministic set-up cost is assumed for each process. Lead-time of the processes can be more or less than one time period. Before the model is presented, the notation is given.

Sets

i, k :	Index for component $i, k \in I, I = \{1, 2, 3\}$
j :	Index for product $j \in J, J = \{1, 2\}$
l :	Index for parts $l \in L, L = \{1, 2, 3, 4, 5\}$
t :	Index for time period $t \in T, T = \{1, 2, 3, 4\}$

Parameters

α :	Percentage of demand for new spare components
γ :	Upper bound limit for disposal rate of component *i*
BOM_{ij} :	Bill of Materials for product *j*
$BOM2_{li}$:	Bill of Materials for component *i*
Ct_i:	Manufacturing cost of component *i*
CT_j :	Aggregated cost of assembly, material handling, and packaging for product *j*
$Ctcan_{li}$:	Cannibalization cost of disassembled component *i*
$Ctr1_i$:	Repair (type I) cost of component *i*
$Ctr2_i$:	Repair (type II) cost of component *i*
$Ctrm_i$:	Remanufacturing cost of component *i*
$CtShortp_j$:	Unit shortage cost of product *j*
$CtStucan_{li}$:	Set-up cost of cannibalization of disassembled component *i*
$Ctstum_i$:	Set-up cost of manufacturing of component *i*

$Ctstur1_i$: Set-up cost of repair (type I) of component *i*

$Ctstur2_i$: Set-up cost of repair (type II) of component *i*

$Ctsturm_i$: Set-up cost of remanufacturing of component *i*

$CtstuRZ2_i$: Set-up cost of assembly of parts *l* to produce component *i*

$Ctstutrm_{ik}$: Set-up cost of transforming of component *i* to component *k*

$Cttrm_{ik}$: Transforming cost of component *i* to component *k*

Def_{it} : Number of defective components *i* produced at period *t*

$Defrat_i$: Defect rate of manufacturing of component *i*

$Demp_{jt}$: Demand for product *j* at period *t*

$Dems1_{it}$: Demand for new spare component *i* at period *t*

$Dems2_{it}$: Demand for used spare component *i* at period *t*

H_i : Inventory carrying cost per unit for component *i*

$H2_l$: Inventory carrying cost per unit for part *l*

Hrm_i : Remanufacturing hours of component *i*

$Hrm1_i$: Remanufacturing hours of non-repairable disassembled component *i*

Hrp_i : Manufacturing hours of component *i*

$Hrr1_i$: Repairing (type I) hours of component *i*

$Hrr2_i$: Repairing (type II) hours of component *i*

HRS : Summation of labor hours available for certain processes

$Hrtrm_{ik}$: Transforming hours of component *i* to component *k*

P_i : Disposal cost of component *i*

$Prc1_i$: Price of new spare component *i*

$Prc2_i$: Price of used spare component *i*

$PRCP_j$: Price of product *j*

$Prcz1_i$: Price of customer's repaired component *i*

$Prcz2_i$: Price of customer's remanufactured component *i*

$RCtSturm_i$: Set-up cost of remanufacturing of disassembled component *i*

$RCtSturm1_i$: Set-up cost of remanufacturing of non-repairable disassembled component *i*

$RCtStur2_i$: Set-up cost of repair of disassembled component *i*

$RCtrm_i$: Remanufacturing cost of disassembled component *i*

$RCtrm1_i$: Remanufacturing cost of non-repairable disassembled component *i*

$RCtr2_i$: Repair cost of disassembled component *i*

$RDefrat_i$: Defect rate of disassembled component *i*

$RW1rat_i$: Lower bound limit for disposal of component *i* after disassembly

$RW2rat_i$: Lower bound limit for cannibalization of component *i* after disassembly

$R2Ctr2_i$: Cost of assembling component *i* of parts *l*

$Salrat_l$: Defect rate of part *l* during cannibalization

t_1 : Lead-time of manufacturing

t_2 : Lead-time of remanufacturing

t_3 : Lead-time of repair (type I)

t_4 : Lead-time of repair (type II)

t_5 : Lead-time of transforming

t_6 : Lead-time of repair of disassembled component

t_7 : Lead-time of remanufacturing of disassembled component *i*

t_8 : Lead-time of cannibalization of disassembled component *i*

t_9 : Lead-time of assembly of cannibalized part

t_{10} : Lead-time of remanufacturing of non-repairable disassembled component *i*

t_{11} : Turnaround time of overhaul of product

$t_s \ and \ t_e$: Start and end periods for labor hour restriction

$Wrat_i$: Lower bound limit for disposal of component *i*

$Xrat_i$: Upper bound limit for repair (type I) of component *i*

Variables

$Invn_{it}$: Inventory of new component *i* at period *t* before assembling product *j*

$Invnf_{it}$: Inventory of new component *i* at period *t* after assembling product *j*

$InvSubpr_{lt}$: Inventory of part *l* at period *t*

$Invu_{it}$: Inventory of used component *i* at period *t*

Pr_{it} : Number of component *i* produced at period *t*

PRP_{jt} : Number of product *j* assembled at period *t*

Q_{it} : 1 if component *i* is manufactured at period *t*, otherwise 0

$R1_{it}$: 1 if component *i* is repaired (type I) at period *t*, otherwise 0

$R2_{it}$: 1 if component *i* is repaired (type II) at period *t*, otherwise 0

$RDef_{it}$: Number of defective component *i* disassembled at period *t*

$RPro_{jt}$: Number of returned product *j* at period *t*

Rm_{it} : 1 if component *i* is remanufactured at period *t*, otherwise 0

$RR2_{it}$: 1 if disassembled component *i* is repaired at period *t*, otherwise 0

RRm_{it} : 1 if disassembled component *i* is remanufactured at period *t*, otherwise 0

$RRm1_{it}$: 1 if non-repairable disassembled component *i* is remanufactured at period *t*, otherwise 0

$RRz2_{it}$: 1 if component *i* is produced of cannibalized part *l* at period *t*, otherwise 0

RS_{it} : 1 if component *i* is cannibalized at period *t*, otherwise 0

$Rw1_{it}$: Number of returned component *i* sent for disposal at period *t*

$Rw2_{it}$: Number of returned component *i* sent for cannibalization at period *t*

Ry_{it} : Number of component *i* remanufactured from repairable disassembled components at period *t*

$Ry1_{it}$: Number of component *i* remanufactured from non-repairable disassembled components at period *t*

Rz_{it} : Number of component *i* repaired from disassembled components at period *t*

$Rz2_{it}$: Number of used component *i* produced from cannibalized parts *l* at period *t*

$Short2_{it}$: Shortage of used component *i* at period *t*

$ShortP_{jt}$: Shortage of product *j* at period *t*

$Subpr_{lt}$: Part *l* produced as a result of cannibalization at period *t*

T_{ikt} : 1 if component *i* is transformed to component *k* at period *t*, otherwise 0

v_{ikt} : Number of component *i* transformed to component *k* at period *t*

w_{it} : Number of component *i* scraped at period *t*

x_{it} : Number of component *i* repaired (type I) at period *t*

y_{it} : Number of component *i* remanufactured at period *t*

z_{it} : Number of component *i* repaired (type II) at period *t*

Mathematical representation of the objective function is:

Maximize Z =

$$\begin{aligned}&\sum_j \sum_t (PRP_{jt} * (PRCP_j - CT_j) - ShortP_{jt} * CtShortp_j) + \sum_i \sum_t ((Dems1_{it} + \\ &Short2_{it}) * Prc1_i + (Dems2_{it} - Short2_{it}) * Prc2_i) + \sum_i \sum_t (Prcz1_i * Rz_{it+t_6} + \\ &Prcz2_i * Ry_{it+t_7}) - (\sum_i \sum_{t>t_1} (Pr_{it} * Ct_i + Ctr1_i * x_{it+t_3} + Ctrm_i * y_{it+t_2} + Ctr2_i * \\ &z_{it+t_4} + Ctstum_i * Q_{it-t_1} + Ctsturm_i * Rm_{it} + Ctstur1_i * R1_{it} + Ctstur2_i * R2_{it}) + \\ &\sum_i \sum_k \sum_{t>t_1} (T_{ikt} * Ctstutrm_{ik} + Cttrm_{ik} * v_{ikt+t_5}) + \sum_i (\sum_{t>t_1} (H_i * (Invu_{it} + \\ &Invnf_{it}) + P_i * (w_{it} + Rw1_{it} - Ry1_{it+t_{10}})) + \sum_t (RCtr2_i * Rz_{it+t_6} + RCtSturm_i * \\ &RRm_{it} + RCtSturm1_i * RRm1_{it} + RCtrm_i * Ry_{it+t_7} + RCtrm1_i * Ry1_{it+t_{10}} + \\ &RCtStur2_i * RR2_{it}) + \sum_t (\mathrm{Rz2}_{\mathrm{it}+t_9} * R2Ctr2_i + CtstuRZ2_i * \mathrm{RRz2}_{\mathrm{it}})) + \\ &\sum_l \sum_t H2_l * \mathrm{InvSubpr}_{\mathrm{lt}} + \sum_t \sum_i \sum_l (CtStucan_{li} * RS_{it} + \mathrm{Ctcan}_{\mathrm{li}} * \mathrm{Rw2}_{\mathrm{it}}))\end{aligned} \tag{3.1}$$

The above objective function will be maximized with the following constraint functions:

$$Def_{it} < Defrat_i * Pr_{it}, \ \forall\, i \in I, t \in T \tag{3.2}$$

$$x_{it+t_3} \leq Xrat_i * Def_{it}, \ \forall\, i \in I, t \in T \tag{3.3}$$

$$w_{it} \geq Wrat_i * Def_{it}, \ \forall\, i \in I, t \in T \tag{3.4}$$

$$y_{it+t_2} + z_{it+t_4} + w_{it} + x_{it+t_3} + \sum_k v_{ikt+t_5} = Def_{it}, \ \forall\, i \in I, t \in T \tag{3.5}$$

$$Invu_{it} - Short2_{it} = Invu_{it-1} + z_{it} + Rz2_{it} - Dems2_{it}, \ \forall\, i \in I, \ t \in T \tag{3.6}$$

$$Invn_{it} = Invnf_{it-1} - Short2_{it} + (1 - Defrat_i) * Pr_{it} + x_{it} + y_{it} + Ry1_{it} + \sum_k v_{kit} - Dems1_{it}, \forall\, i \in I, t \in T \tag{3.7}$$

$$Invnf_{it} = Invn_{it} - \sum_j BOM_{ij} * PRP_{jt} , \ \forall \, i \in I , \ t \in T \tag{3.8}$$

$$\sum_j BOM_{ij} * PRP_{jt} \leq \ Invn_{it} \ , \forall \, i \in I , j \in J, t \in T \tag{3.9}$$

$$PRP_{jt} \leq Demp_{jt} , \ \forall \ j \in J, t \in T \tag{3.10}$$

$$ShortP_{jt} = ShortP_{jt-1} + Demp_{jt} - PRP_{jt} , \ \forall \ j \in J, t \in T \tag{3.11}$$

$$ShortP_{jt} = 0 , \ \forall \, j \in J , t = \text{last period} \in T \tag{3.12}$$

$$Pr_{it} \leq 100000 * Q_{it-t_1} , \ \forall \ i \in I, t_1 < t \in T \tag{3.13}$$

$$x_{it+t_3} \leq 100000 * R1_{it} , \forall \ i \in I, t_1 < t \in T \tag{3.14}$$

$$y_{it+t_2} \leq 100000 * Rm_{it} , \forall \ i \in I, t_1 < t \in T \tag{3.15}$$

$$z_{it+t_4} \leq \ 100000 * R2_{it} , \ \forall \ i \in I, t_1 < t \in T \tag{3.16}$$

$$v_{ikt+t_5} \leq \ 100000 * T_{ikt} \ , \forall \, i , k \in I \ \text{ and } k - i = 1, \mathrm{t}_1 < \ t \in T \tag{3.17}$$

$$Ry_{it+t_7} \leq \ 100000 * RRm_{it} \ , \forall \, i \in I , t \in T \tag{3.18}$$

$$Rz_{it+t_6} \leq \ 100000 * RR2_{it} \ , \forall \ i \in I, t \in T \tag{3.19}$$

$$Rw2_{it} \leq 100000 * RS_{it} \ , \forall \, i \in I , t \in T \tag{3.20}$$

$$Rz2_{it+t_9} \leq 100000 * RRz2_{it} \ , \ \forall \ l \in L, t \in T \tag{3.21}$$

$$Ry1_{it+t_{10}} \leq \ 100000 * RRm1_{it} \ \ , \ \forall \, i \in I , t \in T \tag{3.22}$$

$$RDef_{it} < \ \ RDefrat_i * \sum_j BOM_{ij} \ * RPro_{\mathrm{jt}} \ , \ \forall \, i \in I , j \in J, t \in T \tag{3.23}$$

$$Rw1_{it} \geq \ RW1rat_i * \ RDef_{it} \ , \ \forall \, i \in I , t \in T \tag{3.24}$$

$$Rw2_{it} \geq \ RW2rat_i * \ RDef_{it} \ , \ \forall\, i \in I\, , t \in T \tag{3.25}$$

$$Ry_{it+t_7} + Rz_{it+t_6} + Rw1_{it} + \ Rw2_{it} \ = RDef_{it}\, , \ \forall\, i \in I\, , t \in T \tag{3.26}$$

$$Ry1_{it+t_{10}} \leq \gamma * \ Rw1_{it} \ , \forall\, i \in I\, , t \in T \tag{3.27}$$

$$Subpr_{lt+t_8} = \textstyle\sum_i (1 - Salrat_l) * BOM2_{li} * \ Rw2_{it} \ , \ \forall\, i \in I\, , l \in L, t \in T \tag{3.28}$$

$$InvSubpr_{lt} = \ InvSubpr_{lt-1} + Subpr_{lt} - \textstyle\sum_{\boldsymbol{i}} BOM2_{li} * \ Rz2_{it+t_9}$$

$$\forall\, l \in L, t \ \in T \tag{3.29}$$

$$\textstyle\sum_{\boldsymbol{i}} BOM2_{li} * \ \ Rz2_{it+t_9} \leq Invsubpr_{lt}\, , \ \forall\, i \in I\, , l \in L, t \ \in T \tag{3.30}$$

$$Rw1_{it} + Rw2_{it} = Dems1_{it+t_{11}} + Dems2_{it+t_{11}}\, , \forall\, i \in I\, , t \in T \tag{3.31}$$

$$Dems1_{it+t_{11}} = \alpha * (Rw1_{it} + Rw2_{it}\ )\, , \forall\, i \in I\, , t \in T \tag{3.32}$$

$$(\textstyle\sum_i \sum_{t_s < t < t_e} (Hrp_i * Pr_{it} + Hrm_i * \ y_{it} + Hrm1_i * \ Ry1_{it} + z_{it} * Hrr2_i + x_{it} *$$

$$Hrr1_i\ ) + \ \textstyle\sum_{i<k} \sum_k \sum_{t_s < t < t_e} v_{ikt} * Hrtrm_{ik}) < HRS \ , \ \forall\, i, k \in I\, , t \in T \tag{3.33}$$

Equations (3.2) to (3.5) define defects in the forward flow and put limitations on the number of components sent for repair (type I) and scrap in the forward flow. Equations (3.6) to (3.8) show the relationship between different types of components and inventories. At each period, the demand for used and new spare components is satisfied first. Shortage of used components is satisfied with new spares, and then the assembly of final products starts with the remaining components, as per Equations (3.9) to (3.12). In each period, if a process is taking place there will be set-up cost; Equations (3.13) to

(3.22) explain these cost allocations. After the returned products are disassembled, defective components are sent for repair, remanufacturing, scrap or cannibalization, as shown in Equations (3.23) to (3.26). Equation (3.27) places a limit on the number of company owned remanufacturable components. Cannibalized parts inventory and their assembly to produce used components are demonstrated in Equations (3.28) to (3.30). Demand for new and used spare components is calculated in Equations (3.31) and (3.32). Finally, Equation (3.33) puts limits on the labor hours available for certain processes at specific time periods. The purpose of adding this constraint is to allocate more labor hours in those periods to overhaul processes.

3.4 Numerical Example

A numerical example is presented to illustrate the developed model. The Bill of Material for two final products (A1 and A2) is shown in Figure 3.3. Three components (M, N, and P) with the quantity of three of each per product and five parts (K, G, O, S, F) with the quantity of one per component are considered. The labor rate is assumed at \$25 per hour. The cost per unit of raw materials for M, N, and P are: \$50, \$30, and \$40, respectively; while their production hours are 5, 3, and 4. Various lead-times of different processes are displayed in Table 3.1. New product demands and returned products in different time periods are highlighted in Table 3.2.

Table 3.3 presents some of the relationships used to generate input data. This is based on discussion with managers of service engineering and spare sales in two aerospace companies. For example, manufacturing cost of each component is the summation of the cost of raw materials and processing cost. Repair type I cost is a summation of the processing cost and 10% of raw materials used for manufacturing a new component. To remanufacture a new, but defective component, however, the required raw material is only 30% of the raw materials required to assemble a new component. Inventory carrying cost per unit is assumed to be 9% of the cost for a completed component. Component disposal cost is assumed at 20% of its manufacturing cost. The profit margin for repair of disassembled components is 25%.

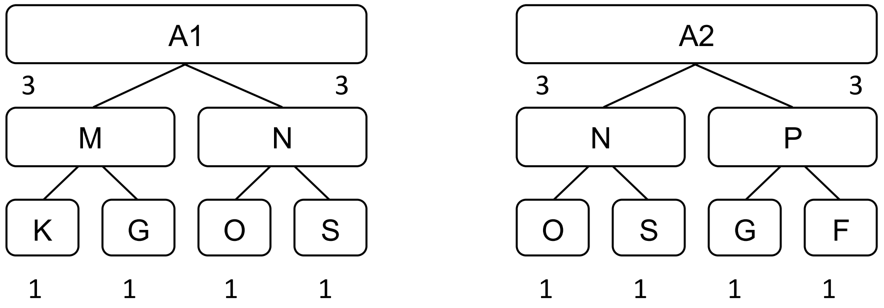

Figure 3.3: Products and their subassemblies

Table 3.1: Lead-time of different processes

Lead-time / Components	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	t_{10}
M	2	1	0	1	-*	1	2	-**	0	2
N	1	0	0	0	1	1	1	-**	0	2
P	2	1	0	0	1	1	1	-**	0	2

* No component can be transformed to M

** Applicable to parts and is considered less than one time period

Table 3.2: Demand and returns at each period

	T = 1	T = 2	T = 3	T = 4
Demand for Product A1	600	1200	900	200
Demand for Product A2	1200	900	810	200
Returned Product A1	300	320	480	0
Returned Product A2	320	210	510	0

Table 3.3: Relationships between input data

Description	Formula
Manufacturing cost of component	(Labor rate) x (Process hour) + Raw material cost
Repair (type I) cost of component	(Labor rate) x (Process hour) + 0.1 x (Raw material cost)
Repair (type II) cost of component	(Labor rate) x (Process hour) + 0.2 x (Raw material cost)
Remanufacturing cost of component	(Labor rate) x (Process hour) + 0.3 x (Raw material cost)
Transforming cost of component	(Labor rate) x (Process hour) + 0.15 x (Raw material cost)
Inventory carrying cost for one unit of component	0.09 x (Manufacturing cost)
Disposal cost of component	0.2 x (Manufacturing cost)
Price of new spare component	1.7 x (Manufacturing cost + set-up cost)
Price of used spare component	0.7 x (Price of new spare component)
Price of product	1.3 x (Manufacturing cost + set-up cost)
Price of customer's repaired component	1.25 x (Repair cost + set-up cost)
Price of customer's remanufactured components	0.8 x (Price of new spare component)
Repair cost of disassembled component	(Labor rate) x (Process hour) + 0.35 x (Raw material cost)
Remanufacturing cost of disassembled component	(Labor rate) x (Process hour) + 0.7 x (Raw material cost)
Remanufacturing cost of company owned disassembled component	(Labor rate) x (Process hour) + 0.8 x (Raw material cost)
Shortage cost of product	0.1 x (Price of product)

LINGO version 10 was used to run this example problem. A personal computer with a 64-bit operating system and 2.33 GHz CPU was used for all computational work. The optimal solution was obtained within several minutes of computation. The model statistics are 661 variables including 554 integer variables and 347 constraints. The corresponding profit and total inventory carrying cost are $1,522,955 and $707,913, respectively. Some of the outcome variable values are presented in Table 3.4. The numbers are summations over all periods. The results show that, transforming and remanufacturing increase profit and have non-zero values. Also, the model chose remanufacturing over repair, which is less time consuming, for customer owned disassembled components. As expected, inventory cost is high because of the labor hour limitation imposed by Equation (3.33). This cost can be reduced by increasing labor hours, especially during the periods when demand for repaired or remanufactured components is high. Different strategies such as adding extra shifts, allowing over-time hours or part-time or seasonal employment could be considered to overcome labor hour shortages where costs are justified. For example, a 10% labor hour increase in Equation (3.33) will reduce the total scraps by 19 units and increases sales by $7,710.

Table 3.4: Results of running the model

Variable	*Pr*	*Def*	*x*	*y*	*z*	*v*	*w*	*p*	*Sh1*	*Rz*	*Ry*	*Ry1*
Value	38520	3354	1677	1337	230	8	102	1955	713	0	4418	1785

3.5 Sensitivity Analysis

Sensitivity analysis is performed to compare the effect of some parameter changes on profitability, inventory cost, and inventory turnover ratio, as shown in Table 3.5 and Table 3.6. Table 3.5 presents solutions for different runs when remanufacturing costs, inventory carrying costs, and lead-times are reduced. Table 3.6 mirrors Table 3.5 for runs with costs and lead-time increases. In calculating inventory carrying cost, both complete units and work-in-process (WIP) units are considered. Unit carrying cost of WIP was assumed to be 50% less than for that complete unit. Also, two different approaches were used in calculating inventory turnover ratio: sales over inventory cost and profit over inventory cost. Based on this analysis, inventory carrying costs and remanufacturing costs have the highest effect on profit. In this example, the defect rate of production is low and many of the defective components can be corrected by repair type I. Therefore, there are not many components left to be transformed. As a result, the effect of the transforming cost is less than other factors. When defect rate increases or the percentage of defective components that could be repaired (type I) decreases, the effect of transforming costs will be more significant.

The third column in Table 3.5 and Table 3.6 are the original run. As the results show, an increase in remanufacturing lead-time of company owned disassembled components has less effect on profit than its decrease. This is consistent with the findings of Van der Laan et al. (1999).

Table 3.5: Results of sensitivity analysis with input factor decrease

		Base Run	Inventory Cost (-10%)	Transforming Cost (-10%)	Remanufacturing Cost (-10%)	Scrap Cost (-10%)	Lead-time Remanufacturing (-50%)
Summation of values over all time periods	*Pr*	38520	38520	38520	38520	38520	38980
	Def	3354	3354	3376	3354	3354	3398
	x	1677	1677	1688	1677	1677	1699
	y	1337	1337	938	1342	1337	1307
	z	230	230	220	232	230	235
	w	102	102	103	102	102	103
	v	8	8	427	0	8	54
	Ry	4418	4418	4418	4418	4418	4418
	RW1	3638	3638	3638	3638	3638	3632
	RW2	932	932	932	932	932	938
	Rz2	428	428	428	428	428	431
	Ry1	1785	1785	1785	1785	1785	1322
	Rz	0	0	0	0	0	0
KPI Value	Inventory Cost ($)	707913	627567	710427	707900	707913	723116
	Scraps (units)	1955	1955	1956	1955	1955	2413
	Profit ($)	1522955	1603301	1521783	1589816	1528353	1480559
	Sales ($)	8450074	8450074	8450894	8449910	8450074	8449418
	ITO Ratio (profit)	2.15	2.55	2.14	2.25	2.16	2.05
	ITO Ratio (sales)	11.94	13.46	11.90	11.94	11.94	11.68
% KPI Change	Inventory Cost	-	-11%	0%	0%	0%	2%
	Scraps	-	0%	0%	0%	0%	23%
	Profit	-	5%	0%	4%	0%	-3%
	ITO Ratio (profit)	-	19%	0%	4%	0%	-5%
	ITO Ratio (sales)	-	13%	0%	0%	0%	-2%

Table 3.6: Results of sensitivity analysis with input factor increase

		Base Run	Inventory Cost (+10%)	Transforming Cost (+10%)	Remanufacturing Cost (+10%)	Scrap Cost (+10%)	Lead-time Remanufacturing (+50%)
Summation of values over all time periods	Pr	38520	38520	38520	38520	38520	39330
	Def	3354	3354	3354	3376	3356	3433
	x	1677	1677	1677	1688	1678	1715
	y	1337	1337	1342	938	1329	1480
	z	230	230	233	220	233	0
	w	102	102	102	103	102	104
	v	8	8	0	427	14	134
	Ry	4418	4418	4418	4418	4418	4418
	$RW1$	3638	3638	3638	3638	3638	3642
	$RW2$	932	932	932	932	932	928
	$Rz2$	428	428	428	428	428	467
	$Ry1$	1785	1785	1785	1785	1784	1132
	Rz	0	0	0	0	0	0
KPI Value	Inventory Cost ($)	707913	764644	707910	710427	708026	731319
	Scraps (units)	1955	1495	1955	1956	1956	2614
	Profit ($)	1522955	1466224	1522995	1453702	1517531	1509700
	Sales ($)	8450074	8450074	8449828	8450894	8449828	8528367
	ITO Ratio (profit)	2.15	1.92	2.15	2.05	2.14	2.06
	ITO Ratio (sales)	11.94	11.05	11.94	11.90	11.93	11.66
% KPI Change	Inventory Cost	-	8%	0%	0%	0%	3%
	Scraps	-	-24%	0%	0%	0%	34%
	Profit	-	-4%	0%	-5%	0%	-1%
	ITO Ratio (profit)	-	-11%	0%	-5%	0%	-4%
	ITO Ratio (sales)	-	-7%	0%	0%	0%	-2%

To further gain insight into the behaviour of this model, the effects of different remanufacturing costs were studied separately. First, the effect of the remanufacturing cost of customer owned disassembled components, and subsequently that of company owned disassembled components were analyzed. The results are presented in Figures 3.4 and 3.5. As the cost of remanufacturing for customer owned components increases, the profit margin decreases. At a certain point (80% cost increase), this margin becomes less than the profit margin to repair the disassembled components. At this point, the model chooses repair over remanufacturing. The relationship between the profit and the cost of remanufacturing of company owned components is linear with no turning point. This means that after a certain point, this process is not profitable anymore and the demand is satisfied by manufacturing of new components. Figure 3.6 presents the effect of inventory carrying cost on profit. It is also a linear function with a steeper slope compared to that shown in Figure 3.5.

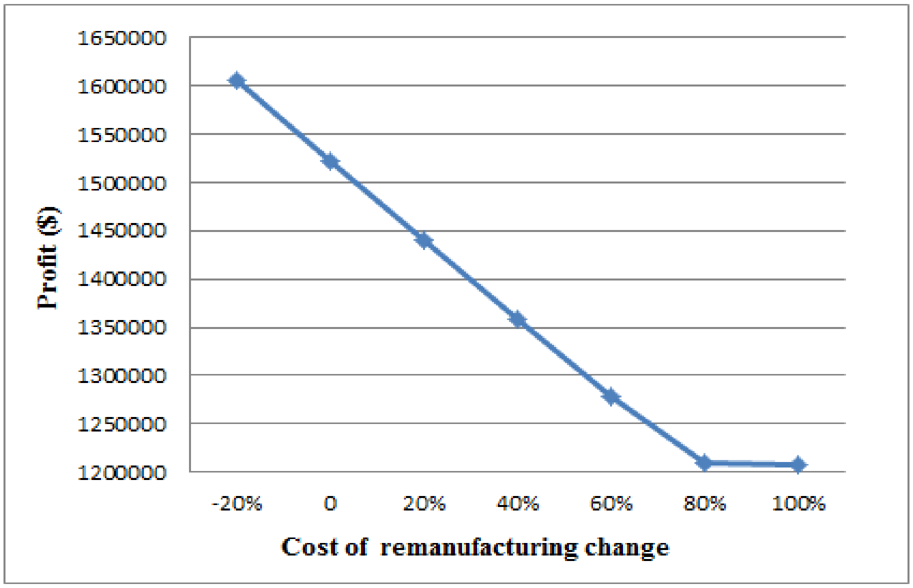

Figure 3.4: Effect of remanufacturing cost of customer owned disassembled component change on profit

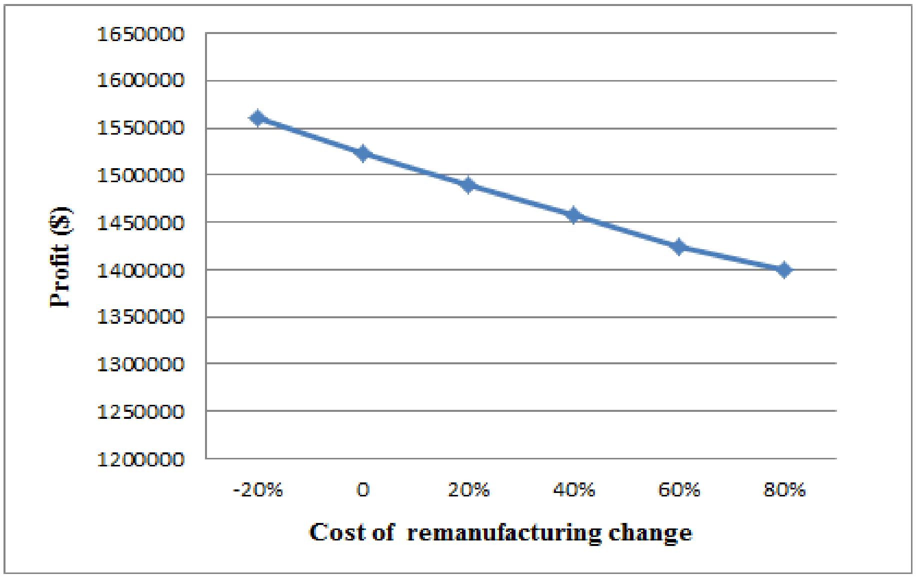

Figure 3.5: Effect of remanufacturing cost of company owned disassembled component change on profit

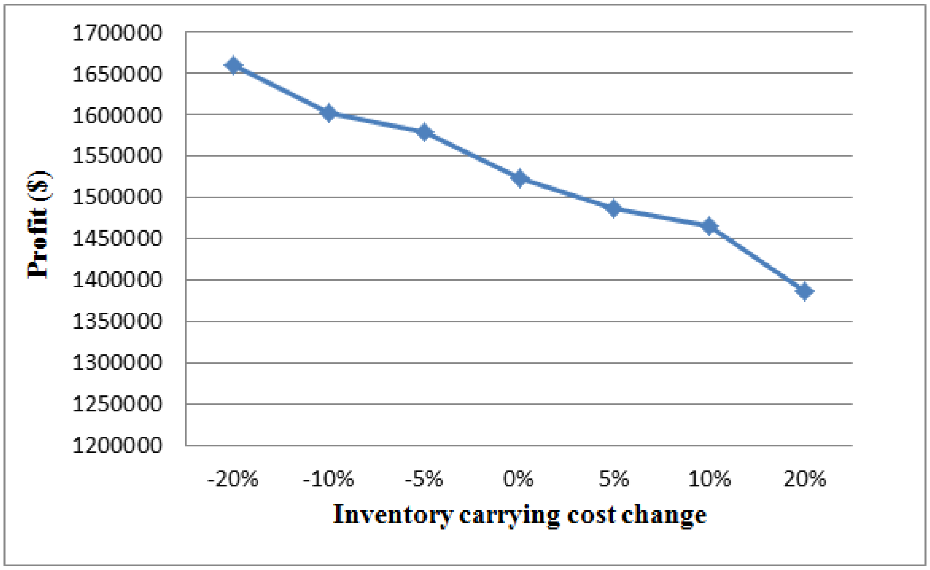

Figure 3.6: Effect of inventory carrying cost change on profit

CHAPTER 4

SCENARIO-BASED UNCERTAINTY ANALYSIS

4.1 Introduction

Many studies have been done on supply chain optimization, most of which are based on a deterministic approach. However, in real world, there are numerous sources of technical and business uncertainties such as production yield, lead-times, and demands. Based on the literature review, the two major methodologies used to introduce uncertainty to deterministic models are: Scenario Analysis and Stochastic Programming. In scenario analysis, possible future events are analyzed by considering different possible outcomes. Usually combinations of optimistic, pessimistic and most likely scenarios are defined with different weights assigned to each outcome. There is no limitation on how far in the future the forecast must go. Stochastic programming, on the other hand, puts emphasis on the decision to be made today given present recourse options, future uncertainties, and possible recourse actions in the future. It generates many more variables compared to scenario analysis for solving the same problem; therefore it becomes much more difficult to solve as the number of time periods increases. In this chapter, the model presented in the previous chapter is modified and uncertainty is incorporated into it. Different scenarios affecting lead-time and defect rate of disassembled components are considered. Numerical examples are provided to illustrate the new model. A commercial mathematical programming solver was used to solve the problem.

4.2 Problem Definition

In the previous chapter, a mathematical model for a typical supply chain network for an aerospace manufacturing company was presented. The considered company also conducts repair and remanufacturing activities. Two processes were introduced in order to reduce environmental impact through energy consumption and landfill reduction. These were transforming of new defective components and remanufacturing of customer owned disassembled components. The capacity constraint was introduced by limiting the total labor hours available for forward flow processes during periods with peak returns. As a result of this constraint, more components were produced and stored in advance to satisfy the high demand over these periods. Based on the sensitivity analysis performed in Chapter 3, inventory carrying cost and remanufacturing cost variation had the highest effect on profit change.

In this chapter, more emphasis is put on the reverse flow characteristic. The closed-loop supply chain network from the previous chapter is modified, as shown in Figure 4.1, by eliminating repair type I, cannibalization, and remanufacturing of new defective components. The two reasons for this elimination are:

1. The variation in quantity of cannibalized components and repair type I was insignificant through different runs performed for sensitivity analysis. That is, although these processes increase profitability, they are less sensitive to the input factors that were changed in the study.
2. The size of the problem can be reduced while the overall generality of the model will be kept.

An outsourcing option for remanufacturing of customer owned disassembled components is added. It is assumed that this option is more costly than in-house remanufacturing but has a more reliable lead-time. Lead-time of in-house remanufacturing is considered variable. Such situations arise when there are machine break-downs, material shortages, or operator absenteeism. Finally, capacity limitation is studied by switching the availability of total labor hours from forward flow processes to reverse flow processes.

Details of the considered problem and the corresponding mixed integer linear programming model as well as scenario-based approach are given in the following sections.

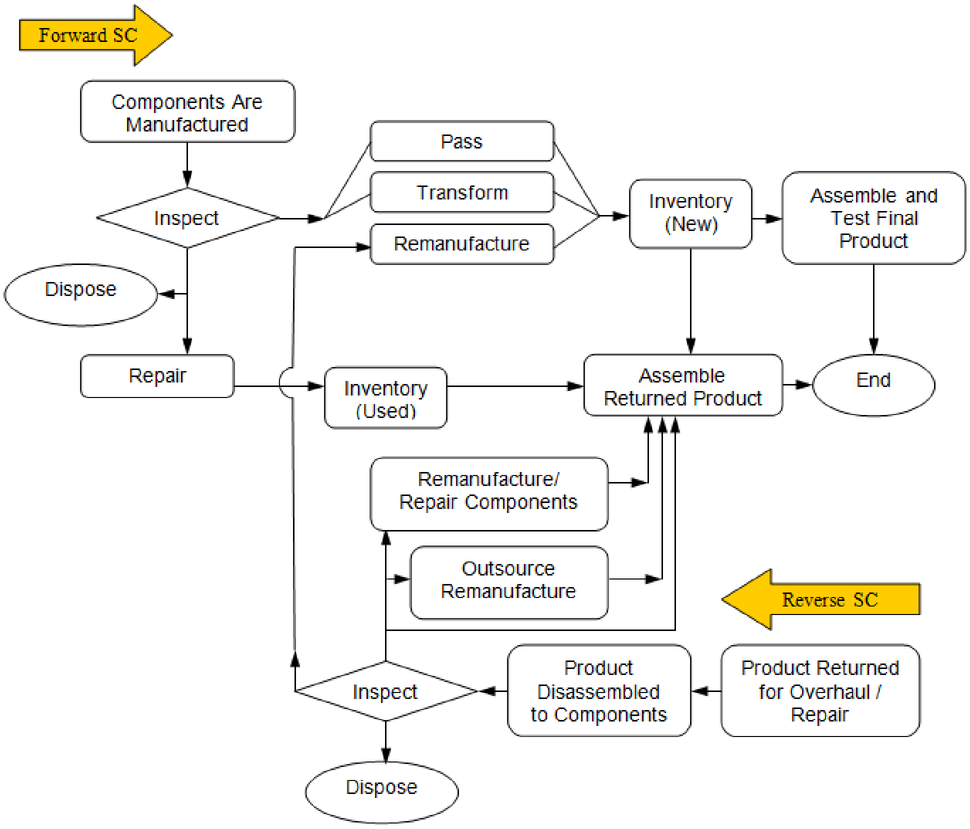

Figure 4.1: Closed-loop supply chain network for scenario-based model

4.3 Mathematical Model

In this section, a deterministic mathematical model for the supply chain network is developed as shown in Figure 4.1. Elements of uncertainty are then added, one at a time, to this model.

4.3.1 Deterministic Model

The model presented here is a maximization model with linear constraints and predefined demand and lead-times. The objective function is to maximize the profit, which is the total revenue minus the total cost. The total revenue includes revenue generated from the sales of final products, new spare components, used spare components, and from repair and remanufacturing of customer owned components. The total cost is comprised of costs of manufacturing, repair, remanufacturing, transforming, outsourced remanufacturing and the corresponding set-up costs as well as inventory carrying costs and scrap costs. Major constraints are for: adding set-up cost of each process; linking products to their components; calculating the inventory level of components; linking defects to quantity of components sent through each process.

Some of the assumptions made in developing the model in the previous chapter still hold, such as:

- An aggregated cost is considered for each product which includes assembly cost, material handling cost and new product packaging cost.
- Spare demand is assigned priority, that is, demand for new and used spare components are satisfied at each period before assembly of new products commences. Also, no backlog is permitted on spare demand.

- Manufacturing process is associated with a certain defect rate. However, repair, transforming, and remanufacturing are considered with no defects because defective components are rigorously inspected prior to these processes.
- The capacity of the system, presented by labor hours, is considered finite at service centers i.e. no over-time or turnover is allowed.

In this model, repair type I and remanufacturing are eliminated from the forward flow. To prevent the model from sending all new defective components through the transforming process, an upper bound limit is introduced for this process.

As the global airline fleet increases, with a projection of doubling by 2033, original equipment manufacturers (OEMs) are forced to outsource a portion of their refurbishing activities to independent shops. In this model remanufacturing of customer owned disassembled components is allowed to be outsourced up to a certain level.

Since the main objective of this study is to explore the model behaviour when there is uncertainty in the reverse supply chain, system capacity is redefined by placing limitations on total labor hours available for repair and in-house remanufacturing in the reverse flow. The notation is defined as follows.

Sets

i, k :	Index for component	$i, k \in I, I = \{1, 2, 3\}$
j :	Index for product	$j \in J, J = \{1, 2\}$
t :	Index for time period	$t \in T, T = \{1, 2, 3, 4\}$

Parameters

α :	Percentage of demand for new spare components
$\beta 1$:	Upper bound limit for transforming process of component *i*
$\beta 2$:	Upper bound limit for outsourced remanufacturing process of component *i*
γ:	Upper bound limit for disposal rate of component *i*
BOM_{ij} :	Bill of Materials for product *j*
Ct_i :	Manufacturing cost of component *i*
CT_j :	Aggregated cost of assembly, material handling, and packaging for product *j*
Ctr_i :	Repair cost of new but defective component *i*
$CtShortp_j$:	Unit shortage cost of product *j*
$Ctstum_i$:	Set-up cost of manufacturing of component *i*
$Ctstur_i$:	Set-up cost of repair of new but defective component *i*
$Ctstutrm_{ik}$:	Set-up cost of transforming of component *i* to component *k*
$Cttrm_{ik}$:	Transforming cost of component *i* to component *k*
Def_{it} :	Number of defective components *i* produced at period *t*
$Defrat_i$:	Defect rate of manufacturing of component *i*
$Demp_{jt}$:	Demand for product *j* at period *t*
$Dems1_{it}$:	Demand for new spare component *i* at period *t*
$Dems2_{it}$:	Demand for used spare component *i* at period *t*
H_i :	Inventory carrying cost per unit for component *i*
$Hrrm_i$:	Remanufacturing hours of disassembled component *i*
$Hrr2_i$:	Repairing hours of disassembled component *i*

HRS : Summation of labor hours available for certain processes

P_i : Disposal cost of component *i*

$Prc1_i$: Price of new spare component *i*

$Prc2_i$: Price of used spare component *i*

$PRCP_j$: Price of product *j*

$Prcz1_i$: Price of customer's repaired component *i*

$Prcz2_i$: Price of customer's remanufactured component *i*

$RCtSturm_i$: Set-up cost of remanufacturing of disassembled component *i*

$RCtSturm1_i$: Set-up cost of remanufacturing of non-repairable disassembled component *i*

$RCtStur2_i$: Set-up cost of repair of disassembled component *i*

$RCtrm_i$: Remanufacturing cost of disassembled component *i*

$RCtrm1_i$: Remanufacturing cost of non-repairable disassembled component *i*

$RCtrm2_i$: Outsourced remanufacturing cost of component *i*

$RCtr2_i$: Repair cost of disassembled component *i*

$RDefrat_i$: Defect rate of disassembled component *i*

$RW1rat_i$: Lower bound limit for disposal of component *i* after disassembly

t_1 : Lead-time of manufacturing

t_2 : Lead-time of repair of new but defective component

t_3 : Lead-time of transforming of component *i* to component *k*

t_4 : Lead-time of remanufacturing of disassembled component *i*

t_5 : Lead-time of remanufacturing of non-repairable disassembled component *i*

t_6 : Lead-time of outsourced remanufacturing of disassembled component *i*

t_7 : Lead-time of repair of disassembled component *i*

t_8 : Turnaround time of overhaul of product

$t_s \ and \ t_e$: Start and end period for labor hour restriction

$Wrat_i$: Lower bound limit for disposal of component *i*

Variables

$Invn_{it}$: Inventory of new component *i* at period *t* before assembling product *j*

$Invnf_{it}$: Inventory of new component *i* at period *t* after assembling product *j*

$Invu_{it}$: Inventory of used component *i* at period *t*

Pr_{it} : Number of component *i* produced at period *t*

PRP_{jt} : Number of product *j* assembled at period *t*

Q_{it} : 1 if component *i* is manufactured at period *t*, otherwise 0

$R2_{it}$: 1 if component *i* is repaired at period *t*, otherwise 0

$RDef_{it}$: Number of defective component *i* disassembled at period *t*

$RPro_{jt}$: Number of returned product *j* at period *t*

$RR2_{it}$: 1 if disassembled component *i* is repaired at period *t*, otherwise 0

RRm_{it} : 1 if disassembled component *i* is remanufactured at period *t*, otherwise 0

$RRm1_{it}$: 1 if non-repairable disassembled component *i* is remanufactured at period *t*, otherwise 0

$Rw1_{it}$: Number of disassembled component *i* sent for disposal at period *t*

Ry_{it} : Number of component *i* remanufactured from disassembled components at period *t*

$Ry1_{it}$: Number of component *i* remanufactured from non-repairable disassembled components at period *t*

$Ry2_{it}$: Number of disassembled component *i* outsourced for remanufacturing at period *t*

Rz_{it} : Number of component *i* repaired from disassembled components at period *t*

$Short2_{it}$: Shortage of used component *i* at period *t*

$ShortP_{jt}$: Shortage of product *j* at period *t*

T_{ikt} : 1 if component *i* is transformed to component *k* at period *t*, otherwise 0

v_{ikt} : Number of component *i* transformed to component *k* at period *t*

w_{it} : Number of component *i* scraped at period *t*

y_{it} : Number of component *i* remanufactured at period *t*

z_{it} : Number of component *i* repaired at period *t*

The mixed integer linear programming model is formulated as follows.

Maximize Z =

$$\sum_j \sum_t \left(PRP_{jt} \ast (PRCP_j - CT_j) - ShortP_{jt} \ast CtShortp_j\right) + \sum_i \sum_t \left((Dems1_{it} + Short2_{it}) \ast Prc1_i + (Dems2_{it} - Short2_{it}) \ast Prc2_i\right) + \sum_i \sum_t \left(Prcz1_i \ast Rz_{it+t_7} + Prcz2_i \ast (Ry_{it+t_4} + Ry2_{it+t_6})\right) - \Big(\sum_i \sum_{t>t_1} (Pr_{it} \ast Ct_i + Ctr_i \ast z_{it+t_2} + Ctstum_i \ast Q_{it-t_1} + Ctstur_i \ast R2_{it}) + \sum_i \sum_{t>t_1} \left(H_i \ast (Invu_{it} + Invnf_{it}) + P_i \ast (w_{it} + Rw1_{it} - Ry1_{it+t_5})\right) + \sum_i \sum_k \sum_{t>t_1} (T_{ikt} \ast Ctstutrm_{ik} + Cttrm_{ik} \ast v_{ikt+t_3}) + \sum_i \sum_t (RCtr2_i \ast Rz_{it+t_7} + RCtSturm_i \ast RRm_{it} + RCtSturm1_i \ast RRm1_{it} + RCtrm_i \ast Ry_{it+t_4} + RCtrm2_i \ast Ry2_{it+t_6} + RCtrm1_i \ast Ry1_{it+t_5} + RCtStur2_i \ast RR2_{it})\Big) \qquad (4.1)$$

Constraints:

$$Def_{it} < Defrat_i * Pr_{it} \;, \forall\, i \in I\,,\; t \in T \tag{4.2}$$

$$w_{it} \geq Wrat_i * Def_{it} \;, \forall\, i \in I\,,\; t \in T \tag{4.3}$$

$$v_{ikt+t_3} \leq \beta 1 * Def_{it} \;, \forall\, i \in I\,,\; t \in T \tag{4.4}$$

$$z_{it+t_2} + w_{it} + \sum_k v_{ikt+t_3} = Def_{it} \;,\; \forall\, i \in I\,, t \in T \tag{4.5}$$

$$Invu_{it} - Short2_{it} = Invu_{it-1} + z_{it} - Dems2_{it} \,, \forall\, i \in I\,, t \in T \tag{4.6}$$

$$Invn_{it} = Invnf_{it-1} - Short2_{it} + (1 - Defrat_i) * Pr_{it} + Ry1_{it} - Dems1_{it} + \sum_k v_{kit}$$

$$\forall\, i \in I\,,\; t \in T \tag{4.7}$$

$$Invnf_{it} = Invn_{it} - \sum_j BOM_{ij} * PRP_{jt} \;, \forall\, i \in I\,,\; t \in T \tag{4.8}$$

$$\sum_j BOM_{ij} * PRP_{jt} \leq Invn_{it} \;,\; \forall\, i \in I\,, j \in J, t \in T \tag{4.9}$$

$$PRP_{jt} \leq Demp_{jt} \;, \forall\; j \in J, t \in T \tag{4.10}$$

$$ShortP_{jt} = ShortP_{jt-1} + Demp_{jt} - PRP_{jt} \;,\; \forall\, j \in J\,,\; t \in T \tag{4.11}$$

$$ShortP_{jt} = 0 \,, \forall\, j \in J\,, t = \text{last period} \in T \tag{4.12}$$

$$Pr_{it} \leq 100000 * Q_{it-t_1} \,,\; \forall\, i \in I\,, t_1 < t \in T \tag{4.13}$$

$$z_{it+t_2} \leq 100000 * R2_{it} \,,\; \forall\, i \in I\,, t_1 < t \in T \tag{4.14}$$

$$v_{ikt+t_3} \leq 100000 * T_{ikt} \;,\; \forall\, i\,, k \in I \text{ and } k - i = 1, t_1 < t \in T \tag{4.15}$$

$$Ry_{it+t_4} \leq 100000 * RRm_{it} \;,\; \forall\, i \in I\,,\; t \in T \tag{4.16}$$

$$Rz_{it+t_7} \leq 100000 * RR2_{it} \;,\; \forall\, i \in I\,,\; t \in T \tag{4.17}$$

$$Ry1_{it+t_5} \leq 100000 * RRm1_{it} \,, \forall\, i \in I\,,\; t \in T \tag{4.18}$$

$$RDef_{it} = \ RDefrat_i * \sum_j BOM_{ij} \ * RPro_{\mathrm{jt}}, \ \ \forall\, i \in I\,,\ t\ \in T \tag{4.19}$$

$$Ry_{it+t_4} + Rz_{it+t_7} + Ry2_{it+t_6} + \ Rw1_{it} \ = RDef_{it}\,, \forall\, i \in I\,,\ t\ \in T \tag{4.20}$$

$$Rw1_{it} \geq \ RW1rat_i * \ RDef_{it} \ \ , \ \forall\, i \in I\,,\ t\ \in T \tag{4.21}$$

$$Ry1_{it+t_5} \leq \gamma * \ Rw1_{it} \ \ , \ \forall\, i \in I\,,\ t\ \in T \tag{4.22}$$

$$Ry2_{it+t_6} \leq \ \beta 2 * \ RDef_{it} \ \ , \forall\, i \in I\,,\ t\ \in T \tag{4.23}$$

$$Rw1_{it} = Dems1_{it+t_8} + Dems2_{it+t_8}\,, \ \forall\, i \in I\,,\ t\ \in T \tag{4.24}$$

$$Dems1_{it+t_8} = \alpha * Rw1_{it} \ \ , \forall\, i \in I\,,\ t\ \in T \tag{4.25}$$

$$\sum_i \sum_{t_s\ <t<\ t_e} (Hrrm_i * Ry_{it} + Rz_{it} * Hrr2_i) < HR\,, \forall\, i \in I\,,\ t\ \in T \tag{4.26}$$

Equations (4.2) to (4.5) define defects in the forward flow and put a lower boundary on the number of scraped and transformed components in the forward flow. Equations (4.6) to (4.8) show the relationship between new and used component inventories. At each period, the demand for used and new spare components is satisfied first. Shortage of used components is satisfied with new spares. Then the assembly of final products starts with the remaining components, as per Equations (4.9) to (4.12). At each period, if a process is taking place there will be set-up costs; Equations (4.13) to (4.18) ensure these cost allocations. After returned products are disassembled, defective components are sent for repair, remanufacturing or scrap, as shown in Equations (4.19) to (4.21). Equation (4.22) places a limit on the number of company owned disassembled remanufacturable components. There is a tendency to keep outsourcing activity limited as shown in Equation (4.23). Demand for new and used spare components is calculated in Equations

(4.24) and (4.25). Finally, Equation (4.26) puts limits on the labor hours available for remanufacturing and repair of disassembled components at the peak periods.

4.3.2 Scenario-based Approach

Considering the large number of variables in the model and knowing that more than one or two time periods in the future are required for planning, a scenario-based approach is employed to model an uncertain defect rate of disassembled components and lead-time of in-house remanufacturing of customer owned components. This approach is best described by Birge and Louveaux (2011) and has been used by different authors such as Eppen et al. (1989), Escudero et al. (1993), and Salema et al. (2007).

The following example is used to explain the uncertainty approach. Ɓ is considered the set of all possible scenarios and β ∈ Ɓ is a particular scenario. Binary variable y is related to s, which is the vector of the set-up costs. The vector of costs is presented by c; and p_β is the vector of price related to variable z in the objective function. A simplified model for scenario β can be stated as follows:

Max $p_\beta z - (s_\beta y + c_\beta x)$

s.t $A_\beta x \le a_\beta x$

$B_\beta x \le Cy$

$y \in \{0,1\}, \quad x \ge 0,$

where A_β, B_β and C are metrics and a_β is a vector. If the probability of each scenario β is shown by $Ƥ_\beta$, the uncertainty model can be formulated as:

Max $\sum_\beta Ƥ_\beta\ (p_\beta z - (s_\beta y + c_\beta x))$

s.t $A_\beta x \le a_\beta x$

$$B_{\beta}x \leq Cy$$

$$y \in \{0,1\}, \quad x \geq 0,$$

In a study conducted by Escudero et al. (1993), different variables were considered scenario dependent in a multi-product, multi-period production planning model. They concluded that more recourse variables will lead to better results. In this proposed model, the defect rate of disassembled components and the lead-time of in-house remanufacturing of customer owned components are considered recourse variables. All other variables are allowed to be influenced by this variation. To do so, index *l* is added to all the variables. Demand for new products, returned products, and total labor hours available are not scenario-dependent. The same nomenclature defined for the deterministic model will be employed. However, the followings are modified to add the scenario index.

Set

l :	Index for scenario	$l \in L, L = \{1, 2, 3\}$

Parameters

ρ_l :	Probability of occurrence of scenario *l*
$Dems1_{itl}$:	Demand for new spare component *i* at period *t* for scenario *l*
$Dems2_{itl}$:	Demand for used spare component *i* at period *t* for scenario *l*
$RDefrat_{il}$:	Defect rate of disassembled component *i* for scenario *l*

Variables

Def_{itl} :	Number of defective components *i* produced at period *t* for scenario *l*
$Invn_{itl}$:	Inventory of new component *i* at period *t* before assembling product *j* for scenario *l*

$Invnf_{itl}$: Inventory of new component *i* at period *t* after assembling product *j* for scenario *l*

$Invu_{itl}$: Inventory of used component *i* at period *t* for scenario *l*

Pr_{itl} : Number of component *i* produced at period *t* for scenario *l*

PRP_{itl} : Number of product *j* assembled at period *t* for scenario *l*

Q_{itl} : 1 if component *i* is manufactured at period *t*, otherwise 0 for scenario *l*

$R2_{itl}$: 1 if component *i* is repaired at period *t*, otherwise 0 for scenario *l*

$RDef_{itl}$: Number of defective component *i* disassembled at period *t* for scenario *l*

$RR2_{itl}$: 1 if disassembled component *i* is repaired at period *t*, otherwise 0 for scenario *l*

RRm_{itl} : 1 if disassembled component *i* is remanufactured at period *t*, otherwise 0 for scenario *l*

$RRm1_{itl}$: 1 if non-repairable disassembled component *i* is remanufactured at period *t*, otherwise 0 for scenario *l*

$Rw1_{itl}$: Number of returned component *i* sent for disposal at period *t* for scenario *l*

Ry_{itl} : Number of component *i* remanufactured from repairable disassembled components at period *t* for scenario *l*

$Ry1_{itl}$: Number of component *i* remanufactured from non-repairable disassembled components at period *t* for scenario *l*

$Ry2_{itl}$: Disassembled component *i* outsourced for remanufacturing at period *t* for scenario *l*

Rz_{itl} : Number of component *i* repaired from disassembled components at period *t* for scenario *l*

$Short2_{itl}$: Shortage of used component *i* at period *t* for scenario *l*

$ShortP_{jtl}$: Shortage of product *j* at period *t* for scenario *l*

T_{iktl} : 1 if component *i* is transformed to component *k* at period *t*, otherwise 0 for scenario *l*

v_{iktl} : Number of component *i* transformed to component *k* at period *t* for scenario *l*

w_{itl} : Number of component *i* scraped at period *t* for scenario *l*

y_{itl} : Number of component *i* remanufactured at period *t* for scenario *l*

z_{itl} : Number of component *i* repaired at period *t* for scenario *l*

Employing these changes, the model can be re-written as follows.

Maximize Z =

$$\begin{aligned}
&\sum_l \rho_l * (\sum_j \sum_t \ (PRP_{jtl} * (PRCP_j - CT_j) - ShortP_{jtl} * CtShortp_j) + \\
&\sum_i \sum_t ((Dems1_{itl} + Short2_{itl}) * Prc1_i + (Dems2_{itl} - Short2_{itl}) * \ Prc2_i \ ) \ + \\
&\sum_i \sum_t \ (Prcz1_i * Rz_{it+t_7 l} \ + Prcz2_i * (Ry_{it+t_4 l} + Ry2_{it+t_6 l})) - \ (\sum_i \sum_{t>t_1} (Pr_{itl} * \ Ct_i + \\
&Ctr_i * z_{it+t_2 l} + Ctstum_i * Q_{it-t_1 l} + Ctstur_i * R2_{itl}) + \sum_i \sum_{t>t_1} (H_i * (Invu_{itl} + \\
&Invnf_{itl}) + P_i * (w_{itl} \ + Rw1_{itl} - Ry1_{it+t_5 l})) + \sum_i \sum_k \sum_{t>t_1} (T_{iktl} * Ctstutrm_{ik} + \\
&Cttrm_{ik} * v_{ikt+t_3 l}) + \ \sum_i \sum_t (RCtr2_i * Rz_{it+t_7 l} \ + RCtSturm_i * \ RRm_{itl} + \\
&RCtSturm1_i * RRm1_{itl} \ + RCtrm_i * Ry_{it+t_4 l} + RCtrm2_i * Ry2_{it+t_6 l} + \ RCtrm1_i * \\
&Ry1_{it+t_5 l} + RCtStur2_i * RR2_{itl} \ ) \ ) \ )
\end{aligned} \tag{4.1}$$

Constraints:

$$Def_{itl} < \ Defrat_i * \ Pr_{itl} \ , \ \forall \, i \in I \ , \ t \ \in T, l \in L \tag{4.2}$$

$$w_{itl} \geq \ Wrat_i * Def_{itl} \ , \forall \, i \in I \ , \ t \ \in T, l \in L \tag{4.3}$$

$$v_{ikt+t_3 l} \leq \ \beta 1 * Def_{itl} \ , \forall \, i \in I \ , \ t \ \in T, l \in L \tag{4.4}$$

$$z_{it+t_2 l} + w_{itl} + \sum_k v_{ikt+t_3 l} = Def_{itl} \ , \forall \, i \in I \, , t \ \in T, l \in L \tag{4.5}$$

$$Invu_{itl} - Short2_{itl} = \ Invu_{it-1l} + z_{itl} \ - Dems2_{itl} \ , \forall \, i \in I \ , \ t \ \in T, l \in L \tag{4.6}$$

$$Invn_{itl} = Invnf_{it-1l} - Short2_{itl} + (1 - Defrat_i) * Pr_{itl} + Ry1_{itl} - Dems1_{itl} + \sum_k v_{kitl} \ , \forall\, i \in I\,,\ t \in T, l \in L \tag{4.7}$$

$$Invnf_{itl} = Invn_{itl} - \sum_j BOM_{ij} * PRP_{jtl} \ , \forall\, i \in I\,,\ t \in T, l \in L \tag{4.8}$$

$$\sum_j BOM_{ij} * PRP_{jtl} \leq Invn_{itl} \ , \forall\, i \in I\,, j \in J, t \in T, l \in L \tag{4.9}$$

$$PRP_{jtl} \leq Demp_{jt} \ , \forall\, i \in I\,, j \in J, t \in T, l \in L \tag{4.10}$$

$$ShortP_{jtl} = ShortP_{jt-1l} + Demp_{jt} - PRP_{jtl} \ , \forall\, j \in J, t \in T, l \in L \tag{4.11}$$

$$ShortP_{jtl} = 0\,,\ \forall\, j \in J\,, t = \text{last period} \in T, l \in L \tag{4.12}$$

$$Pr_{itl} \leq 100000 * Q_{it-t_1l} \ ,\ \forall\, i \in I\,, t_1 < t \in T, l \in L \tag{4.13}$$

$$z_{it+t_2l} \leq 100000 * R2_{itl} \ ,\ \forall\, i \in I\,, t_1 < t \in T, l \in L \tag{4.14}$$

$$v_{ikt+t_3l} \leq 100000 * T_{iktl}\,, \forall\, i\,, k \in I \text{ and } k - i = 1, t_1 < t \in T, l \in L \tag{4.15}$$

$$Ry_{it+t_4l} \leq 100000 * RRm_{itl} \ ,\ \forall\, i \in I\,,\ t \in T, l \in L \tag{4.16}$$

$$Rz_{it+t_7l} \leq 100000 * RR2_{itl} \ ,\ \forall\, i \in I\,,\ t \in T, l \in L \tag{4.17}$$

$$Ry1_{it+t_5l} \leq 100000 * RRm1_{itl}\,,\ \forall\, i \in I\,,\ t \in T, l \in L \tag{4.18}$$

$$RDef_{itl} = RDefrat_{il} * \sum_j BOM_{ij} * RPro_{\mathrm{jt}}\,,\ \forall\, i \in I\,,\ t \in T, l \in L \tag{4.19}$$

$$Ry_{it+t_4l} + Rz_{it+t_7l} + Ry2_{it+t_6l} + Rw1_{itl} = RDef_{itl}\,, \forall\, i \in I\,,\ t \in T, l \in L \tag{4.20}$$

$$Rw1_{itl} \geq RW1rat_i * RDef_{itl} \ ,\ \forall\, i \in I\,,\ t \in T, l \in L \tag{4.21}$$

$$Ry1_{it+t_5l} \leq \gamma * Rw1_{itl}\,,\ \forall\, i \in I\,,\ t \in T, l \in L \tag{4.22}$$

$$Ry2_{it+t_6l} \leq \beta2 * RDef_{itl} \ , \forall\, i \in I \ , \ t \in T, l \in L \tag{4.23}$$

$$Rw1_{itl} = Dems1_{it+t_8l} + Dems2_{it+t_8l} \ , \forall\, i \in I \ , \ t \in T, l \in L \tag{4.24}$$

$$Dems1_{it+t_8l} = \alpha * Rw1_{itl} \ , \ \forall\, i \in I \ , \ t \in T, l \in L \tag{4.25}$$

$$\sum_l \sum_i \sum_t (Hrrm_i * Ry_{itl} + Rz_{itl} * Hrr2_i) < HRS \ , \ \forall\, i \in I \ , \ t \in T, l \in L \tag{4.26}$$

4.4 Numerical Examples

Numerical examples are presented in this section to illustrate this model and highlight the differences between the deterministic and scenario-based models. In the following sub-sections, examples are presented for the deterministic model and those with added elements of uncertainty.

4.4.1 Deterministic Analysis

This numerical example is a modified version of the initial example presented in Section 3.4. Two final products (A1 and A2) and three components (M, N, and P), with the quantity of three of each per product are considered, as shown in Figure 4.2. Table 4.1 presents lead-times of different processes. Demand for new products and the number of returns at different time periods are shown in Table 4.2. The labor rate and cost of raw materials for M, N, and P are the same as presented in Section 3.3. The model allows up to 50% of defective disassembled components to be outsourced for remanufacturing and up to 20% of new defective components to be sent through the transforming process.

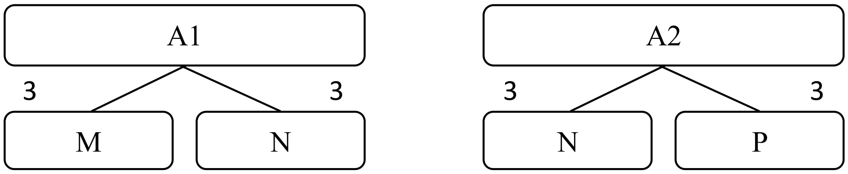

Figure 4.2: Products and their components

Table 4.1: Lead-time of different processes

Components \ Lead-time	t_1	t_2	t_3	t_4	t_5	t_6	t_7
M	2	1	-*	2	2	1	2
N	1	1	1	2	2	1	2
P	2	1	1	2	2	1	2

* No component can be transformed to M

Table 4.2: Demand and returns at each period

	T = 1	T = 2	T = 3	T = 4
Demand for Product A1	600	1000	900	200
Demand for Product A2	720	900	810	200
Returned Product A1	480	870	780	0
Returned Product A2	780	900	690	0

The deterministic model was run with defect rates for disassembled components being 0.2, 0.5, and 0.7. LINGO version 10 was used to solve the model. A personal computer with a 64-bit operating system and 2.33 GHz CPU was used for all computational work. The optimal solution was obtained within several minutes of computation. The model statistics are 551 variables including 420 integer variables and 295 constraints. Some of the results are presented in the subsequent figures. The following observations were made:

- Total profit is reduced as the defect rate is decreased as shown in Figure 4.3. That occurs due to reduction in demand for spares. This is aligned with Womack and Jones's (2003) statement about the importance of aftermarket services on profitability: "Spare parts account for the great majority of the profits of every aircraft engine company, due to the industry practice of selling new engines at substantial discounts in order to capture market share and create a large user base for their highly profitable, captive spare-part business".
- Defect rate reduction reduces the number of disassembled components sent for repair. A reduction in the number of defective disassembled components makes remanufacturing of all of them feasible under the current total labor hour availability. At a defect rate of 0.2, the total number of defects falls significantly and no disassembled component is repaired, as shown in Figure 4.4. Hence, under the current cost model, an increase in the number of remanufactured components, which has a higher profit margin compared with repair, cannot overcome the disadvantage of demand reduction for spares.
- Figure 4.5 presents the effect of defect reduction on total scraps. The number of scraps is increased in forward flow because of the reduction in demand for used spare components. However, the number of defective disassembled components is reduced significantly in the reverse flow which results in a reduction of the total number of scraps.

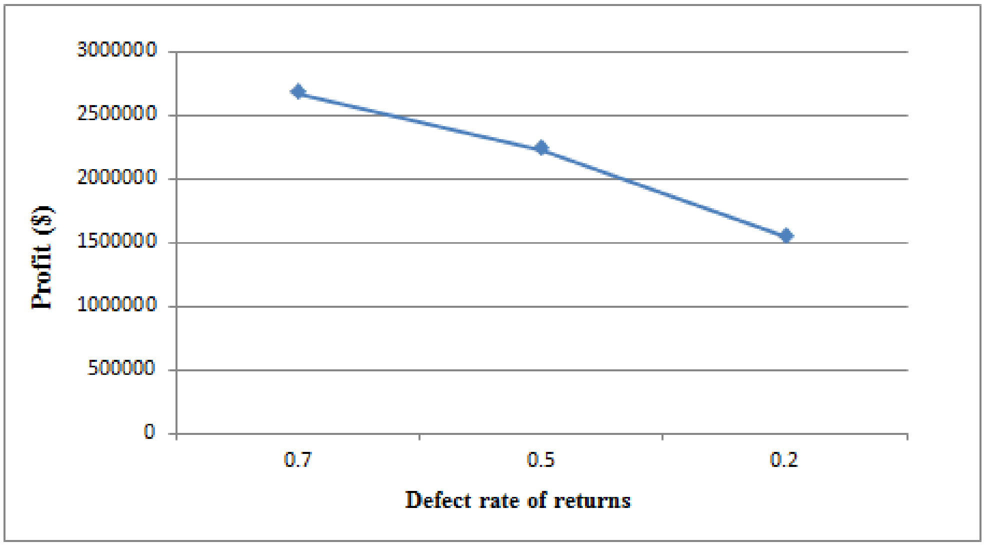

Figure 4.3: Effect of defect rate change on profit in deterministic model

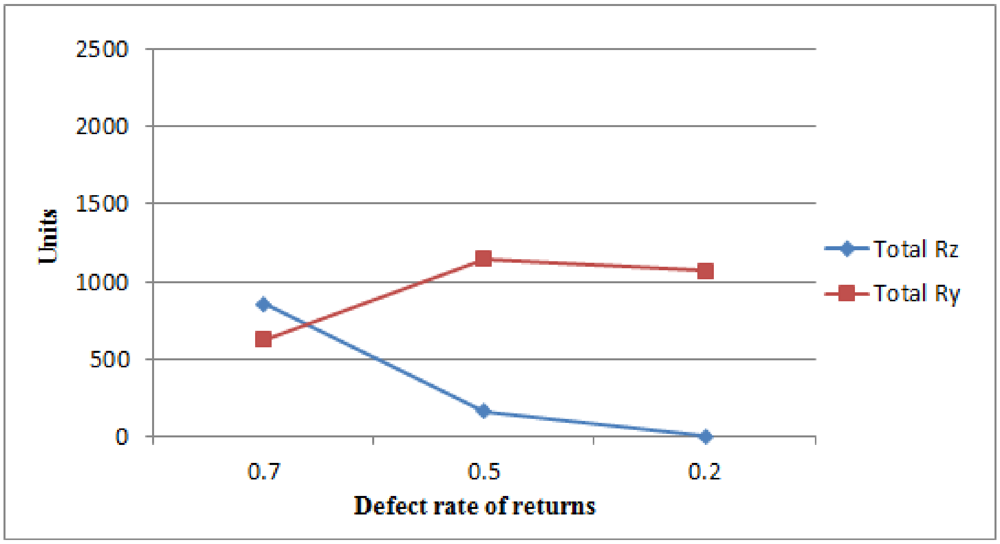

Figure 4.4: Effect of defect rate change on number of repaired and remanufactured components in deterministic model

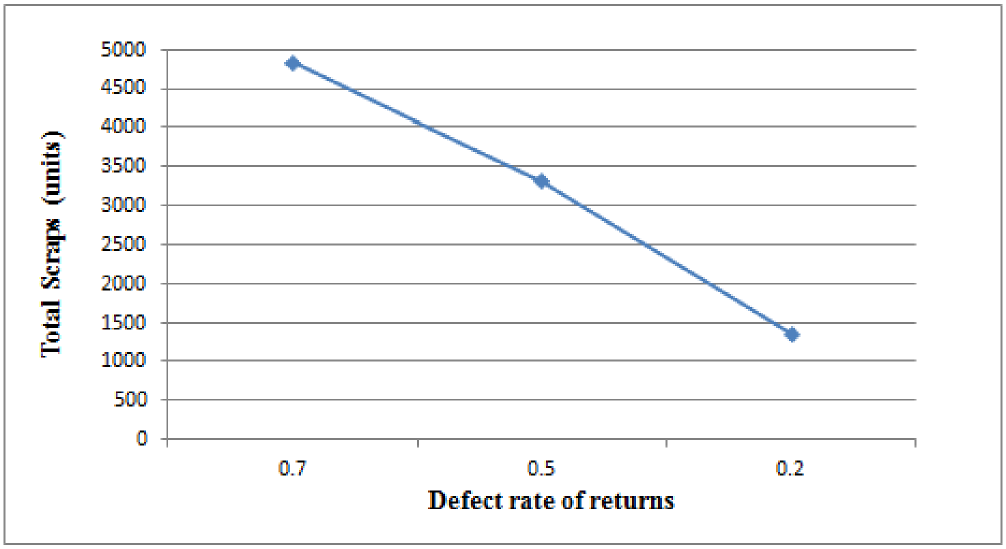

Figure 4.5: Effect of defect rate change on number of scraps in deterministic model

4.4.2 Scenario-based Analysis with Different Defect Rates

Considering the high cost and long lead-time of production for major products such as aircraft engines, fuselages and other major components, the demand is often known before production starts. Although the assumption of deterministic demand for new products seems reasonable in a make-to-order environment, the rate of return for repair and overhaul is often uncertain. For example, an aircraft engine might be brought into a service center for: 1) "Foreign Object Damage", 2) replacement of expired components, or 3) complete overhaul to have up to 80% components replacement. The number of components that need repair or replacement in each case may be different. In the second set of runs, uncertainty was introduced into the demand for components in the reverse flow by making the defect rate of disassembled components uncertain. Three scenarios were considered in this study. The model was run for four times as described below.

1. "A", defect rate of all scenarios (S1, S2, and S3) is equal to 0.7.
2. "D", defect rate of all scenarios is equal to 0.5.

3. "G", defect rate of all scenarios is equal to 0.2.
4. "J", the three scenarios, S1, S2 and S3, with defect rates of 0.7, 0.5, and 0.2 respectively, and corresponding probability of occurrences of 25%, 50%, and 25%.

Figure 4.6 presents the summary of the results. The model has 1647 variables including 1362 integer variables and 881 constraints. It is observed that the expected values of scraps, inventory, and company owned remanufactured components show the same change pattern as the profit, but at different change rates. For example, changes in profit for "D", "G", and "J" comparing to "A" are 17%, 42%, and 19%, respectively, while changes in the expected value of scraps are 31%, 72%, and 34%, respectively (see Appendix A for more details). Since the total hours available for the reverse flow processes are considered the same for all runs, as the defect rate of disassembled components is decreased, the total number of defective disassembled component is decreased. As a result, more components can be remanufactured in-house rather than being repaired. However, the profit gained from more components being remanufactured is not high enough to cover the loss caused by the reduction in demand for spares. For example, in run "A", the expected value of scraps is 4768 units whereas in run "G" it is only 1349 units. There is a positive correlation between the number of scraps and the demand for spares. Although the expected value of remanufactured disassembled components is increased in run "G" compared to run "A" (1674 units versus 1007 units), run "A" sells more spares.

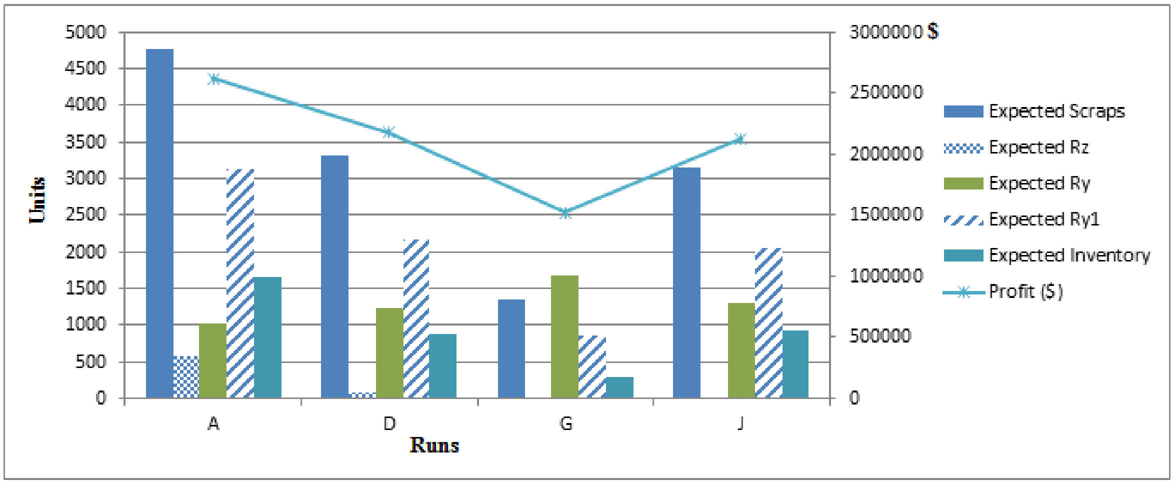

Figure 4.6: Results of running scenario-based model with different defect rates for disassembled components

4.4.3 Scenario-based Analysis with Different Defect Rates and Variable Lead-time

Lastly, lead-time variability is introduced to this example. Table 4.3 lists all runs and describes the defect rates as well as lead-times of in-house remanufacturing of customer owned components. The runs “A”, “D”, “G”, and “J” are the same as described in the previous sub-section. Figure 4.7, 4.8, and 4.9 show the effect of lead-time changes on scenario one and scenario two for cases with defect rates of 0.7, 0.5, and 0.2, respectively.

Table 4.3: List of different runs

Defect Rate			Lead-time of In-house Remanufacturing	Run
S1	S2	S3		
0.7	0.7	0.7	Equal to turnaround time for all scenarios	A
			Greater than turnaround time for scenario one	B
			Greater than turnaround time for scenario two	C
0.5	0.5	0.5	Equal to turnaround time for all scenarios	D
			Greater than turnaround time for scenario one	E
			Greater than turnaround time for scenario two	F
0.2	0.2	0.2	Equal to turnaround time for all scenarios	G
			Greater than turnaround time for scenario one	H
			Greater than turnaround time for scenario two	I
0.7	0.5	0.2	Equal to turnaround time for all scenarios	J
			Greater than turnaround time for scenario one	K
			Greater than turnaround time for scenario two	L
			Greater than turnaround time for scenario three	M

The turn-around time (TAT) was assumed to be two time periods in all runs. Consequently, if after disassembling a product, the in-house remanufacturing lead-time of its components is estimated as more than two time periods, the component may be repaired or outsourced for remanufacturing. The effect of lead-time variation, where the defect rate is 0.7, is presented in Figure 4.7. At run “A”, no lead-time variation is considered. At run “B”, about 25% of the time this lead-time is greater than TAT. At run “C”, about 50% of the time this lead-time is greater than TAT. It is observed that at run “C”, the expected profit is reduced by 1.5% compared to “A”, while at run “B” this reduction is only 0.1%. These profit changes are mainly caused by changes in the expected value of in-house remanufactured components and the expected value of the repaired components (see Appendix A for more details).

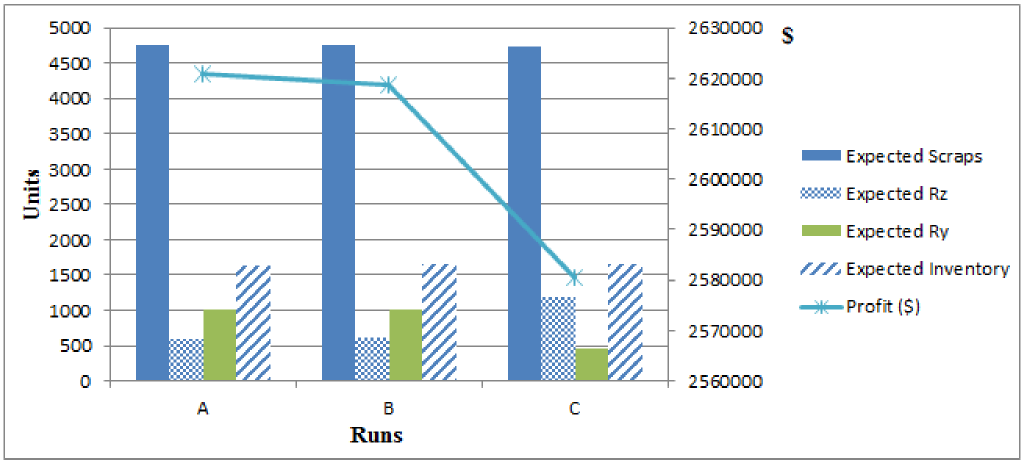

Figure 4.7: Effect of lead-time variation in different scenarios when defect rate is 0.7

Figure 4.8 shows the effect of remanufacturing lead-time variation for situations with a defect rate of 0.5. The effect of remanufacturing lead-time variation, where the defect rate is 0.2, is presented in Figure 4.9. Both figures show the same pattern for profit change as Figure 4.7. Comparing these two figures, it is noticed that under the current cost model, the profit gained from selling more spare components is higher than that gained from reducing inventory carrying cost and disposal cost. As the cost of landfill and environmental tax increases a different result might be observed.

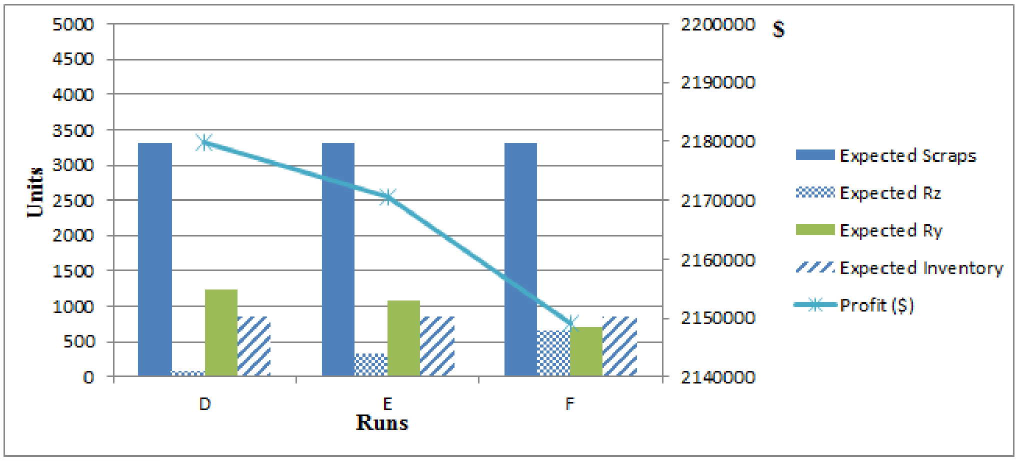

Figure 4.8: Effect of lead-time variation in different scenarios when defect rate is 0.5

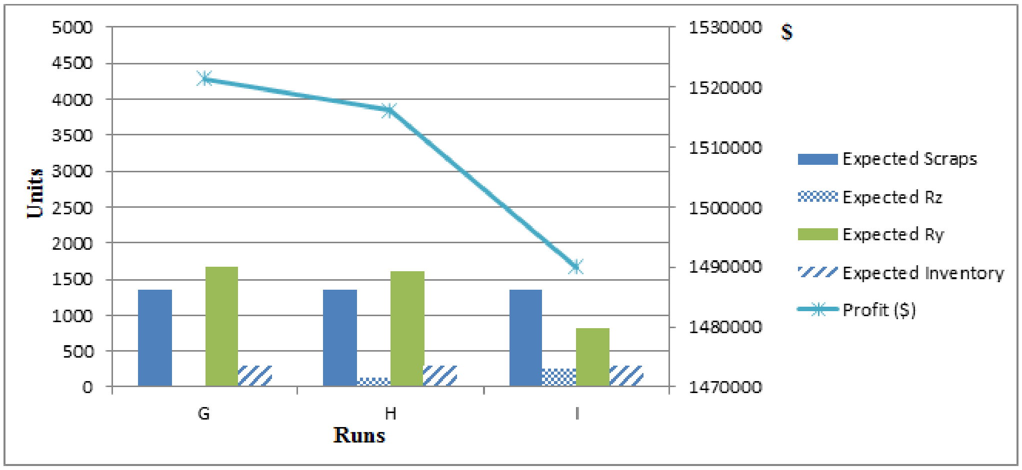

Figure 4.9: Effect of lead-time variation in different scenarios when defect rate is 0.2

Several more runs are performed (“K”, “L”, and “M”) where different scenarios have different defect rates and variable remanufacturing lead-times. Figure 4.10 presents the expected value of selected variables for each of these runs. The profit changes for “K”, “L”, and “M” compared to “J” are 0.9%, 2%, and 0.2 % lower, respectively. In run “M”, lead-time variation is applied to the scenario with the lowest defect rate (0.2) which is why profit reduction is not significant compared to “J”. Comparing the summary results of “D”, “G”, and “J” with “A”, it is concluded that the effect of the defect rate change is much higher than that caused by lead-time variations.

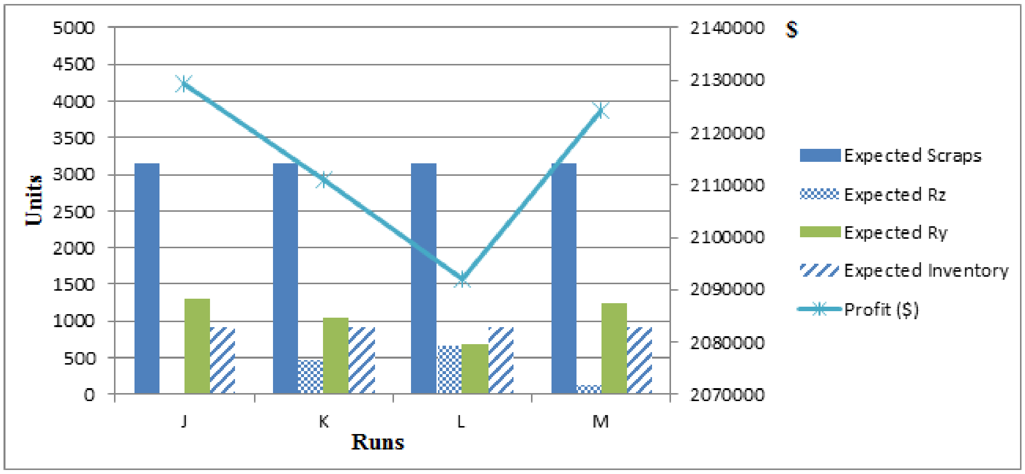

Figure 4.10: Effect of lead-time variation in different scenarios when defect rate varies in each scenario

CHAPTER 5

ANALYSIS OF THE CLOSED-LOOP AEROSPACE SUPPLY CHAIN

5.1 Introduction

In the previous chapters, the literature on remanufacturing and production planning with uncertainty was first reviewed. Then, a generic mathematical model for a closed-loop supply chain network was developed in a deterministic setting. The deterministic model was also modified to account for demand uncertainty and lead-time variations. In this chapter, through sensitivity analysis, the impact of several input factors on profit and selected key performance indicators (KPIs) are studied with the implications of these findings discussed.

5.2 Sensitivity Analysis

Original equipment manufacturers and third-party service providers go through multiple cycles of strategic planning prior to setting up service centers. Some of the factors to consider are fixed cost, taxes and government regulations, availability of skilled labor, maximum capacity, and landfill cost. In the following sub-sections sensitivity analysis is performed on some of the input factors to better understand the effect of these changes on profitability. The model presented in Sub-section 4.3.2 and the input data used in Section 4.4, are used for this analysis. The expected values of scraps, inventory, repaired disassembled components, and remanufactured disassembled components are selected as key performance indicators to compare different runs.

5.2.1 Sensitivity Analysis on the Model with Different Defect Rates

The model with different defect rates and deterministic lead-time, known as run "J" in the previous chapter, is selected as the base model for sensitivity analysis. Inventory carrying cost per unit, total labor hours available in the reverse flow, upper bound limit for outsourced remanufacturing, cost of outsourced remanufacturing per unit, and probability of scenarios one and two are factors selected for this analysis. For the first three factors, we consider cases with 25% increase and decrease. For the fourth factor, only the case with 25% increase is considered. At the last run, the probability of occurrence of the first scenario has been increase by 5% from 25% to 30% and probability of occurrence of the second scenario has been decreased from 50% to 45%. Table 5.1 lists different runs and the description of changes for each run compared to base run "J".

Table 5.1: List of different runs with description of changes against the base model with no lead-time variation

Description of Changes	Run
Inventory carrying cost per unit is decreased by 25%	N
Inventory carrying cost per unit is increased by 25%	O
Total labor hours available are decreased by 25%	P
Total labor hours available are increased by 25%	Q
Upper bound is decreased for outsourcing by 25%	R
Upper bound is increased for outsourcing by 25%	S
Outsourcing cost is increased by 25%	T
Probability of the first scenario is increased by 5%	U

Figure 5.1 presents the key performance indicators (KPI) for each run. It is observed that:

- A decrease in the inventory carrying cost per unit increases profit, by 0.57%, as well as the amount of inventory units. As this cost increases, however, inventory units remain the same and profit is decreased by 0.68%. Thus, the increase and decrease of this cost do not have symmetrical effects on profit and inventory units.
- Labor hour variation has an asymmetric effect on the inventory level and the amount of scraps. As the total labor hours decrease, the expected value of scraps increases, while the increase in labor hours does not change the amount of scraps. This factor has less effect on the expected inventory units than the inventory carrying cost per unit.
- The decrease in the upper bound limit of outsourced remanufacturing has the highest effect on the expected values of: scraps, inventory level, remanufacturing and repair of disassembled components. This decrease eliminates in-house remanufacturing of disassembled components, which requires more labor hours compared with repairs. Increase in this upper bound limit has less effect on profit and other KPIs.
- Increase in the cost of outsourced remanufacturing has the highest effect on profit, while other KPIs remain the same. This highlights the importance of maintaining a long-term relationship between an OEM and its sub-contractors.
- Finally, when the probability factor for scenario one is increased the profit increases slightly. The changes in the expected values of selected variables are solely the results of probability changes.

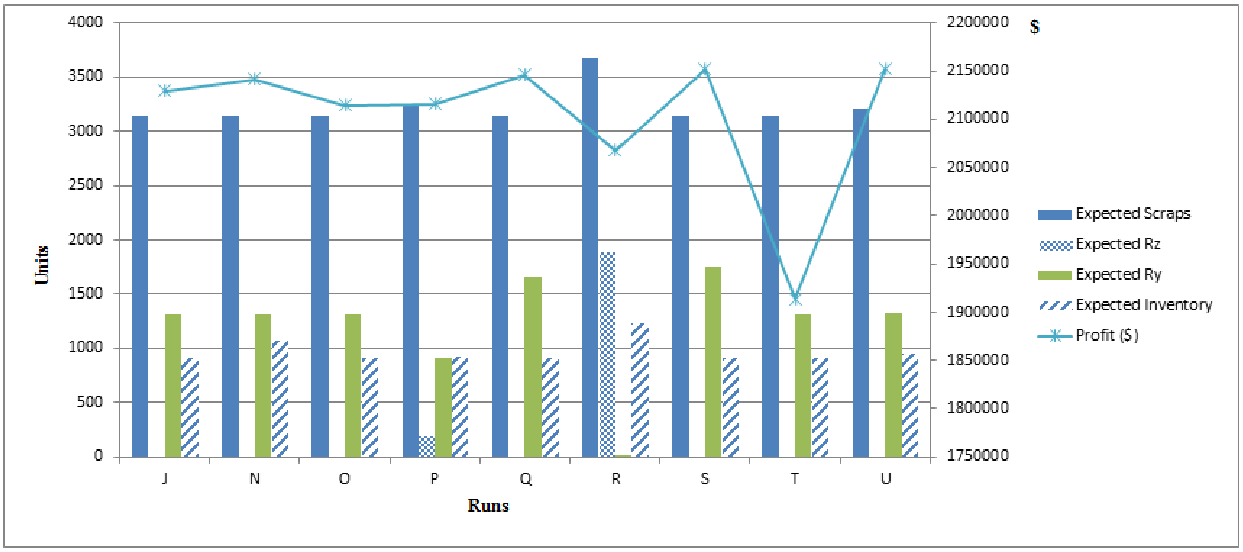

Figure 5.1: Effect of different input factor change on the base model with no lead-time variation

5.2.2 Sensitivity Analysis on the Model with Different Defect Rates and Variable Lead-time for the First Scenario

In this sub-section, input factor changes are incorporated into the model with variable defect rate for disassembled components and variable lead-time for in-house remanufacturing for scenario one. More specifically, it is considered that 25% of the time, the defect rate of disassembled components is 0.7 and the lead-time of remanufacturing of customer owned disassembled components is more than two time periods. Table 5.2 lists the new runs as well as a description for each factor change. Figure 5.2 shows the KPIs of each run.

Table 5.2: List of different runs with description of changes against the base model with lead-time variation for scenario one

Description of Change	Run
Total labor hours available are decreased by 25%	V
Total labor hours available are increased by 25%	W
Upper bound is decreased for outsourcing by 25%	X
Outsourcing cost is increased by 25%	Y
Probability of the first scenario is increased by 5%	Z

This set of runs shows a similar change pattern as those presented in Section 5.2.1.

Findings include:

- A decrease in labor hour capacity increases the number of scraps and repairs in the reverse flow and reduces the number of units that are sent for in-house remanufacturing. As a result, profit is decreased. An increase in capacity, however, only increases in-house remanufactured units and profit whereas it has no effect on other variables. Therefore, if a company's goal is to reduce amount of scrap, increasing capacity moderately may not be sufficient.
- Decrease in the upper bound limit of outsourced remanufacturing increases the number of defective components that are processed internally. To deal with this increase more components are scraped and in-house remanufacturing is completely eliminated. Knowing that the profit margin of repair is lower than that of remanufacturing, a decrease in the number of disassembled components that are remanufactured reduces the profit.
- In the last run the probability of scenario one is increased to 30% and the probability of scenario two is decreased to 45%. This change has no effect on the

value of variables; however, because the probability has changed, the expected values of variables are changed.

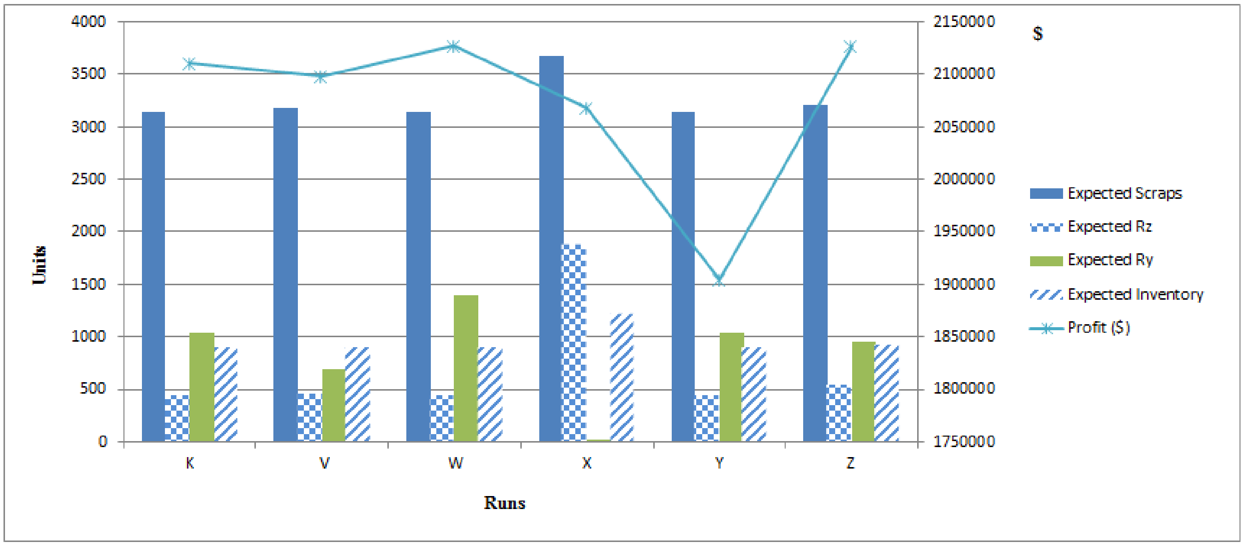

Figure 5.2: Effect of different input factor change on the model with variable lead-time for scenario one

5.2.3 Sensitivity Analysis on the Model with Different Defect Rates and Variable Lead-time for the Second Scenario

Here similar changes to those in Section 5.2.2, are introduced into the model. Variable defect rates are used for disassembled components and variable lead-time of in-house remanufacturing are used for the second scenario. Table 5.3 lists this new set of runs, and the results are presented in Figure 5.3. This figure shows the same pattern as Figure 5.2.

Table 5.3: List of different runs with description of changes against the base model with lead-time variation for scenario two

Description of Change	Run
Total labor hours available are decreased by 25%	LA
Total labor hours available are increased by 25%	LB
Upper bound is decreased for outsourcing by 25%	LC
Outsourcing cost is increased by 25%	LD
Probability of the first scenario is increased by 5%	LE

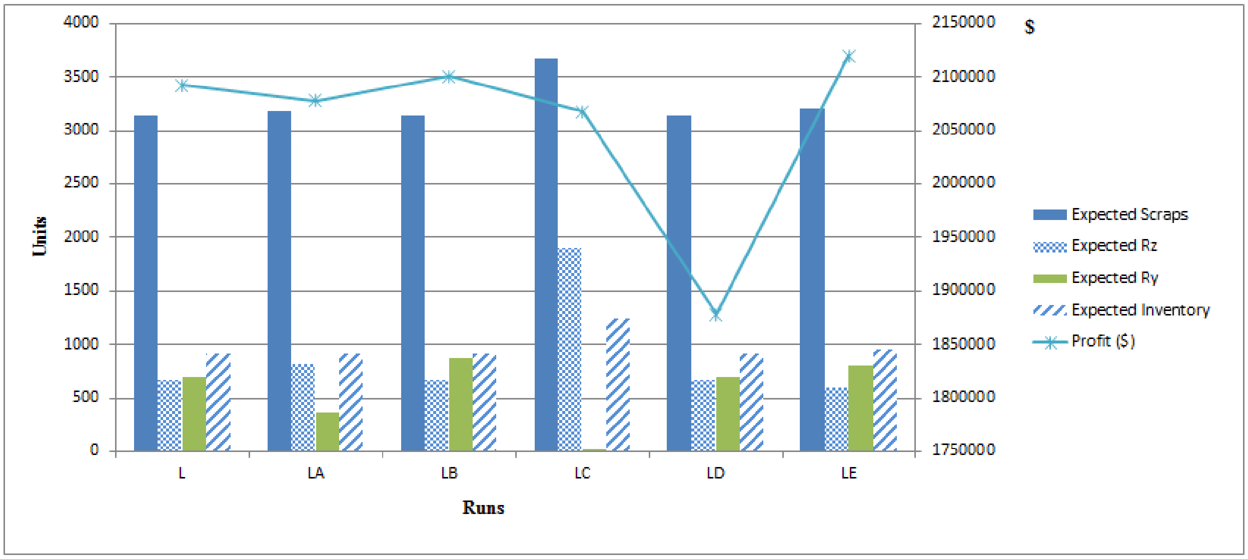

Figure 5.3: Effect of different input factor change on the model with variable lead-time for scenario two

Lastly, Figure 5.4 integrates all results in one chart for better comparison. Table 5.4 presents: percentage of changes in profit, expected value of number of scraps, expected value of inventory cost and inventory turnover ratio (ITO) calculated as profit divided by inventory cost. To calculate inventory cost, in dollars, the numbers of new and used components as well as work-in-process components are counted at the end of each period for each scenario. Inventory carrying cost per unit for work-in-process components is considered as 50% of the corresponding completed ones. The observations are as follows:

- Comparing the 3 sets (set "P, Q, R, T, U", set "V, W, K, Y, Z", and set "LA, LB, LC, LD, LE") of runs, it is noticed that when there are lead-time variations the profit is reduced. This reduction is more pronounced as the percentage of lead-time variation increases. The only exception to this rule occurs when less outsourcing is permitted. When comparing the solution of run "R" with those of

“X” and “LC”, the changes seem negligible. This is because the reduction makes in-house remanufacturing of customer owned components infeasible. Therefore, a change in the lead-time of this process has no effect on KPIs.

- The effect of variation in lead-time of in-house remanufacturing for the run with an increased cost of outsourced remanufacturing is observed by comparing the profit of “Y” and “LD” against “T”. Lead-time change has no effect on the number of scraps, however a change was noticed in inventory cost and inventory turnover ratio. As lead-time variation is introduced in the first scenario, profit decreases slightly, but inventory costs remains the same, resulting in an ITO reduction.
- Inventory carrying cost change has a slight effect on profit, while it has no effect on the expected number of scraps. Its effect on expected inventory carrying cost and inventory turnover ratio is significant.

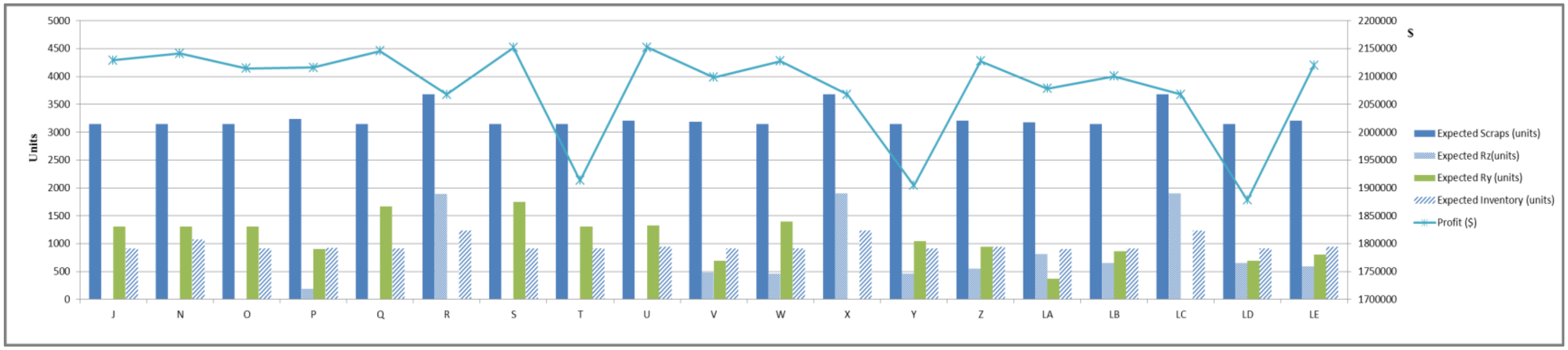

Figure 5.4: Results of sensitivity analysis

Table 5.4: Results of comparing different runs against run with different defect rates and no lead-time variation

	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	LA	LB	LC	LD	LE
Profit	- 0.9%	-1.7%	-0.2%	0.6%	-0.7%	-0.6%	0.8%	-2.9%	1.1%	-10.1%	1.1%	-1.5%	-0.1%	-2.9%	-10.6%	-0.1%	-2.4%	-1.4%	-2.9%	-11.8%	-0.4%
Expected Scrap	0.0%	0.0%	0.0%	0.1%	0.0%	2.9%	0.0%	16.9%	0.0%	0.0%	2.1%	1.3%	0.0%	16.9%	0.0%	2.1%	1.1%	0.0%	16.9%	0.0%	2.1%
Expected Inventory	0.7%	-5.6%	0.2%	-18.3%	24.9%	-4.9%	9.8%	6.7%	12.6%	0.0%	2.1%	-7.2%	10.5%	6.8%	0.7%	1.3%	-10.6%	-0.7%	6.8%	-5.6%	-2.2%
ITO Ratio (Profit)	-1.5%	4.1%	-0.5%	23.1%	-20.5%	4.5%	-8.2%	-9.0%	-10.3%	-10.2%	-1.0%	6.2%	-9.6%	-9.1%	-11.2%	-1.3%	9.2%	-0.6%	-9.1%	-6.5%	1.8%

5.3 Implication of Findings

In this section, potential applications of the findings in the aftermarket segment in aerospace are discussed. Aging aircrafts, flight increases, and high competition in the aftermarket segment are factors leading to higher demand for better and cheaper spare parts. More OEMs are interested in aftermarket services as they provide opportunities for higher revenue. Also, small suppliers specializing in aircraft part/components can provide different services, from airframe maintenance to technical assistance. When OEMs are more involved in aftermarket services and supplying used components, they may be faced with many challenges such as:

- The optimum level of inventory for new and used components must be determined as well as the maximum number of periods to keep used components before they are sent for scrap or recycling.
- The best location to store the inventory must be identified. This becomes an important factor to consider when inventory carrying cost is different from region to region. For example, a component distribution center for European customers can be located in one of the North African countries, where taxes and building costs are lower. This, however, increases the response time and affects customer service inversely.
- In the case of outsourcing processes such as repair or remanufacturing, especially if the third-party spare servicing company depends on an OEM to obtain certification by regulatory authorities for their processes; the maximum capacity of outsourced company and process cost per unit affect the profitability and must be considered beforehand.

- The optimum flight hours and flight cycles for the rotational components such as turbine blades and fan blades in engines must be defined. Manufacturing cost increases caused by using higher value alloys in order to get higher flight hours should be justified.
- The number of flight hours for overhaul and inspections must be identified. The effect of extending the life cycle of components in operation costs and maintenance costs must be studied.

Since many companies are moving toward the new business model (Ijomah, 2009), assessing the cost of a product over its life cycle becomes more important. For example, overhaul may be performed on an aircraft after 80,000 flight hours. In theory, all replaceable components should have a life cycle slightly longer than 80,000 hours since they are going to be removed at overhaul. In reality, there are components with lower and higher life cycles i.e. 50,000 and 110,000 flight hours. Those with higher flight hours will be removed in overhaul and will be kept as used spare components in case unexpected damages occur. For those with a lower life cycle, there are two options: replace them with higher quality material to extend their life cycle or bring the whole aircraft into the service center to replace these components before 50,000 flight hours. The second option causes higher in-service costs. In the traditional model, the customer would pay for the service, thus the service centers actually benefit from this extra shop visit. However, in the new business model customers are provided with services in the form of powered-by-the-hour and will pay a certain amount per flight hour to cover the overhaul costs. Any extra shop visit is a cost to the manufacturer. This new business model forces the OEM to improve the quality of its products and components in the design phase.

In this chapter, the effect that inventory carrying cost variation can have on profit, inventory level and amount of scraps was showed. Based on the results, this cost does not change inventory level and scraps significantly, but its effect on total inventory cost and inventory turnover ratio is significant.

Capacity limit was introduced through labor hour availability. However, there are many other factors that can limit capacity of a system such as the number of machines and space for processing and storage. A variation in labor hours causes less variation in profit. One of the options to increase capacity is outsourcing. The effect of variation in cost of outsourcing and maximum number of units allowed to be outsourced was studied and it was noticed that both factors had significant effect on the profitability of the system. Long-term agreements with third-party service providers encourage them to reduce their cost of remanufacturing and invest in increasing capacity. Boeing, for example, is asking its supplier to provide more components for aftermarket service and to set limits on the spare part/component price (Broderick, 2014).

CHAPTER 6

SUMMARY, CONCLUSION AND FUTURE RESEARCH

6.1 Summary and Conclusion

A considerable amount of work has recently been applied to the development of processes to reduce the negative environmental impacts of the disposal of products. As the landfill and energy consumption reduction gain more attention by governments, new regulations are introduced to require companies to develop new ways to mitigate the human footprint on our planet. Remanufacturing, which recaptures the value added to materials when a product was first manufactured, has been one of the responses to this challenge. The literature on waste reduction in aerospace industry is limited. Aerospace industry is an extremely regulated industry with safety being the number one concern. Other characteristics that make aerospace industry different are: application of high technology, use of high value materials, design of very complex components, and long lead-time of production. Considering the very high cost of repair and overhaul, research and development (R & D) plays a very important role in controlling cost and maintaining profit margin. The main focus of this study was on a manufacturing company in the aerospace industry that provides aftermarket services such as repair and overhaul. New processes were introduced to a closed-loop supply chain network to reduce the amount of scrap through extending components' life cycle.

To start, a deterministic mathematical model was developed to study the effect of remanufacturing and transforming on the profit and the amount of scraps. The model determines the quantity of components sent for two types of repairs, remanufacturing, transforming, and scrap in the forward flow and repair, remanufacturing, cannibalization and scrap in the reverse flow. A numerical example has been presented to validate the mathematical model and a sensitivity analysis has been performed. The results confirmed that remanufacturing and transforming increase the profit. Inventory carrying cost per unit and remanufacturing costs have significant impact on the profit change.

Although the assumption of deterministic demand for components would be appropriate in a make-to-order system with perfect production processes, in real-world it is difficult to design processes with yield of one. Moreover, providing aftermarket services exposes the company to unexpected product break-downs, which make demand for components variable. To consider uncertainty, the scenario-based approach was incorporated into the model. Different scenarios with different probabilities of occurrence were defined for the defect rate of disassembled components and lead-time of in-house remanufacturing of customer owned components. Also, it was allowed to outsource remanufacturing of customer owned components to a third-party service provider up to a specified level. Numerical examples were presented for the deterministic model and scenario-based model with three scenarios. It was observed that as the defect rate is reduced; demand for spare components is reduced which in turn causes profit reduction. A decrease on defect rates, however, allows more defective components to be remanufactured. As a result, the number of scraps and inventory level are reduced.

The effect of remanufacturing lead-time variations was investigated by incorporating uncertainty into the first and the second scenarios separately. It was noticed that the expected inventory level remains the same under lead-time variations. The profit change was a result of increase in the expected value of repaired disassembled components and outsourced remanufacturing as well as reduction in the expected value of the in-house remanufactured disassembled components.

At the design phase, when cost analysis is carried out over the life cycle of a product, it is crucial to know the effect of different input factor changes. The expected values of scraps, inventory, repaired disassembled components, and remanufactured disassembled components were selected as the key performance indicators to compare different runs. Through sensitivity analyses, the impact of changes in: inventory carrying cost, outsourcing cost, upper bound limits of outsourced remanufacturing, total labor hours available for reverse flow, and probability of the first and second scenarios, was studied. It was observed that the increase in the cost of outsourced remanufacturing had the highest effect on profit with no effect on expected scraps. The second most sensitive factor was the upper bound limit of outsourced remanufacturing. The effect of variations in inventory carrying cost per unit on profit was not as significant as other factors, but it changes the total inventory cost and inventory turnover ratio significantly.

6.2 Future Prospects

In this thesis, a generic model was developed for the closed-loop supply chain network of a manufacturing company in the aerospace industry. Defect rate(s) were assumed to be deterministic for manufacturing of new components. Lead-times of processes, with the exception of lead-time of in-house remanufacturing of customer owned components were also deterministic. An extension of the model could make the defect rate of manufacturing and lead-time of the rest of processes uncertain.

Remanufacturing, repairs, and transforming processes were considered perfect with the yield of one. This was a push system, meaning that all defective components were processed right away and there was no inventory of defective components. In future work, these assumptions could be relaxed by making yield of all processes less than one and allowing the company owned components to be processed at a later time.

In the first model, the capacity limitation was introduced by the total labor hours available for forward flow processes. In the second model, the capacity limit was put on the total labor hours available for reverse flow processes. An extension of this work can include both constraints and relax the assumption of fixed capacity to allow capacity variations through the provision of over-time and part-time labor.

In the second model, the number of products returned at each period was considered to be deterministic. Uncertainty in demand of components was a result of variable defect rates of disassembly. An extension of the model can make both, the number of returned products and defect rate of disassembly, variable.

Both proposed models had integer variables which made the computational time long in some cases. The models were very sensitive to changes of input data. Since this is the first attempt in solving this type of problems, the main objective of this work was to propose a mathematical modelling approach for the considered manufacturing system with transforming and remanufacturing activities. The developed model can be solved to optimality with an acceptable computational time for the considered example problems. Efficient solution methods can be developed in future work in this area so that much larger problems can be tackled properly. Such solution methods can be based on heuristic, meta-heuristic, optimization, or the combinations of these approaches.

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APPENDIX

Table A.1: Detailed Results of Different Runs

	KPI	S 1	S 2	S 3	Expected Value
Run: A **Profit: 2620861**	Total Inventory	1663	1613	1669	1640
	Total Scraps	4931	4611	4920	4768
	Total Ry1	3252	3040	3244	3144
	Total Rz	1163	0	1177	585
	Total Ry	159	1852	165	1007
Run: B **Profit: 2618801**	Total Inventory	1670	1610	1672	1641
	Total Scraps	4912	4612	4912	4762
	Total Ry1	3240	3040	3240	3140
	Total Rz	1352	0	1048	600
	Total Ry	0	1852	304	1002
Run: C **Profit: 2580605**	Total Inventory	1664	1610	1701	1646
	Total Scraps	4892	4612	4839	4739
	Total Ry1	3228	3040	3192	3125
	Total Rz	506	1852	557	1192
	Total Ry	877	0	915	448
Run: D **Profit: 2179964**	Total Inventory	870	870	870	870
	Total Scraps	3308	3308	3308	3308
	Total Ry1	2176	2176	2176	2176
	Total Rz	248	0	115	91
	Total Ry	1064	1312	1197	1221
Run: E **Profit: 2170684**	Total Inventory	870	870	870	870
	Total Scraps	3308	3308	3308	3308
	Total Ry1	2176	2176	2176	2176
	Total Rz	1312	0	0	328
	Total Ry	0	1509	1312	1083
Run: F **Profit: 2149013**	Total Inventory	870	870	870	870
	Total Scraps	3308	3308	3308	3308
	Total Ry1	2176	2176	2176	2176
	Total Rz	0	1312	0	656
	Total Ry	1508	0	1313	705
Run: G **Profit: 1521456**	Total Inventory	298	298	298	298
	Total Scraps	1349	1349	1349	1349
	Total Ry1	880	880	880	880
	Total Rz	0	0	0	0
	Total Ry	500	2847	500	1674

Table A.1: Detailed Results of Different Runs (continued)

Run: H **Profit: 1516113**	Total Inventory	298	298	298	298
	Total Scraps	1349	1349	1349	1349
	Total Ry1	880	880	880	880
	Total Rz	500	0	0	125
	Total Ry	0	2981	500	1616
Run: I **Profit: 1489960**	Total Inventory	298	298	298	298
	Total Scraps	1349	1349	1349	1349
	Total Ry1	880	880	880	880
	Total Rz	0	500	0	250
	Total Ry	1552	0	1668	805
Run: J **Profit: 2129176**	Total Inventory	1610	870	298	912
	Total Scraps	4612	3308	1349	3144
	Total Ry1	3040	2176	880	2068
	Total Rz	0	0	0	0
	Total Ry	1852	1437	500	1307
Run: K **Profit: 2110884**	Total Inventory	1610	870	298	912
	Total Scraps	4612	3308	1349	3144
	Total Ry1	3040	2176	880	2068
	Total Rz	1852	0	0	463
	Total Ry	0	1830	500	1040
Run: L **Profit: 2092143**	Total Inventory	1614	870	298	913
	Total Scraps	4612	3308	1349	3144
	Total Ry1	3040	2176	880	2068
	Total Rz	0	1312	0	656
	Total Ry	2023	0	734	689
Run: M **Profit: 2124274**	Total Inventory	1613	870	301	914
	Total Scraps	4612	3308	1348	3144
	Total Ry1	3040	2176	880	2068
	Total Rz	0	0	500	125
	Total Ry	1852	1543	0	1235
Run: N **Profit: 2141210**	Total Inventory	1611	1193	298	1074
	Total Scraps	4611	3314	1349	3147
	Total Ry1	3040	2176	880	2068
	Total Rz	0	0	0	0
	Total Ry	1852	1435	500	1306
Run: O **Profit: 2114663**	Total Inventory	1612	870	298	913
	Total Scraps	4611	3308	1349	3144
	Total Ry1	3040	2176	880	2068
	Total Rz	0	0	0	0
	Total Ry	1852	1436	500	1306

Table A.1: Detailed Results of Different Runs (continued)

Run: P **Profit: 2116084**	Total Inventory	1663	870	315	930
	Total Scraps	4821	3308	1503	3235
	Total Ry1	3180	2176	980	2128
	Total Rz	506	0	250	189
	Total Ry	996	1312	0	905
Run: Q **Profit: 2145608**	Total Inventory	1610	870	298	912
	Total Scraps	4612	3308	1349	3144
	Total Ry1	3040	2176	880	2068
	Total Rz	0	0	0	0
	Total Ry	1852	2151	500	1664
Run: R **Profit: 2067904**	Total Inventory	2473	1041	398	1238
	Total Scraps	5696	3685	1637	3676
	Total Ry1	3760	2424	1068	2419
	Total Rz	2321	2291	682	1896
	Total Ry	0	24	0	12
Run: S **Profit: 2151712**	Total Inventory	1610	870	298	912
	Total Scraps	4612	3308	1349	3144
	Total Ry1	3040	2176	880	2068
	Total Rz	0	0	0	0
	Total Ry	0	3493	0	1747
Run: T **Profit: 1913371**	Total Inventory	1611	870	298	912
	Total Scraps	4613	3308	1349	3145
	Total Ry1	3040	2176	880	2068
	Total Rz	0	0	0	0
	Total Ry	1852	1437	500	1307
Run: U **Profit: 2152128**	Total Inventory	1610	870	298	949
	Total Scraps	4613	3308	1349	3210
	Total Ry1	3040	2176	880	2111
	Total Rz	0	0	0	0
	Total Ry	1852	1437	500	1327
Run: V **Profit: 2098290**	Total Inventory	1609	870	302	913
	Total Scraps	4654	3308	1473	3186
	Total Ry1	3068	2176	960	2095
	Total Rz	1782	0	155	484
	Total Ry	0	1312	145	692
Run: W **Profit: 2127316**	Total Inventory	1610	870	298	912
	Total Scraps	4612	3308	1349	3144
	Total Ry1	3040	2176	880	2068
	Total Rz	1852	0	0	463
	Total Ry	0	2544	500	1397

Table A.1: Detailed Results of Different Runs (continued)

Run: X **Profit: 2067862**	Total Inventory	2474	1041	408	1241
	Total Scraps	5695	3686	1637	3676
	Total Ry1	3760	2424	1068	2419
	Total Rz	2321	2301	682	1901
	Total Ry	0	14	0	7
Run: Y **Profit: 1904150**	Total Inventory	1611	870	298	912
	Total Scraps	4612	3308	1349	3144
	Total Ry1	3040	2176	880	2068
	Total Rz	1852	0	0	463
	Total Ry	0	1830	500	1040
Run: Z **Profit: 2127456**	Total Inventory	1610	870	298	949
	Total Scraps	4613	3308	1349	3210
	Total Ry1	3040	2176	880	2111
	Total Rz	1852	0	0	556
	Total Ry	0	1830	500	949
Run: LA **Profit: 2078233**	Total Inventory	1613	870	292	911
	Total Scraps	4618	3308	1484	3180
	Total Ry1	3044	2176	968	2091
	Total Rz	489	1312	162	819
	Total Ry	1353	0	118	368
Run: LB **Profit: 2100347**	Total Inventory	1613	870	302	914
	Total Scraps	4611	3308	1349	3144
	Total Ry1	3040	2176	880	2068
	Total Rz	0	1312	1	656
	Total Ry	2736	0	733	867
Run: LC **Profit: 2067611**	Total Inventory	2474	1041	408	1241
	Total Scraps	5695	3686	1637	3676
	Total Ry1	3760	2424	1068	2419
	Total Rz	2297	2315	682	1902
	Total Ry	24	0	0	6
Run: LD **Profit: 1878169**	Total Inventory	1610	870	298	912
	Total Scraps	4612	3308	1349	3144
	Total Ry1	3040	2176	880	2068
	Total Rz	0	1312	0	656
	Total Ry	1959	0	798	689
Run: LE **Profit: 2120215**	Total Inventory	1611	870	298	949
	Total Scraps	4612	3308	1349	3209
	Total Ry1	3040	2176	880	2111
	Total Rz	0	1312	0	590
	Total Ry	2257	0	500	802