Strategic network design for reverse logistics

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2008

Mutha Akshay Kiran. (2008). Strategic network design for reverse logistics. Master' s thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/13482>

<https://doi.org/10.32657/10356/13482>

**NANYANG
TECHNOLOGICAL
UNIVERSITY**

**STRATEGIC NETWORK DESIGN FOR REVERSE
LOGISTICS**

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2008**

ABSTRACT

Reverse logistics (RL) is gaining importance both in terms of research and industrial applications due to the thrust by the government, environmentalists and consumers to conserve resources. The issue in RL is to take back the used products, so that the product or its parts are appropriately disposed, recycled, reused, or remanufactured.

Most of the researchers do not recognize the complexity in handling returns of modular products. Also, most of the models proposed in the literature are not suitable for multi-product configurations. Thus, a deterministic optimization model is proposed to design network for recovery of products. The model considers supply of return products, demand for the remanufactured products, supply of reusable modules and materials in the secondary market and is suitable for multi-product configurations. The network also considers suppliers of new modules to be used during the final assembly of the product. However, in practice, the return of used products and the demand for remanufactured products is uncertain. Hence, the base model is modified to incorporate stochastic supply and demand scenarios.

The proposed networks are analyzed by using simulated data to show the applicability of the model in real life situations. Scenario analyses performed on the model to depict real life situations. The proposed network can assist in strategic decision making in RL networks.

ACKNOWLEDGEMENTS

I would like to thank my research supervisor, Assoc. Prof. Shaligram Pokharel, for his invaluable suggestions, advice and guidance. Professor Pokharel's mentorship has always inspired me to seek new challenges. His enthusiasm and willingness to share his vast knowledge and experiences; and his unwavering support and outstanding patience throughout the progress of this research can hardly be put in words.

I would also like to thank Assoc. Prof. Arun Kumar, my first year report examiner. Professor Kumar's insightful comments helped me to consolidate my research.

I also wish to thank my friends from the centre, who have always supported me in my work. I acknowledge their company, encouragement and camaraderie. I would also like to thank all my other friends in India and Singapore who have encouraged me to scale new heights at all times.

I want to express my gratitude towards my family, above all my parents. Their love, unconditional support and confidence have always inspired me to achieve higher standards.

Akshay Kiran Mutha

January, 2008

TABLE OF CONTENTS

Abstract	i
Acknowledgements	ii
Table of contents	iii
List of figures	v
List of tables	vi
List of symbols	vii
 CHAPTER 1 INTRODUCTION	 1
1.1 Environmental perspectives and green manufacturing	2
1.2 Reverse logistics	5
1.3 Product recovery options and reverse logistics activities	9
1.4 Research objective	11
1.5 Research scope and methodology	12
1.6 Organization of the thesis	15
 CHAPTER 2 LITERATURE REVIEW	 16
2.1 Facility location	18
2.2 Models for strategic decision making	25
2.3 RL in recycling industry	29
2.4 RL in electronic and electrical waste recycling	34
2.5 RL in product remanufacturing.....	39
2.6 RL in product recovery	42
2.7 RL in waste management.....	46
2.8 Stochastic models for facility location.....	49
2.9 Other relevant research in RL	52
2.10 summary of literature review	54
 CHAPTER 3 METHODOLOGY FOR MODEL FORMULATION	 59
3.1 Deterministic model formulation.....	61
3.2 Stochastic model formulation	64
 CHAPTER 4 DETERMINISTIC MODEL AND ANALYSIS	 68
4.1 Balance equations	68

4.2 Costs associated with the network	71
4.3 Capacity constraints	75
4.4 Analysis and results	76
 CHAPTER 5 STOCHASTIC MODEL AND ANALYSIS	 90
5.1 Balance equations	90
5.2 Costs associated with the network	94
5.3 Capacity constraints	98
5.4 Analysis and results	99
 CHAPTER 6 CONCLUSIONS AND FUTURE WORKS.....	 108
5.1 Conclusions	108
5.2 Limitations and future works	111
 REFERENCES	 115
 GLOSSARY OF TERMS	 127
 APPENDIX A – Data for deterministic model.....	 129
 APPENDIX B – Data for stochastic model	 133

LIST OF FIGURES

Figure 1.1: A generic forward and reverse supply chain [White et al., 2003].....	10
Figure 3.1: Proposed reverse logistics structure for deterministic model.....	61
Figure 3.2: Proposed reverse logistics structure for stochastic model.....	64
Figure 3.3: Assumed network structure	67
Figure 4.1: Network structure when $Q = 25,000$ units	79
Figure 4.2: Network and inventory cost variation when inventory cost at reprocessing centre is varied	79
Figure 4.3: Distribution variation when inventory cost at reprocessing centre is varied	80
Figure 4.4: Network structure when $Q = 20,000$ units	81
Figure 4.5: Network structure when $Q = 30,000$ units	82
Figure 4.6: Network and new module cost variation when $Q = 25,000$	84
Figure 4.7: Transportation and inventory holding cost variation when $Q = 25,000$	86
Figure 4.8: Network and new module cost variation when $Q = 20,000$	86
Figure 4.9: Transportation and inventory holding cost variation when $Q = 20,000$	87
Figure 4.10: Network and new module cost variation when $Q = 30,00$	87
Figure 4.11: Transportation and inventory holding cost variation when $Q = 30,000$	88
Figure 5.1: Network structure when $Q=N(21000,1800)$ and $D=N(15000,450)$	100
Figure 5.2 Network structure when $Q=N(16000,1800)$ and $D=N(15000,450)$	101
Figure 5.3 Network structure when $Q=N(21000,1800)$ and $D=N(10000,450)$	102
Figure 5.4: Network and transport cost variation due to variation in demand but constant supply.....	104
Figure 5.5: New module and disposal cost variation due to variation in demand but constant supply	105
Figure 5.6: Network and transport cost variation due to variation in supply but constant demand	106
Figure 5.7: New module and disposal cost variation due to variation in supply but constant demand.....	107

LIST OF TABLES

Table 2.1: Summary of literature review	51
Table 3.1: Notations for parameters (Deterministic model)	62
Table 3.2: Notations for decision variables (Deterministic model).....	63
Table 3.3: Notations for parameters (Stochastic model)	65
Table 3.4: Notations for decision variables (Stochastic model)	66
Table 4.1: Variation in quantity of modules sent for recycling and stored at reprocessing centres due to change in inventory costs at reprocessing centres...	78
Table 4.2: Processing capacity reduction at reprocessing centres	82
Table 4.3: Variation in disposal and recycling percentage	88
Table 5.1: Key cost ocmponents under various scenarios	102
Table 5.2: Network cost variation under varying demand and constant supply [N(15000,450)]	103
Table 5.3: Network cost variation under varying supply and constant demand [N(21000,1800)]	105

LIST OF SYMBOLS

Notation	Description
f	Set of assembling factories in the network, $f = 1, 2, 3, \dots, f$
h	Set of distribution centre's (DC's) which serve as secondary markets, $h = 1, 2, 3, \dots, H$
j	Set of reprocessing centre's (RPC's) in the network, $j = 1, 2, 3, \dots, J$
n_p	Module 'n' of product 'p', $n = 1, 2, 3, \dots, N$
r	Set of retailers in the network, $r = 1, 2, 3, \dots, R$
s	Set of markets for spare products, $s = 1, 2, 3, \dots, S$
v	Set of possible disposal sites, $v = 1, 2, 3, \dots, V$
w	Set of warehouses in the network, $w = 1, 2, 3, \dots, W$
x	Set of possible recycling centre's, $x = 1, 2, 3, \dots, X$
z	Set of new module suppliers for product p, $z = 1, 2, 3, \dots, Z$
$C_{d_{np}v}$	Unit disposal fees for module 'n' of product 'p' at site v
C_f	Fixed cost of factory f
C_{in_pj}	Inventory carrying cost/module/time at RPC j
C_{in_pf}	Inventory carrying cost/module/time at factory f (for deterministic model) & Material handling cost/module/time at factory f (for stochastic model)
C_j	Fixed cost of RPC j
C_{n_pz}	Unit cost of module 'n' of product 'p' from supplier z
C_p	Unit cost of returned product 'p'
C_{pA_f}	Assembly cost/product 'p' for factory f
C_{pi_j}	Inventory carrying cost/product/time at RPC j (for deterministic model) & Material handling cost/product/time at RPC j (for stochastic model)
C_{pi_w}	Inventory carrying cost/product/time at warehouse w (for deterministic model) & Storage cost/product/time at warehouse w (for stochastic model)
$C_{R_{np}j}$	Unit reprocessing cost for module 'n' of product 'p' at RPC j
$C_{s_{np}}$	Cost for new module 'n' of product 'p' for spare market s
C_w	Fixed cost of warehouse w
D	Total deterministic demand for all products at all distribution centre's
D_f	Demand of factory f

Notation	Description
D_{h_p}	Demand for product 'p' at distribution centre h
$D_{n_p s}$	Demand for module 'n' of product 'p' at spare market s
E_j	Storage capacity of RPC j
$E_{Re j}$	Processing capacity of RPC j
E_v	Capacity of disposal site v
E_w	Storage capacity of warehouse w
E_x	Capacity of recycling centre x
K	Stochastic demand for product 'p' at all distribution centre's with density function $f(k)$ and distribution function $F(k)$
M_{n_p}	Quantity of returned module 'n' of product 'p'
$M_{n_p f}$	Quantity of module 'n' of product 'p' at factory f
$M_{n_p j}$	Quantity of product 'p' (in modular form) at RPC j
$M_{n_p r}$	Quantity of product 'p' (in modular form) at retailer r
$M_{n_p s}$	Quantity of module 'n' of product 'p' sent to spare market s
$M_{n_p v}$	Quantity of module 'n' of product 'p' at disposal site v
$M_{n_p w}$	Quantity of product 'p' (in modular form) at warehouse w
$M_{n_p x}$	Quantity of module 'n' of product 'p' at recycling centre x
$M_{n_p z}$	Quantity of module 'n' of product 'p' procured from supplier z
N^B	Balance quantity of module 'n' of product 'p' available for manufacturing or storing
N^f	Quantity of module 'n' of product 'p' sent to factory
N^I	Quantity of module 'n' of product 'p' stored at RPC for future demand
N^s	Quantity of module 'n' of product 'p' sent to spare market
N^v	Quantity of module 'n' of product 'p' to be disposed
N^x	Quantity of module 'n' of product 'p' sent for recycling
N^ϕ	Quantity of new module 'n' of product 'p' required to meet the demand for remanufactured products
N^ψ	Quantity of new module 'n' of product 'p' required to meet the spare market demand
Q	Total quantity of products returned by the customers (for deterministic model) & Stochastic quantity of products returned by the customers with density function $f(q)$ and distribution function $F(q)$
Q_{j_p}	Quantity of product 'p' with RPC j
Q_p	Quantity of product 'p' returned by the customers
Q_{r_p}	Quantity of product 'p' with retailer r
Q_{w_p}	Quantity of product 'p' with warehouse w
T_{n_p}	Transport cost/module n of product 'p' (for a given distance)

Notation	Description
T_p	Transport cost/product ‘p’ (for a given distance)
T_{pfg}	Transport cost/finished product ‘p’ (for a given distance)
V_{n_p}	Unit volume of module n of product ‘p’
V_p	Unit volume of product ‘p’
σ_{n_p}	Disposal fraction of module n of product p
ρ_{n_p}	Recyclability fraction of module n of product p
χ_{n_p}	Recyclability fraction of module n of product ‘p’

1. INTRODUCTION

Preservation and sustainability are fields of growing interest among environmentalists and academics. Concern for environmental restoration and resource conservation is increasing among consumers. Implementation of legislation, social responsibility, corporate imaging, and economic benefits are other drivers that are forcing companies not only to provide more environmentally friendly products but also to take back the products after its end of life. Original equipment manufacturers (OEMs) have begun to respond to this situation through the 'extended producer responsibility' (EPR). This has credible implications on the logistics activities related to product recovery. This paradigm shift results in the development of product recovery management systems (PRM). PRM encompasses all activities used in handling used and discarded products to capture the latent economic (and ecological) value embedded in them and to ultimately reduce wastes. Implementation of PRM requires setting up of appropriate logistics infrastructure to handle the return flow of products.

Logistics is the art and science of strategically managing and controlling the flow of goods, energy, information and other resources like products, services, and people, from the source of production to the point of consumption. It involves the integration of information, transportation, inventory, warehousing, material handling, and packaging. The operating principle of logistics is the geographical repositioning of raw materials, work in process, and finished inventories where required at the lowest cost possible. Broadly logistics can be defined as *having the*

right item in the right quantity at the right time for the right price and is the science of process and incorporates all industry sectors.

1.1 Environmental Preservation and Green Manufacturing

Managers consider improvements in environmental performance as one of their basic priorities along with costs, lead time and quality (Azzone et al., 1997; Guide et al., 2003a, Klassen and Vachon, 2003). Walton et al. (1998) and Vachon and Klassen (2006) emphasize that companies need to act as a whole system that includes customers, suppliers and other players in the supply chain to thrive in the environmental management. In firms where managers do not recognize the importance of an effective RL program, there is a risk of seriously harming the organization's reputation and alienating customers (Daugherty et al., 2001).

With increasing concerns on landfilling by recyclable or reusable products, "take back" actions are becoming a norm (Thierry et al., 1995; Ayres et al., 1997; and Carter and Ellram, 1998). Preserving the environment along with maintaining economic growth has become a top priority for many countries. In several countries take-back obligations have been enacted or are underway for products such as cars (The Netherlands, Taiwan), packaging materials (Germany) and electronic equipment (European Union (EU), Japan). The Waste Electrical and Electronic Equipment (WEEE) Directive of the EU has made producers responsible for taking back and recovering their products (see WEEE). Thus, government at all levels are issuing directives, legislations, or incentive programs to encourage alternative disposition of wastes and considering policies to make

the producer more responsible for ensuring their safe disposition (Yang, 1995; Boks et al., 1998; Castell et al., 2004). The European community has been particularly active in legislation in response to public concern for the environment (Cooper, 1994). The development of international certification standards have also resulted in the practice of responding to environmental issues in a socially responsible manner (Melynk et al., 1999). Thus, on a global scale, research has begun to examine the impact of supply chain on the environment (New, 1997). OEMs have responded to such legislation by practicing green manufacturing. They have started incorporating environment friendly inputs that either facilitates resource reduction, reuse or recycling (Wu and Dunn, 1995; Gupta and Isaacs, 1997; Carter and Ellram, 1998) in their manufacturing processes. This is also known as 'lean consumption' (Womack and Jones, 2005). Florida (1996) and King and Lenox (2001) have also emphasized on lean manufacturing practices for effective greening of the supply chain.

Green manufacturing aims to reduce the ecological impact by using the appropriate material and technologies. It aims to minimize the deleterious impacts resulting from industrial activity and optimize the total materials cycle from virgin material, to finished materials, to component, to product, to obsolete product and to ultimate disposal (Graedel and Allenby, 1995). Green manufacturing forces companies to share their product responsibility during the design and manufacturing stage so that minimum of new resources are used and the lifecycle of the products could be extended beyond the first lifecycle (Azapagic, 2002). One of the ways for green manufacturing is to use the waste from one industrial process as the raw materials for another (Frosch and Gallopoulos, 1989). For

example, printed circuit boards recovered from discarded computers may be used in making high-tech toys (White et al., 2003). Gungor and Gupta (1999), Goggin et al. (2000), Fergusson and Browne (2001) and Toffel (2004) have discussed issues in environment friendly manufacturing and product recovery.

Green product design is an important aspect of green manufacturing (Zu et al., 2006), and influences the recovery process (Tsoufas et al., 2002). This requires a lifecycle approach whereby the material and components that are chosen at the beginning of a product's lifecycle will enable easy disassembly and reuse of these materials at the end of its useful life.

Earlier, Jones (1992) had identified green logistics as an important area for research. Handfield and Nichols (1999) also argued that environment is likely to be one of the major challenges facing logistics and supply chain management in the future. This growing importance of resource conservation is driven mainly by the escalating deterioration of the environment, for example diminishing raw material resources, overflowing waste sites and increasing levels of pollution (Ayres et al., 1997). Environmental concern is also spreading among the consumers who have recognized the importance of waste reduction and resource conservation (Ferrer and Ayres, 2000; Ravi and Shankar, 2005). Many companies have found that green products will be greener if the value adding logistics activities also become green (Wu and Dunn, 1995).

1.2 Reverse Logistics

Reuse of used products by some value addition is not a new concept. Earlier, while research efforts stopped at the so-called point of consumption, consumer behaviour and business practices in the market place continued beyond this point. For example, supply chains that are dedicated to satisfying second hand markets (Svensson, 2007). Also, industries are using remanufacturing for expensive products such as turbines used in airplane and electricity generation systems. In these cases recovery of used products is economically more attractive than disposal (Koh et al., 2002). Environmental issues also have a significant impact on salvage and scrap disposal as well as return goods handling (Murphy and Poist, 2003). It has led to new techniques to design products and supply chains that are both economically and ecologically feasible (Lau et al., 2004). RL and environmental supply chain concepts focus on re-engineering the supply chain toward the development of a closed-loop system emphasizing flows of material from consumers back to manufacturers (Giuntini, 1996; Handfield et al., 1997).

Thus, PRM is both, 'waste stream driven' system and 'market driven' system (Guide and van Wassenhove, 2001). This increasing emphasis on product take-back and product recovery has led to a phenomenal research in the area of handling returns i.e. reverse logistics (RL). Rogers and Tibben-Lembke (1999) define RL as:

'The process of planning, implementing, and controlling the efficient, cost effective flow of raw materials, in-process inventory, finished goods and related

information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal.

Thus, the traditional supply chain is extended to include supply flow of returns and recyclables. Hence, the supply chain does not end at the point of consumption, but at another (or new) point of origin (Svensson, 2007). Such a system which utilizes waste or scrap from one stage of production as inputs to other stages of production is also referred to as a 'closed loop supply chain' (Inman, 2002). It is recommended that RL be considered in the initial stages of product life cycle, while designing and managing the manufacturing systems and forward supply chains (Poist, 1989; Nakashima et al., 2002). This concept of RL represents the cradle-to-grave responsibilities of the OEM. It is based broadly on the principles of extension of product life.

According to a recent study, RL is one of the 21 top warehousing trends in the twenty-first century (Brockmann, 1999). However, it is not just about being environmentally friendly; it is also about being profitable in this endeavor. Thus, this has a business aspect and is not merely a cost centre (Meyer, 1999; Guide and van Wassenhove, 2003). Instead of a single time, a product may generate revenues multiple times, possibly in different markets. Indulging in product take-back and recovery services can be highly profitable for most of the companies (Porter and van der Linde, 1995; Cottrill, 1997; Andel, 1997; van Hillegersberg et al., 2001) and generate economic benefits (Toktay et al., 2004). The ability to extract value from product remanufacturing (Cohen, 1988; Heeb, 1989; Toensmeier, 1992), report that companies that make use of remanufacturing practices in product

recovery can potentially save about 40 – 60 percent of the costs compared to manufacturing a completely new product, the ability to reduce the cost of quality (Fassoula, 2005), the ability to reduce manufacturing lead times and efficient management of end of use returns and warranty returns have led to companies adopt greener industrial ethics and develop sustainable supply chains. An effective logistics process could result in either increased demand for the product by reducing the customers purchase cost or could increase the average profit margin by reducing direct costs (Yalabik et al., 2005). Efficient handling of returned goods also improves relationships along the supply chain (Sarkis et al., 2004); customer service (Turner et al., 1994; Wise and Baumgartner, 1999); and customer retention (Srivastava, 2007). As a result, companies can experience an increase in sales to environmentally conscious customers, decrease in liabilities and regulation penalties and potentially reduced costs (Handfield et al., 1997). RL also helps in managing products in a more cost effective manner (Rogers and Leuschner, 2004, Min et al., 2006b). Winsemius and Guntram (2002) found that designing a computer for recycling can reduce its assembly cost by 50%. Wright et al. (2005) found that redesigning a fibre optic cable can reduce environmental impact by 30% to 60% and can lead to a 40% reduction in economic costs.

Kopicki et al. (1993) suggested three strategies in RL, namely reactive, proactive and value-seeking. Bowen et al. (2001) also suggest focused and proactive approaches to efficiently implement green supply chains. A proactive approach can lead to stronger engineering capability, and eventually, competitive advantage (Newman and Hanna, 1996; Russo and Fouts, 1997; Heese et al., 2005). Also, an

early start of a formal RL program can help companies gain significant first mover advantages (Richey et al., 2004).

The main sources of reverse flow are customers themselves (Rogers and Tibben-Lembke, 1999 and Tibben-Lembke, 2002). The returns are handled through retailers or wholesalers and distribution centres, which are often called intermediary customers for the OEM. Generally, the returns from these intermediate customers would be:

- due to abnormal distribution quantity resulting of inefficient forward logistics (Wu and Cheng, 2006);
- end of season returns as in the fashion and clothing industry; marketing returns typically seen during the initial stages of a product life-cycle of products that have not been received by the customers as anticipated by the marketing team;
- obsolete products; and
- returns due to in-transit damage to the goods.

The customers would return the products for the following reasons:

- defective products;
- unwanted products and unsatisfied customers;
- warranty returns;
- product recalls;
- product upgrades or trade-in's; and
- environmental and disposal issues.

Besides these, packaging materials are also returned to the suppliers or manufacturers. Reverse flow of empty totes, cans, bins, bottles, pallets and other packaging and material handling equipment are common examples. In most cases they are cleaned and reused. Figure 1.1 shows the general activities in the forward and reverse supply chains.

1.3 PRODUCT RECOVERY OPTIONS AND RL ACTIVITIES

Companies have a number of options available for a returned product: repair, remanufacture or complete recycling of the material. However, the correct choice among these options may be dictated by the economics of product recovery and by the condition and age of the returned product (Guide et al., 2000). Johnson and Wang (1995), Thierry et al. (1995), Melissen and de Ron (1999), Goldsby and Closs (2000), and Inderfurth et al. (2001) have discussed various product recovery options and practices. The various options available for product recovery are as follows:

1. Reuse
2. Repair
3. Refurbish
4. Remanufacturing
5. Resell
6. Cannibalization
7. Recycling
8. Disposal

A brief description of these terms is provided in the glossary.

The increasing adoption of RL by various companies has promoted a large amount of research in the area of network design, distribution planning, vehicle and transport routing. Production planning, inventory control, supply scheduling, and product pricing are other areas which are also getting attention. RL has also led to research in the area of design for environment, design for recycling, disassembly and remanufacturing techniques and optimal product design.

1.4 RESEARCH OBJECTIVE

The main objectives of this research are:

1. Understanding reverse logistics from the perspective of OEMs by assuming supply of used products and demand for remanufactured products in a simulated RL network which includes remanufacturing facilities.
2. Developing a mathematical model for strategic decision making under deterministic supply and demand scenarios with regard to facility location and allocation to handle modular structure of various types of returned products.
3. Developing a mathematical model for strategic decision making under stochastic supply and demand scenarios with regard to facility location and allocation to handle modular structure of various types of returned products.
4. Analyzing the models for better decision making in RL.

1.5 RESEARCH SCOPE AND METHODOLOGY

The scope of this research is listed below:

1. To review the existing literature on RL.
2. To review the mathematical models published in the literature for RL network design.
3. Based on the gap analyzed in the literature, to develop mathematical models for RL network design.
4. To Implementing the mathematical model in GAMS® software and to test scenarios by changing supply and demand quantities.

In this research, a deterministic model is developed as a starting point in designing a reverse distribution network. Then, stochastic parameters i.e. stochastic supply and stochastic demand are incorporated in the model to assist in decision making under uncertainty. Simulated data is used to test the model and to interpret various strategic outcomes for the design of a network. As discussed by Jayaraman et al. (1999) and Tan and Kumar (2006), this research provides answers to the following questions:

1. *How many facilities should be opened?*

Companies need to determine the number of facilities to be opened for product recovery keeping in mind the return rate, the environmental policy, the legal

implications, and the business strategy of the firm. The stochastic nature of supply and demand in RL and the uncertainty in timing of return makes decision making complex.

2. Where should each facility be located?

Due to global sourcing, global markets, and e-commerce, OEMs need to consider world wide options for locating the facilities for product recovery. RL is characterized by uncertainty in origin of used products; this makes it difficult for the decision maker to decide the location of various facilities; for example, the location of collection centres or warehouses to consolidate the returned products.

3. What should be the capacity of each facility?

Depending on the demographic distribution of the products and the market share of the company, the decision maker must decide the capacity of each facility. The decision maker must also bear in mind the long term aspects like marketing strategy, legislative actions, and integrated logistics network. Uncertainty in the quantity of returns and demand affects this decision. The OEM may install a high capacity by investing huge amount of capital or have low capacity which may be insufficient to handle the returns.

4. How should the returns be allocated to each of the facilities?

Decision makers need to decide the allocation of returns to various reprocessing units considering objectives like shortest travel path, cheapest mode of transport or safest transport route (while transporting hazardous material wastes). The demand for remanufactured products from various secondary markets also

influences this decision. However, this demand is stochastic in nature and locations of secondary markets and spare markets may also change over time, thus increasing the complexity of the decision.

Besides the above mentioned questions, the research also addresses the following issues:

1. *What quantity of new modules should be ordered from the suppliers to meet the market demand?*

Since it is practically impossible to reuse all components/modules of a returned product, OEMs may need to procure new modules to meet the market demand. OEMs may need to consider supplier lead times, costs and material inventory before scheduling the new modules. However, the market demand is uncertain and the demand for spare parts is also not fixed. Also, the yield of each module of each product may be different which further complicates this problem.

2. *How to allocate the demand of remanufactured products from the factories to the secondary markets?*

Depending on the production capacity of the remanufacturing units and the market demand for remanufactured units, OEMs need to allocate the market demand to the remanufacturing factories based on strategies like cost minimization, customer satisfaction, time to market etc. The demand being stochastic, the decision maker faces difficulty in deciding the optimum allocation of remanufactured products.

1.6 ORGANIZATION OF THE THESIS

In this chapter, the drivers of RL or the initiators of product recovery activity are discussed. The reasons for product returns and various options for return handling are identified. Based on the various recovery options discussed in the above chapter, the existing literature based on logistics networks for remanufacturing, recycling, product recovery, and waste management activity is reviewed in Chapter 2. It also discusses the recent advances in RL, its strategic importance and RL modeling. The methodology for model formulation is presented in Chapter 3. A deterministic mathematical model is formulated and analyzed in chapter 4. The stochastic model is formulated and analyzed in Chapter 5. Chapter 6 concludes the research and puts forth the possible future research areas.

2. LITERATURE REVIEW

The research in reverse logistics is focused mainly in the areas of production planning and inventory control, network structures, and distribution planning. While some issues involve operational and tactical decision-making, this research focuses on the strategic decision-making in RL.

In a general collection and/or distribution function in which demand is served by multiple drop off and/or pickup routes involving several facilities, the overall efficiency depends not only on the distance from the individual demands but also upon the efficiency of the vehicle routes needed to serve the multiple demands. Such problems are referred to as location-routing problems (Current et al., 2002). Location – routing problems involve three inter-related, fundamental decisions: where to *locate* the facilities, how to *allocate* customers to facilities, and how to *route* the vehicles to serve customers (Perl and Daskin, 1985). It is thus obvious that the underlying network is important in facility location and location-routing problems. In this, one must determine which arcs should be included in the network and where to locate the facilities which are connected by these arcs. Examples of such problems include the design of railway systems, power transmission systems, water distribution channels and computer networks.

The location of facilities depending on the sources of supply, the demand locations or the location of disposal sites has been considered by several researchers (Schmenner, 1982; Brandeau and Chin, 1989; Appa and Giannikos,

1994; Gianinikos, 1998; Pushchak and Rocha, 1998). Works of Current (1988) and Current and Pirkul (1991) serve as classical examples for facility location-network design in logistics. The network here is a path and the facilities are ‘entry locations’ (e.g. station) for demand to enter the path (e.g. rail line). The objective is to minimize the network and facility costs as well as the cost of arcs needed for demand to reach a facility on the path.

Similarly, the airline hub and spoke location problem is also an example of network design. The location of the hubs, the assignment of the non-hub airports to the hubs i.e. the links to be used in the spoke part of the network, and the connectivity of the hubs are to be simultaneously determined. Other examples include the telecommunication, power transmission and computer network problems.

The focus or research of RL is growing since the Seventies. It was understood that the pressure to reduce wastes and reuse or recycle materials will have a major impact on the logistics infrastructure. Zikmund and Stanton (1971) identified the issues in recycling solid wastes and introduced the concept of the “backward” channel. Gilson (1973) studied the economic and environmental implications of a ban on convenience packaging. Schary (1977) discussed the role of transportation rates in recycling while Fuller (1978) discussed the alternative channels for recycling solid wastes. Various strategies and models were proposed during and after the Eighties. Chandran and Lancioni (1981) suggested that firms should develop strategies to locate the product in the distribution system for efficient product recalls. While Murphy (1986) studied the transportation issues in product

recovery, Min and Cooper (1990) proposed strategies for backhauling and freight consolidation.

2.1 FACILITY LOCATION

A typical supply chain consists of several participants. It includes raw material suppliers, component and sub-assembly suppliers, manufacturing facilities, warehouses, markets and disposal sites. These form the various nodes of a network which are connected by transportation routes. The location and capacity of each of these is based on economic, business and demographic parameters, thus making it a strategic decision for OEMs. In RL, the problem is more complex as the network also involves collection centres for used products, reprocessing and recycling centres for returned products, and secondary markets for sale of remanufactured products. Some OEMs combine the manufacturing and remanufacturing facilities and share the same transport network and warehouses for new and remanufactured products. At times, the remanufactured product is also sold in the same market as new products, but at a lower price.

Facility location is a long-term decision (De Brito and de Koster, 2003). As product recovery can be a risky venture (Horvath et al., 2005), companies need to decide whether to set up new facilities dedicated to return material handling or to handle them in a separate area in the same facility. This involves a trade-off between the high complexities in material handling in shared resources and high investment costs in dedicated facilities (De Koster et al., 2002). Companies have to ensure that sufficient handling and storage capacities are available for return

materials (incase the facilities used in forward and reverse flows are the same). Companies also need to decide transportation of 'cores' (used products) from the customers to the collection/remanufacturing centres and the remanufactured products from these locations to the customers. In the return flow, proximity to supply sources of cores and to the markets for the remanufactured products also influences the location of the distribution and/or remanufacturing facilities (Jayaraman et al. 1999). Furthermore, depending on the customer demands for various remanufactured products, the right quantity of remanufactured products should be stored in each distribution facility. Thus, companies are confronted with several criteria such as costs, profits, customer service etc. in designing their logistics systems. It involves trade-offs in economies of scale in transportation, manufacturing and facility investment, consolidation versus responsiveness, and labour cost savings versus transportation (Fleischmann et al., 2004). With regard to such high investments and a higher portion of logistic cost, as compared to the traditional supply chain (up to 50% and more) the importance of logistically optimizing EOL networks clearly turns out (Nagel and Meyer, 1999). Mathematical models are formulated to tackle three key issues affecting a RL network (Harrington, 1994):

1. The structure of the network;
2. The planning of material flows; and
3. The classification and routing of materials.

Coordinating between disposer market and resale market, supply uncertainty and return disposition decisions (Fleischmann et al., 2000, 2001; Hess and Meyhew,

1997; Yalabik et al., 2005) are some of the features that complicate the network design for product recovery systems. Global supply chains, global markets, stricter environmental norms and the fast rate of technology up gradation causing products to get obsolete quickly further complicate the problem of network design. In process industries, improper shipping and storage conditions can cause product contamination or degradation which makes network design complex (French and LaForge, 2006). World class companies are recognizing the strategic value of having a reverse logistics management system in place; ensuring goods that are kept on the retail shelf and in the warehouse are fresh in quality and demand; gaining a more favorable customer perception and maintaining brand equity by eradicating possible spoilt product from the chain (Rowley, 2000). The location of a facility also influences the competitive capabilities of a company (Prallinski and Kocabasoglu, 2006).

Increasing scarcity of natural resources and regulatory pressures have forced facilities to locate relative to sources of recycled materials, or to choose 'brownfield' sites (i.e. sites contaminated from earlier operations) (Apsan, 1996). Locating close to customer markets becomes important as the need for recycling products is increasingly demanded by customers and regulators (Angell and Klassen, 1999). Use of environmentally correct material limits logistics manager's choice in the network location analysis of nodal proximity to raw materials versus proximity to customers (Wu and Dunn, 1995). In the return flow, proximity to supply sources of cores and to the markets for the remanufactured products also influences the location of the distribution and/or remanufacturing facilities (Jayaraman et al. 1999). Strategies for installing new capacities or expansion of

old ones have become more complex. Capacities need to be created not only for manufacturing new products but also for remanufacturing, recycling and collection and storing of returned products. This requires complex decision making regarding the number, location and capacity of take-back centres, transportation routes, and third-party providers (Guide et al., 2000).

Therefore, design of a RL network needs to consider the network spectrum from the locations for the acquisition of used products to the locations for secondary markets and sale of remanufactured products. The key premise of the proposed process is the ability of the system to aggregate the necessary supply of recyclable material, transport the material in a cost-effective and efficient manner to a central point for processing and then sell the output of the process to markets where the demand exists (Knemeyer et al., 2002). While well-developed systems and capabilities can offer greater customer loyalty and product feedback, poorly designed and operated systems add significant costs and slow responsiveness (Kocabasoglu et al., 2007). Recovery of products in a manner that protects both the environment and the competitive advantage of the existing supply chain is a complex issue (Pagell et al., 2007). Hameri and Paatela (2005) and Richey et al. (2005) suggest the use of information systems to facilitate return handling better.

Several researchers have studied the design of RL network as it is a strategic option for many companies involved in product take back activities. The design is mainly focused on cost effectiveness of RL network. Studies have concluded that for recycling of the returned products, logistics costs account for a large share of the total costs (Jahre, 1995; Beullens, 2004). The cost of RL could be five times

that of forward logistics (Wu and Cheng, 2006). A conservative approach is that RL accounts for approximately 4 percent of the total logistics cost for a company (Rogers, 2001). In the retail and manufacturing sectors, it is estimated that RL accounts for 5-6 percent of total logistics costs (Raimer, 1997). An empirical study by Daugherty et al. (2001) indicates that, on an average, RL costs account for 9.49 percent of the total logistics costs. It has been estimated that the cost of moving a product back to the producer from the customer may be as much as nine times the original cost of moving the product to the customer from the producer (Lambert and Stock, 1993).

According to Fleischmann (2001), the requirement of additional transportation itself is often conflicting with the environmental benefits of product recovery. The used product has little or no value before the recovery process occurs. Hence, it is crucial to ensure that the volume and quality of the used material is worth the transportation and storage cost. This makes transport planning more complex. Also, with two-way freight flows, lead-times become longer because delivery time also includes time for pickups (Wu and Dunn, 1995). Logistics represents up to 95% of the total cost in recycling (Stock, 1998). The major concern is to assess whether or not the recovery of used products is economically more attractive than disposal. Smaller return quantities and variability in product types also increase the transportation costs (Ammons et al., 1997; Johnson and Leenders, 1997; Tibben-Lembke and Rogers, 2002). Similarly, handling costs, the economics of segregation and secondary processing activities are volume dependant.

Collection and consolidation are important activities in product recovery (Min, 1989). Guide and van Wassenhove (2001) suggest offering attractive incentive to motivate the end-user to return the product. Choi et al. (2004) have developed a model to determine the optimal buyback price for used products which are reworked and sold in an e-marketplace. Yalabik et al. (2005) also proposed a model to determine the optimal refund price for a retailer servicing two distinct markets. Aras et al. (2007) formulate a mixed integer nonlinear facility location-allocation model to find the optimal location of a predetermined number of collection centres. The model also gives the optimal incentive values for the different return types. They recommend a quality dependent incentive policy to maximize profits. Similarly, Liang et al. (2007) have assumed option pricing for the collection of used products of different quality levels.

Biehl et al. (2007) emphasize on the need for collection centres in a reverse production system. Bloemhof-Ruwaard et al. (1999) examined the problem of location of collection points in a RL system. Savaskan and van Wassenhove (2006) analyzed the trade-offs between centralization and decentralization of product collection activity. Min et al. (2006a) have developed a mixed integer non-linear programming model to determine the exact length of holding time for spatial and temporal consolidation at the initial collection points to minimize the total RL costs. Wojanowski et al. (2007) proposed integrated retail and collection sites and through their stochastic model suggested that profitability of the network depends on the accessibility of the customers to the collection centres. However, the return handling activity can be the responsibility of the OEM (individual take-back) or the government (collective take-back) (Webster and Mitra, 2007).

Gooley (1998), Spicer and Johnson (2004) and Krumwiede and Sheu (2002) suggest outsourcing of RL operations as a solution to EPR. Their claims complement the findings of Murphy and Poist (2003) who found that most organizations consider the strategy of using outside or third parties to manage environmental issues. For example, Hallmark cards use a third-party to collect excess seasonal inventory and repackage it for sale in secondary markets (Autry et al., 2000). Meade and Sarkis (2002) have proposed a decision support model based on analytical network process for selecting and evaluating third-party RL providers. Based on a survey of the automobile aftermarket industry Richey et al. (2005) suggest outsourcing or buying RL software for firms handling product returns.

Dowlathshahi (2000) and Knemeyer et al. (2002) identified the internal strategic and operational issues that need to be considered for RL systems. Krikke et al. (2001) also suggested various principles for RLND while optimizing economic, logistic and environmental performance. Tibben-Lembke (2002) suggested various strategies for handling EOL products. However, the strategies and tactics of RL might change over the life of the product, from development to cancellation (Tibben-Lembke, 2000; Tibben-Lembke and Rogers, 2002). The rate of technological change also influences the rate of returns (Guide, 2000). The realization of recycling targets for end-of-life products is dependent on parameters such as changing life time of the product and product design (van Schaik and Reuter, 2004).

Sarkis (2003) identified the components and elements of RL and developed an analytical network process (ANP) for a strategic decision framework for reverse supply chains. Steven (2004) has discussed the various networks in RL. Dowlatshahi (2005) presents a four-stage strategic framework for RL design and implementation. According to the author, the strategic decision making process begins with the customers and their requirements. Meeting customer requirements involves understanding the markets, customers, the competency and potential of the firm itself. The second stage is dominated by the environmental and legal clauses. The author suggests that the firm should not only consider current legal obligations but also those impending. In the next stage, the focus is on costs. It involves strategic (e.g. establishment) and operational (personnel, material handling etc) costs. The last stage involves the remanufactured product quality. The remanufactured product should meet or exceed the quality of the virgin products. Any non-conformance in quality could undermine the firm's effort to develop and implement an effective RL strategy.

2.2 MODELS FOR STRATEGIC DECISION MAKING

Fleischmann et al. (2001) carried out some of the elementary work in RL network design. They presented a generic MILP model based on the warehouse location model. However, only single product flow between incapacitated facilities; and only reprocessing as a product-recovery option was considered. Based on the warehouse location-allocation model, Jayaraman et al. (2003) proposed a model for the design of reverse distribution networks. The MILP model is described in detail and a designated 'weak formulation' is also proposed. They developed

heuristic procedures and applied it to five sets of twenty randomly generated problems. The model is fairly general considering only the reverse flow of goods.

Beamon and Fernandes (2004) focus on the investment and operational costs of the RL network and develop an integer programming model for a four echelon reverse supply chain system. The proposed network consists of manufacturers, warehouses, customers and collection centres. The storage capacities are considered to be infinite and the holding costs for recovered and new products are assumed to be same. The market demand is met by the manufacturer through new and recovered products. It is assumed that the recovered products are of the same quality as that of the new products, and hence will be used to satisfy the market demand. However, this may not be the case always (e.g. photocopiers, mobile phones etc). Also, the model does not include supply of new modules or products that might be required to meet the market demand. In a similar work Kusumastuti et al. (2004) present a multi-objective, multi-period MILP model for RL network design for modular products. The research also included a simulation model to incorporate uncertainty in the network. The model is solved using Genetic Algorithm and spanning tree methodology. The model determines the number of existing forward flow facilities to be used and the number of dedicated facilities to be setup for handling return flows. The model consider a demand for the remanufactured products in the secondary market; however it does not explicitly include a supplier network which may be required to meet this demand. Lau et al. (2004) proposed an infrastructure framework for supporting the design and implementation of RL systems. The framework aims at minimizing the overall logistics cost (forwards and reverse supply chains) and to set up the relevant

information management tools to execute the RL activities at minimum cost. Sim et al. (2004) proposed a multi-period, multi-product model for network design of closed-loop supply chains. The problem is solved using a linear programming based genetic algorithm.

Sheu et al. (2005) presented a composite multi-objective programming model to coordinate the integrated logistics flows (forward and return flows) in a green supply chain. The optimization model seeks equilibrium solutions with a goal of maximizing the profits associated with the manufacturing supply chain and the reverse supply chain respectively. In the integrated logistics operational model the authors incorporate factors such as the used product return ratio and corresponding subsidies from government organizations for used-product recovery, and recycle fees charged to the manufacturers. The authors applied this model to a Taiwanese notebook computer manufacturer and showed that the firms' efficiency can be further increased by 21.1% relative to the existing operational performance of the supply chain. However, the model is formulated for single-product returns only and hence has limited applicability.

Lu and Bostel (2007) present a MILP model for facility location in RL. The model is a two-level location model with three types of facilities to be sited. The market demand is met by traditional new as well as remanufactured goods. This demand is met by the producer; hence the flow of goods from the producer to the customer is termed as 'forward flow' by the authors. However, even though the demand is met by the producer, the model have not considered the supplier network which will supply new modules if required to meet the market demand. Also, the authors

consider demand only in one market, thus neglecting demand from spare market which may add revenue, while disposal and recycling costs are not considered. An algorithm based on Lagrangian heuristic approach is proposed to solve the problem. The limited application of the model is due to incapacitated facilities and non-modular product architecture.

Salema et al. (2007) present a MILP model to analyze the problem of closed loop supply chains. The authors improve upon the model presented by Fleischmann et al. (2001). The model considers multi-product returns with uncertain behaviour but limits the consideration of demand for returned products to factories and not to secondary markets or spare markets. Thus, a supplier network which may be required to manufacture a new product is not considered. Also, this model is not suitable for modular products. A case is presented and solved using standard B&B techniques. The same authors also present a different perspective of this work (see Salema et al., 2006). They model the flow between the facilities as a two-level flow as compared to the single-level flow considered in Salema et al. (2007). Single-level flow considers the total flow of goods between all facilities in the forward flow and all facilities in the reverse flow. Two-level flow considers individual flow between each two types of facilities in the forward flow and similarly in the reverse flow. Penalty fees for any unsatisfied demand or return and a fixed disposal fraction which incurs cost is considered. Several computational benefits and some cost savings are derived from this work. However this model is also not suitable for modular products.

Wang et al. (2007) proposed a location-inventory policy and modeled it as a bi-level programming problem – the upper level determining the appropriate location of the third checking sites (3CS) and the lower level presenting a coordinated inventory replenishment policy in light of the 3CS. Kusumastuti et al. (2008) present a multi-period MILP model to redesign a service network for a computer manufacturer. The model determines the locations of incapacitated local sub hubs and distribution centres and considers modular structure of the product. The model also assumes the cost of purchasing new modules, but does not explicitly consider a supplier network to meet the customer requirement. However, the sale of recovered modules in the spare markets and the recycling of faulty modules is not considered. Also, the model is not suitable for multi-product configurations.

2.3 RL IN RECYCLING INDUSTRY

Reverse logistics is widely practiced in the recycling industry. The need of recycling and product recovery networks was stressed in early 1970s. It was understood that the pressure to reduce wastes and reuse or recycle materials will have a major impact on the logistics infrastructure. In a study on the recycling of solid wastes of America, Zikmund and Stanton (1971) concluded that if recycling is to be a feasible solution to the trash problem, there must be some means to channel the waste material to the firm for future reuse. Thus, recycling was identified as a channels-of-distribution problem because of the major activities of collection, sorting and transportation.

The initial work on analysis of the reverse flow for recyclables was done by Guiltinan and Nwokoye (1975). The authors identified distinct channel structures in RL and analyzed the functions of the channel members. Fuller (1978) discussed the economics of redistribution of materials recovered from solid wastes. Schary (1977) and Murphy (1986) studied the transportation issues in recycling and reverse distribution. Pohlen and Farris (1992) tested Guiltinan and Nwokoye's model and developed different channel structures. The reverse distribution channel structure in plastics recycling is investigated and compaction and routing issues related to transportation in the RL process are analyzed. A detailed description of the various channel members and their functions are also given. The research also gives valuable managerial implications. However, this work is limited only to recycling rather than other forms of product recovery.

Spengler et al. (1997) examined recycling networks for industrial by-products in the German steel industry. The residuals of steel production (approximately 0.5 ton of every one ton produced) have to be recycled in order to comply with environmental regulation and to reduce disposal costs. For this, different processing technologies are available. Recycling facilities can be installed at a set of potential locations and at different capacity levels, with corresponding fixed and variable processing costs. The problem is to determine which recycling processes or process chains to install at which location at what capacity level. The authors assume linear transport costs to propose a modified multi-level warehouse location model based on linear activity analysis and further apply the model for various scenarios. The model also optimizes goods flow.

Barros et al. (1998) report on a case study addressing the design of a logistics network for recycling sand resulting from processing construction wastes in The Netherlands. While one million tons of sand used to be landfilled per year, a group of construction waste processing companies considered reuse in large scale infrastructure projects such as road construction, a potential reuse option which also complies to the environmental legislative requirements. The waste sand available is polluted with oil; hence the sand needs to be analyzed before reuse. Three categories are classified namely clean sand; half-clean sand and polluted sand. The polluted sand needs to be treated before it can be used; hence treatment of sand before reuse becomes an important issue. Cleaning of sand requires installation of expensive treatment facilities. The network for sand recycling encompasses of four levels, namely the crushing companies i.e. the source for polluted sand, regional depots for analyzing the sand and storing half-clean sand, treatment facilities cleaning and storing polluted sand, and infrastructure projects where the sand can be reused i.e. demand locations. The location and source of polluted sand is known from historical data. However, since the demand location and volume is unknown, the authors perform scenario analysis. A MILP model for the multi-level capacitated facility location problem to determine the optimum number, capacities, and locations of the depots and cleaning facilities in the network is proposed. However procurement costs (it is assumed that polluted sand is available freely) and also holding charges are not considered. Disposal costs for waste sand are also not considered which makes the model less applicable in today's environment.

A study on carpet recycling is carried out by Ammons et al. (1997) in USA. A logistics network is investigated that includes collection, processing of carpets and redistribution of recycled materials. With known customer/demand locations, the optimal number and location of collection and processing centres is to be determined. The authors propose a multi-level capacitated MILP model for facility location and conclude that volume is a critical factor for the network layout. Lave et al. (1998) prepared an implementation proposal for a carpet recycling program. Louwers et al. (1999) have considered the design of recycling network for carpet wastes in Europe. Through this network carpet waste is to be collected from former users and pre-processed to allow for material recovery. The pre-processing steps, which include identification and sorting, and shredding and palletizing for ease of transportation and handling are carried out in regional recovery centres from where the homogenized mix is transported to chemical factories for further processing. A continuous location model is proposed to determine appropriate locations and capacities of the regional recovery centres. This model is applied to 'supply-driven' and 'market-driven' cases in Europe and America respectively. Realff et al. (2000) discuss the strategic aspects of reverse production systems and analyze the strategic issues from the carpet recycling perspective. The same authors later proposed a robust multi-period MILP model for facility location in carpet recycling (Realff et al., 2004). The model seeks solutions close to the mathematically optimal solution for a set of alternative scenarios identified by the decision-maker. Because reverse production systems are expensive, have high uncertainty, are difficult to change, and there is not enough quality information to formulate a stochastic programming based approach, the robust optimization approach is adopted.

Ritchie et al. (2000) redesigned the returns handling and recycling system at a pharmaceutical company in UK. Schultmann et al. (2003) developed a capacitated two-level facility-location problem to determine the optimal design of a RL network for recycling spent batteries in the steel-making industry. The authors also developed a flow-sheet based simulation model for different scenarios of supply and recommend a change in the current network structure to achieve almost complete recycling of spent batteries. Guide et al. (2003b) discussed the production planning for closed-loop supply chains with product recovery for remanufacture-to-stock (at Kodak), reassemble-to-order (at Xerox) and remanufacture-to-order (at the US Navy) products. The research found that the planning focus varies across these companies with Kodak focusing on matching the core supply with demand; Xerox focusing on the component mix to meet the demand; and the Navy focusing on replacement materials required to meet the forecasted demand. Gonzalez-Torre et al. (2004) studied the difference between bottling/packaging firms belonging to the food and drinks sector and their suppliers and their customers in Spain and Belgium. Logozar et al. (2006) developed a model to minimize the cost of transporting aluminum scrap for recycling between certain production facilities of an aluminum manufacturing plant. Pati et al. (2006) have formulated a mixed integer goal programming model for analyzing paper recycling network. The model also assists in determining the facility location, and route and flow of different varieties of recyclable wastes.

Economically driven recycling also finds its application in automobiles (Bellmann and Khare, 2000). Schultmann et al. (2006) studied RL practices in the German

automotive industry. A RL network design model for recycling the automotive returns and product take-back is presented. The objective is to meet the legal recycling requirements at minimum costs. The model evaluates network design for separation and reprocessing of plastic components of end-of-life vehicles. The aspect of vehicle routing planning is modeled using linear programming and Tabu search and meta-heuristics for scenario analysis. Kagawa et al. (2006) carried out an empirical study to find out the effect of extending the lifecycle of cars by one year in Japan. The research found that such a provision not only contributes to the economic growth, but also compensates for the economic loss from a decline in car production. Wu and Cheng (2006) studied the RL practices in the publishing industry in China, Hong Kong and Taiwan and found that instead of processing the returned goods, logistics firms and publishers may consider discarding the returned goods directly. The study also found that the loss on material cost is far less than the manpower spent on processing and suggest that publishers can sort returned goods in off-peak season to save cost on RL. Kumar and Yamaoka (2007) discuss how the increasing demand for cars and the Japanese regulation of increasing recycling and reuse of cars affects the export of used cars and the demand for raw material required to meet the increasing demand of cars.

2.4 RL IN ELECTRONIC AND ELECTRICAL WASTE RECYCLING

Recently, due to their fast obsolescence, electrical and electronic equipment wastes have caught the attention of researchers. Researchers are developing RL systems to handle these high-tech wastes more efficiently to minimize disposal and environmental impact. De Fazio et al. (1997) discussed the problems

associated with discarding and scrapping office computers. Johnson (1998) studied the RL system for ferrous scrap in 12 North American manufacturing plants. The study found that volume is an important parameter in determining the strategy used by firms in managing RL activities. The research also highlighted the contribution of the purchasing function to RL. Lee et al. (1998) presented the development and implementation of Taiwan's producer responsibility recycling system. The Taiwanese environmental protection agency established seven foundations by the end of 1997, to manage the recovery and recycling of post-consumer products. These foundations are responsible for planning, organizing, and implementing scrap recovery and recycling, and calculation of the scrap processing fee.

Krikke et al. (1999a) study the recycling of PC-monitors for a municipal waste company in The Netherlands. The research presents a two-step procedure, identifying optimization on the product and group level and the inclusion of stochastics in quality classes and transition probabilities. There is an attempt to analyze the economic viability of monitor recycling using the model. The model determines a profit-optimal product recovery and disposal strategy for each of the six types of monitors considered in the study. The returned products are disassembled into parts/components and optimal recovery and disposal options for both, the components and the entire product as a whole are discussed. The research proposes a strategy which includes options of partial disassembly, mixed and separate recycling. By using this model, the recycling costs can be reduced by about 25% and hence conclude by indicating additional cost savings resulting in overall savings of up to 40%.

Shih (2001) carried out a study of the electrical appliances and computer wastes in Taiwan. The study proposes a MILP model to determine the optimal collection and recycling system plan for end-of-life computers and home appliances encompassing the infrastructure design and reverse network flow operations. The model also helps to determine the location for storage and treatment facilities. Optimal physical flow of end-of-life goods between the various collection points, storage sites, recycling plants and the final disposal sites are obtained. Several scenarios for different take-back rates and operating conditions are simulated. The work is concluded by a case in which the author recommends the need of one additional disassembly plant for appliances take-back as the return rate increases by 20%. The author also recommends sharing of storage facilities in recycling electrical appliances and computers to reduce the total costs. However, there is no need for disassembly plant expansion for computers.

In January 2003, the European Union issued the directive on the waste of electrical and electronic equipment (WEEE) to curb the disposal of consumer goods and durables (Directive 2002/96/EC). Spengler et al. (2003) analyze a short term recovery planning problem for electronic scrap and formulate it as a MILP model, based on linear activity analysis. The purpose of this work is to obtain an optimal choice of recovered products for disassembly and bulk recycling as well as optimal allocation of disassembly activities. When modeled for a multistage electronic scrap recovery facility including disassembly and bulk recycling, it is found that disassembly is only advisable if the product has hazardous or precious parts in it, else recycling is sufficient if returned parts have no functional value.

Menad (1999) discussed the economics of cathode ray tube recycling with different processes. Hameri and Paatela (2005) studied the case of an electronics manufacturing service which created a new business unit for RL giving special focus, management resources and priorities to product returns. Linton et al. (2005) studied a case on television cathode ray tubes and proposed postponement and speculation strategies for reclaiming them. Hicks et al. (2005) discussed the status of WEEE recycling and disposal in China, and its impacts on the environment, human health, and the economy. The study also examined the legislative and market responses to the WEEE and the problems in introducing a formal WEEE management system due to the presence of a large, unlicensed collector and second-hand appliance dealer network in China. Hischer et al. (2005) studied the impact of the WEEE directive on the Swiss recycling systems, the Swiss take-back and recycling systems for computers and house-hold appliances. With a combined approach of material flow analysis (MFA) and life-cycle assessment (LCA), the study estimates the environmental impacts of these two systems, including steps which transform the fractions either into secondary materials or into waste for final disposal. The study also compares the recycling and take-back systems with a system in which there is complete incineration of all WEEE and finds that the Swiss product take-back and recycling systems have an environmental benefit than incineration of all WEEE.

Walther and Spengler (2005) studied the impact of the WEE directive on the German waste treatment system and develop a linear programming model for the recycling of the WEEE in Germany. The research considers disassembly, disposal

and recycling options for the returned WEEE. The objective here is to maximize the profit (the difference between the revenue and the costs) of the system. The model converts the returned product (in units) to material fractions (in kg) for treatment. The activity-based model optimizes the allocation of discarded products, disassembly activities and disassembly fractions to participants of the treatment system. Since variable costs and revenues related to processes and material flows are considered, fixed costs for the facilities are not taken into account. The research proposes changes in the organization and material flow of the German waste treatment system due to the impact of the WEEE directive.

Kara et al. (2007) carry out simulation modeling for the collection of white goods in the Sydney Metropolitan Area, Australia. The research uses simulation modeling to incorporate the high degree of uncertainty of quality and quantity of the returned products. From the scenarios analyzed, it is found that the lowest costs can be achieved when the local councils act as collectors, bi-directional travel is used and by excluding the outer suburbs of Sydney from the network. Highest costs are incurred by using retailers act as collectors and returning the trucks empty to their point of origin. Oguchi et al. (2007) carried out a product flow analysis on 94 consumer durables items in Japan. The study found that total waste weight of the nine target items (air conditioners, CRT TV sets, refrigerators, freezers, washing machines, desktop personal computers (PCs), notebook PCs, CRT displays and LCD displays) of Japan's recycling laws (Home Appliance Recycling Law and Law for the Promotion of Effective Utilization of Resources) account for 68% of the total 94 items. Kodak has also proactively volunteered to design a take-back system for its One-Time-Use-Camera (OTUC) (Kodak.com).

General Motors (GM) has also incorporated environmental responsibility in product development, production, usage and recovery stages and is a part of its corporate responsibility (GM.com).

2.5 RL IN PRODUCT REMANUFACTURING

Remanufacturing refers to an industrial process in which worn-out products are restored to like-new condition (Lund, 1984) and is also referred to as recycling-integrated manufacturing (Hoshino et al., 1995). Remanufacturing used products need to be less expensive than manufacturing from virgin materials in order for it to be attractive to manufacturers (Hammond and Beullens, 2006). Hence, research is also carried out to evaluate the various remanufacturing options and networks in RL. Ferrer (2001) focuses on the development of efficient remanufacturing procedures for generic durable goods at end-of-life. Various strategies like ratio of recyclables', ease on disassembling, potential for reuse, design for remanufacturing and design for environment are proposed by the author in this study.

Ferrer (1997) discussed the economics of tire remanufacturing and proposed that retreading is the sole alternative for maximizing tire utilization. The author proposed a closed-form expression based on the rate of reduction of time between retreads, the value of the new tire and the retreading cost. The expression recommends the number of retreads for each tire that maximizes tire utilization. Lebreton and Tuma (2005) also proposed a linear programming model to assess the profitability of car and truck tire remanufacturing. Krikke et al. (1999b)

analyzed a RL network for photocopiers. The authors implemented a remanufacturing process at a copier manufacturer in The Netherlands. The recovery process involves i) disassembly of return products to a fixed level, ii) preparation which includes inspection and replacement of critical components, and iii) reassembly of the remaining parts together with repaired and new components into a remanufactured machine. In addition, the central stock keeping, the sub-assembly production, and material recycling act as supporting processes. Given fixed supplying processes and disassembly, the study proposes a MILP model to determine optimal locations for the preparation and reassembly operations. The available options include two locations in Venlo (The Netherlands) and one in Prague (Czech Republic) owing to lower personnel costs. The optimal solution minimizing operational costs is compared with the pre-selected managerial solutions. Locating all processes in Prague appears to be optimal with respect to operational costs; however this requires huge investments thus making the overall saving significantly less. Kerr and Ryan (2001) attempt to quantify the life cycle environmental benefits achieved by incorporating remanufacturing into a product system based on a study at a copier manufacturer in Australia. The benefits of remanufacturing as a product recovery option; a way of resource conservation; and a method of reducing waste generation are discussed. The research found that if a particular product (Photocopier DC 265) is designed for disassembly and remanufacturing, the reduction in energy consumption is better than factor 3. Seitz and Peattie (2004) discussed the difficulty in engine remanufacturing at a European car company. The authors also highlighted the differences between the manufacturing and remanufacturing practices.

Franke et al. (2006) developed an optimization model for planning of capacities and production programs for remanufacturing of mobile phones. It considers modular nature of the product and adds disposal as one of the options to be exercised by original equipment manufacturers (OEMs) in RL. The model considers four possible options for product recovery or its modules namely reuse; component retrieval; material recycling; and disposal. The model also includes an external procurement activity (suppliers) to satisfy the market demand. The process capacities and the remanufacturing program are determined by the optimization model. Based on these results, an executable simulation model is generated for the remanufacturing system considering process capacities and resources for transport and storage. The simulation model helps in determining the required transport and storage capacities, and the performance of the remanufacturing system. Chan et al. (2006a) also presented a model for implementing RL in a mobile phone industry. Mutha and Pokharel (2006) formulated a linear programming model to develop a network for remanufacturing returned products. The research considers modular structure of products and demand for remanufactured products from the secondary markets as well as demand for recovered modules in spare markets. The model assumes a nine-echelon network and also explicitly considers a network of new module suppliers which may be required for remanufacturing to meet the demand.

2.6 RL IN PRODUCT RECOVERY

Product recovery is another area which has led to the growth in the research and development of RL. Gilson (1973) explained the economic and environmental implications of the ‘Oregon Model’ in which a five-cent deposit on each can and non-returnable bottle of beer and soft-drinks was legislated in the state of Oregon, USA. Kelle and Silver (1989) considered the forecasting of returns of reusable containers in which the planner must forecast the core availability that depends on the products stage in its life cycle. In this paper, a model for purchase quantities of new containers in a returnable network is formulated. Kroon and Vrijens (1995) studied the design of a logistics system for reusable transportation packaging. The study considers a closed-loop deposit based system for collapsible plastic containers that can be rented as secondary packaging material. The system involves five group actors namely a central agency owning a pool of reusable containers; a logistics service provider being responsible for sorting, delivering, and collecting the empty containers; senders and recipients of full containers; and carriers transporting these full containers from the senders to the recipients. The authors focus on the role of the logistics service providers. The number of containers at the depots needs to be balanced. Since the total number of containers shipped from a depot during a planning period should be equal to the number of containers received, containers may be relocated among the depots. A MILP model that is closely related to an incapacitated warehouse location model is proposed to determine the number of containers required to run the system, the appropriate fee per shipment and where to locate depots for empty systems. Uncertainty is covered via scenario analysis.

Berger and Debaillie (1997) address a similar situation of product recovery and proposed a conceptual model for extending an existing production/distribution network with disassembly centres to allow for recovery of used products. The model, in which the OEM is responsible for the product recovery and bears all the costs, is presented using a fictitious case of a computer manufacturer. The existing distribution network encompasses plants, distribution centres and customers. In the extended network, used products are collected from the customers and inspected in a disassembly centre. Here the products are divided into three categories; i) high quality products that can be repaired and shipped to a distribution centre for re-sale; ii) products containing reusable parts which may be disassembled and shipped to a plant to be reused in the production processes; and iii) other products that need to be disposed. While each plant and distribution centre has a fixed location and capacity, the location and capacity of the disassembly centres needs to be determined. The authors also develop a variant of this model in which the recovery network is extended to another level by separating inspection and disassembly/repair. After inspection, rejected products are disposed, while recoverable products are shipped to a repair/disassembly centre before entering a distribution centre or a plant. The authors propose multi-level capacitated MILP models to address these problems.

Klausner et al. (1998) studied the remanufacturing of electrical motors. Electronic data logs (EDL) were introduced in the motors to record the product history along its lifetime. The EDL measures, compiles, and records parameters indicating the degradation of a motor during its use. McIntyre et al. (1998) studied Xerox's

integrated supply chain which promotes reduction and reuse of packaging and return transport flows of machines, parts, empty toner bottles and print cartridges, packaging and pallets for recycling, reprocessing or remanufacturing. Klausner and Hendrickson (2000) studied the product recovery at a German power tool company and developed a take-back concept which is based on reusing certain high-value components from the used products. A certain fraction of the return flow, which is characterized by almost no technological obsolescence, is remanufactured. A model is developed to optimize the overall net profit of product take-back per product sold (which is a sum of profits of remanufacturing and materials recycling minus the cost of RL scaled to the number of products sold) and assists in determining the optimal amount to be spent for buy-back and the optimal unit cost of RL. The study concludes with managerial insights to the manufacturer wherein, with profits generated from remanufacturing, the manufacturer could afford to offer buy-back plans featuring discounts on new tools, more convenient collection, or even cash payments. Rudi et al. (2000) developed a decision support system to assist the Norwegian National Insurance Administration to decide whether to refurbish or scrap the returned wheelchair.

Bloemhof et al. (2001) studied two types of containers at a milk producing company in The Netherlands. The life-cycle of PC bottles (polycarbonate bottles) and GT packs (glass-top packs); both used in packaging dairy products by the firm is analyzed. The PC bottle returns after use while the GT pack is disposed off after use. The authors develop a tool (CAMP – choice of alternative material packaging) based on activity based costing and LCA to consider the cost and environmental impact of these containers considering the forward and return

flows. Further scenario analysis of these containers is carried out with and without return flows for various container types and number of return loops. The study finds that even though costs in the forward chain are almost same for PC bottles and GT packs, cost in return chain is more for PC bottles. The study also finds that the PC bottle has a better impact on the environment and hence suggests its increased usage. Some material handling strategies like use of roll-in-containers for large volume of PC bottles and GT packs and preferred use of boxes over crates in case of delivery via distribution centres are also recommended. Guide and van Wassenhove (2001) discussed the returns management process at a third-party manufacturer of mobile phones in the US. The authors described the remanufacturers' product acquisition process in which the company purchases used mobile phones through sellers rather than direct purchasing. This strategy has enabled the company to reduce the need to sort and grade phones in-house, thereby reducing the operational costs.

Blackburn et al. (2004) propose an efficient network for products that do not lose much value with respect to time (eg. power tools) and a responsive network for products which have a short product life (eg. computers and electronic products). Savaskan et al. (2004) propose a different kind of product recovery network strategy depending on who collects the used products namely the manufacturer, the retailer, or a designated third-party. The objective of profit maximization is analyzed for each actor in each strategy and is compared with the objective function when a centralized decision making /control strategy is adopted by the manufacturer. The findings suggest that optimal results are achieved when the retailer collects the returned products as it is profitable for both – retailer and

manufacturer as they both are economically benefited by this strategy. However, the research considers the flow of goods in only a two echelon system i.e. retailer and manufacturer and hence fails to address the issues of a complete reverse supply chain. Lee and Dong (2007) study the logistics network design for recovery of end-of-lease computer products. The study proposed a deterministic programming model by considering hybrid processing facilities for forward and return product flows. The optimum RL network is determined by using a two-stage heuristic algorithm.

2.7 RL IN WASTE MANAGEMENT

Reverse logistics also finds applications in the hazardous waste treatment systems. The waste from one industrial process can serve as the raw materials for another, thereby reducing the impact of industry on the environment (Frosch and Gallopoulos, 1989). Fuller (1978) discussed the economics of reverse supply chain and economics of redistribution of recovered materials for solid wastes. Jahre (1995) studied the household waste handling system and implemented the supply chain concept of 'postponement' in handling wastes. Yang (1995) studied the urban waste recycling in Taiwan. Chang and Wei (1999) developed a multi-objective nonlinear mixed integer programming model to effectively allocate recycling drop-off stations of appropriate size and design efficient collection-vehicle routing and scheduling programs for solid waste collection network in Kaohsiung, Taiwan. The model seeks trade-offs between the number and size of drop-off stations, the population covered in the service network, the average

walking distance to the stations, and the distance traveled by the collection vehicles.

Similarly, Grodzinska-Jurczak (2001) studied the generation of industrial and municipal wastes in Poland and proposed the implementation and supervision of waste management systems by national and provincial administration along with waste legislations for efficient system for waste management. Hu et al. (2002) also conducted a study on the RL practice of hazardous waste treatment in Taiwan and presented a cost-minimization model for a multi-time step, multi-type hazardous waste RL system. The research proposes a discrete-time linear analytical model that minimizes total RL operating costs subject to constraints that take into account business strategies and governmental regulations. In the case study, the authors prove the applicability of the model where the model coupled with operational strategies saves the RL costs by more than 49%. Tsoulfas et al. (2002) and Daniel et al. (2003) studied the environmental impact of battery disposal in Greece.

Bautista and Pereira (2006) studied urban waste system in Barcelona for the location of collection areas. Sheu (2006) studied cross-functional product logistics flows and induced-waste reverse flows for regional nuclear power generation and proposed a conceptual framework and operational model. Sheu (2007) also studied the regional hazardous waste management system in Taiwan. The author presented a linear multi-objective analytical model that systematically minimizes both the total RL operating costs and corresponding risks associated with the hazardous materials. Environmental concerns are considered and formulated as

corresponding risk related constraints. The location and capacity of each facility is known and the distribution centre performs collection, storage, treatment, and outgoing distribution activities. From the case study, the author concludes that when the aspect of risk-induced penalties is not considered, the operational costs of regional hazardous-waste management can be efficiently reduced by 58% compared to the existing operational costs.

Georgiadis and Valchos (2004a) propose a generic framework for RL network design using systems dynamics methodology. Georgiadis and Valchos (2004b) have also proposed a model based on system dynamics approach to study the impact of environmental policies and the 'green image' effect on the reverse supply chain with remanufacturing. The model is used to analyze the network behaviour when the capacities of remanufacturing facilities are expanded. Lead times for capacity expansion are also considered. The market behaviour due to the company's practice/strategy of incorporating 'green practices' in manufacturing, and the influence of the legislations on the networks are also modeled. However, the network is limited to collection, inspection, remanufacturing and disposal activities in the reverse channel. Tan and Kumar (2006) also adopt the system dynamics approach to present a decision making model for OEM's to maximize profits in RL operations. The model was tested on a computer manufacturer. The research finds that the parts manufactured in-house (i.e. by the parts designed and made by the manufacturer where the technical know-how is kept within the organization) need to maintain a higher resale price than buy parts (i.e. the parts purchased by the manufacturer from suppliers) in order to breakeven or be profitable. Also, the delays have a significant impact on the RL operations. Delays

associated with make parts caused by transportation have an impact on its profitability while delays associated with buy parts caused by suppliers in collection has the most impact and results in losses.

2.8 STOCHASTIC MODELS FOR FACILITY LOCATION

Guide et al. (2000) and Flapper (1995) discussed differences between forward and reverse supply chains in terms of the difficulty in forecasting product returns as compared to forward distribution which works on a fixed quantity and schedule. A forward supply chain generally has few suppliers and large number of customers; however a reverse supply chain involves a large number of suppliers and a small number of customers (Fleischmann et al. 1997; 2000, Salema et al. 2006). Tibben-Lembke and Rogers (2002) highlighted the uncertainty in the final destination of a returned product.

The return of used products is uncertain in terms of quantity, quality and timing of return (Liang et al., 2007). The demand for remanufactured products is also difficult to predict. Also, as the quality of the returned products is not known in advance, likewise the amount of good quality parts recovered from the returned product is subjected to uncertainty (Inderfurth and Langella, 2006). OEMs need to take this uncertainty into consideration to set-up efficient and cost effective product recovery networks. The design of such a network is one of the most challenging elements of managing RL operations (Pochampally and Gupta, 2005). Some researchers have developed scenario based models for RL network design under uncertainty. However, as reported in Mudchanatongsuk et al. (2005), the

scenario based methods face the following shortcomings: 1) they assume a known discrete description of the uncertainty, which can be a crude approximation of reality; 2) the large number of scenarios used in accurately representing the uncertainty can lead to large, computationally challenging problems; 3) the solution obtained can be sensitive to possible uncertainty outcomes.

Crainic et al. (1993) developed a stochastic model with recourse for the allocation of empty containers. Inderfurth et al. (2001) proposed a periodic review model for product recovery in stochastic remanufacturing systems with multiple reuse options. Vlachos and Dekker (2003) developed a model to determine the simple optimality conditions for the order quantities for products with returns. They consider various return handling options such as resale of returned products in the secondary markets, complete disposal (no recovery) of returned products, and partial or full recovery. This research extends the classical newsboy problem to incorporate returns. Inderfurth (2004) extended the newsboy model to determine optimal policies in hybrid manufacturing/remanufacturing systems for a single-period problem with stochastic returns of used products and stochastic demands of serviceable products.

Listes and Dekker (2005) proposed a two-stage stochastic model for recycling sand. The model for varying demand and supply scenarios suggests that the number and location of newly opened facilities is influenced by the amount and quality of incoming flows and also by the sources and demand points. Yao et al. (2005) used the newsboy model to determine the retailer price and order quantity under return policies. The problem of style-good returns is developed using the

game theory structure for competing retailers. Arcelus et al. (2006) also used the newsboy model to evaluate the manufacturer's buyback policies under price-dependent stochastic demand. The manufacturer's decision is to arrive at an optimal wholesale price and the buyback price. Based on this offer, the retailer in turn sets the optimal amount of merchandise to purchase, as well as the unit selling price to meet a price-dependent uncertain demand.

Inderfurth and Langella (2006) analyzed the problem of disassembly planning of returned product under stochastic yield for each component of the disassembled product. The excess modules are disposed and shortage is fulfilled by procuring new components. A model is formulated to address the question of how to obtain the parts needed for remanufacturing by disassembling different types of returned products or by procuring these parts as an alternative to disassembly. The model assumes a deterministic supply of used products and demand for remanufactured products. Van Ommeren et al. (2006) discussed the repair shop location problem with inventory control. The model is based on scenario analysis.

Biehl et al. (2007) developed a model assuming stochastic collection (having lognormal distribution) and demand (normal distribution) for the US carpet industry. The model is used to determine the quantity of virgin nylon to be ordered by the manufacturers based on the supply of recycled nylon (carpet) to meet the market demand. Listes (2007) presented a generic two-stage, capacitated model for stochastic supply and return network design. The author proposed a decomposition approach to the model based on branch and cut procedure (known as the integer L-shaped method). Lieckens and Vandaele (2007) extended a

facility location-allocation MILP model in RL with queuing relationships to incorporate product life cycle and inventory holding costs, as well as to deal with the uncertainty in RL networks. A mixed integer non linear programming (MINLP) model is formulated to solve the problem of single-product returns.

Mutha and Pokharel (2007) presented a two-stage stochastic model for a RL network. The model considers modular architecture of products and the demand of used modules in the spare markets. However, the model is based on scenario analysis with a known probability of occurrence for each scenario. Wojanowski et al. (2007) proposed integrated retail and collection sites and developed a stochastic model to analyze the network structure for product returns when a refundable-deposit is charged to the customer at the point of sale. The model analyzes the existing network of facilities of a firm when a refundable deposit is added onto the retail price. Scenario analysis is carried out in which the retail price and the area covered by each facility are optimized. The impact of the returned product value on the firms pricing and collection decision is clearly shown. The authors suggest that success of the profitability of the network depends on the accessibility of the customers to the collection centres.

2.9 OTHER RELEVANT RESEARCH IN RL

Research is also done in areas other than network designing in RL. Kim et al. (2006) discuss the aspect of supply planning in RL considering modular structure of products and address the problem of scheduling supplies of new modules from suppliers to meet the demand after a certain recovery of modules from the

returned products. The research presents a MILP model for maximizing the cost savings by optimally deciding which quantity of products/modules are to be refurbished and which are to be outsourced from the suppliers. Even though disposal is considered as an option, the research does not focus on the network design of RL. The authors also carry out sensitivity analysis for capacity change at collection centres, disassembly centres and refurbishing centres. Veerakamolmal and Gupta (2000) propose an optimization based procedure to solve a similar problem of supply chain planning in RL. Simultaneously an attempt to find the most economical combination of products to disassemble in order to fulfill the demand for various types of reusable components, while keeping the quantity of partially discarded products in check, and incur least disposal costs is made. The solution gives the number of each product type to be disassembled in order to fulfill the demand of components needed at minimal disassembly and disposal costs.

Reimer et al. (2006) have developed truck sizing models in collection of wastes and transporting them to recovery centres. Issues such as 'optimal compartment size' and 'optimal compartment capacity' are discussed. Karakayali et al. (2007) developed models to determine the optimal used product acquisition and remanufactured part selling price decisions in centralized as well as remanufacture-and collector-driven decentralized channels. The authors investigated the impact of these decisions on the quantity of used products collected and identify when and why an OEM would outsource the collection or the processing decision.

Blumberg (1999), Amini et al. (2005) and Du and Evans (2008) analyze RL in the repair and after-sales service functions. The competitive value of effective RL operations for the successful and profitable execution of repair service activities is discussed. As logistics activities needed to support service and repair activities include storage and warehousing; collection and sorting; substitution; transportation and distribution; disposal; repair and remanufacturing; and recertification, an attempt is made to design a repair service supply chain (RSSC) which includes analysis of i) Where to stock inventory parts; ii) How much parts inventory to carry; and iii) Where to locate service crew domiciles (Amini et al., 2005). The RSSC is designed for both effectiveness and profitability by achieving quick response time for repair service while minimizing total capital and operational costs. Murthy et al. (2004) discussed issues in location of warehouses and service centres in warranty logistics. Research is also done in areas of vehicle routing and planning in reverse logistics (Dethloff, 2001; Alshamrani et al., 2007).

2.10 SUMMARY OF LITERATURE REVIEW

In recent years, the increasing focus on RL and green industrial practices has led to credible research in the areas of design for disassembly and design for remanufacturing. This has resulted in fundamental changes in the product design concepts and methodology. To facilitate easy disassembly and replacement of part, companies have started developing products with modular architecture.

Modular structures help in remanufacturing related activities as well as in manufacturing and forward supply chain. Modularity helps in standardization of

components and rationalizes the assembly lines (Gershenson and Prasad, 1997). Product variety can be increased with modular architecture (Gershenson et al. 2004). It promotes interchangeability (Gershenson et al. 2003) and reduces life cycle costs by reducing the number of processes and reducing repetitive processes (Gershenson et al. 1999). Since fewer parts are to be procured, modular structure help reduce the order lead times (Ulrich and Tung, 1991). Also, the product is easy to test due to easy coupling and easy to repair due to differential consumption (Ulrich and Tung, 1991).

Due to modular architecture of products, the components can be reused because the life expectancy of many components far exceeds the product's life. Mukhopadhyay and Setoputro (2005) have suggested modular design for optimal return policies in build-to-order products. Krikke et al. (2004) describe the issues in designing CLSC for handling returns of modular products. Thierry et al. (1995), Jorjani et al. (2004) and Kim et al. (2006) also reiterate the importance and benefits of modular products from a RL perspective. Due to these benefits, most companies have started designing their products with modular structures. Modular based design and production can also facilitate on-site assembly and dismantling in warehouses. Fernandez and Kekale (2005) studied the implications of modular product architecture on RL strategies. The authors discussed qualitatively on how a modular structure of products affects the decision-making in terms of destination for a returned product or its modules.

A summary of the above literature is presented in Table 2.1.

Table 2.1: Summary of literature Review

Network type	Author	Facility Location	Capacity	Multi-product	Modular Product	Explicitly consider Suppliers	Secondary markets
Strategic Design	Jayaraman et al. (1999)	Y	Y				
	Fleischmann et al. (2001)	Y	Y				Y
	Jayaraman et al. (2003)	Y	Y				
	Beamon & Fernandes (2004)		Y				Y
	Kusumastuti et al. (2004)	Y	Y	Y	Y		Y
	Sim et al. (2004)	Y	Y	Y			
	Sheu et al. (2005)		Y				
	Min et al. (2006a)	Y	Y				
	Lu & Bostel (2007)	Y					Y
	Salema et al. (2007)	Y	Y	Y			
	Kusumastuti et al. (2008)	Y		Y			
Recycling Networks	Ammons et al. (1997)	Y	Y				Y
	Spengler et al. (1997)	Y	Y	Y			Y
	Barros et al. (1998)	Y	Y				Y
	Louwers et al. (1999)	Y	Y				Y
	Schultmann et al.(2003)	Y	Y				
	Pati et al. (2006)	Y	Y	Y			Y
	Schultmann et al.(2006)		Y				
WEEE Recycling Networks	Shih (2001)	Y	Y				Y
	Walter & Spengler (2005)	Y	Y	Y			Y
Re-Manufacturing	Krikke et al. (1999b)	Y	Y		Y		
	Franke et al. (2006)	Y	Y		Y	Y	Y
	Mutha & Pokharel (2006)	Y	Y		Y	Y	Y
Product Recovery	Kroon & Vrijens (1995)	Y					Y
	Berger & Debaillie (1997)	Y	Y				
	Lee & Dong (2007)	Y	Y				
Stochastic	Krikke et al. (1999a)	Y	Y		Y		
	Listes & Dekker (2005)	Y	Y				Y
	Biehl et al. (2007)	Y	Y				Y
	Lieckens & Vandaele (2007)	Y	Y				
	Listes (2007)	Y	Y				Y
	Mutha & Pokharel (2007)	Y	Y	Y	Y	Y	Y
	Wojanowski et al. (2007)	Y	Y				
	This research	Y	Y	Y	Y	Y	Y

(Y – Addressed)

The above review shows that the design of RL network is an important research problem as the circumstances leading to the model development could be unique. The research emphasizes on the reduction of RL costs through the choice of locations and capacities. While some researchers have focused mainly on used products only, others have recognized that used products do contain modules with different qualities. Researchers have also considered the sale of remanufactured products in the secondary markets. While researchers have discussed the benefits of product modularity in manufacturing and their implications in handling product returns, pragmatic RL network models for modular products need to be developed.

Many researchers have assumed a deterministic supply of used products and a known fixed demand for remanufactured products. Some researchers have extended this work by including the uncertainty in supply and demand by developing two-stage stochastic models. These models incorporate uncertainty in the form of scenarios with known probability and hence are not completely robust. Elementary research in handling returns of modular products is given by Krikke et al. (1999a; b), Kusumastuti et al. (2004), Franke et al. (2006) and Mutha and Pokharel (2006; 2007). However, each work has its own drawback as discussed above. Hence a comprehensive network that can handle returns of products having modular structure needs to be developed. This table explicitly shows that the issue of multi-product, modular structured products is unaddressed. This research deals with growing concern for developing RL network design for multi-product, modular architecture products.

Due to product customization and low life cycles the markets are flooded with product variants. Product variants are also designed to create niche market segments and increase market share. Also, due to marketing strategies, customers often return product modules or the entire product itself to avail offers like trade-ins and product upgrades. This causes reverse flow of 'used' products.

Initially, this research extends the facility location allocation model for reverse flow of products presented by Fleischmann et al. (2001). A deterministic model is presented for modular products with multi-product configurations. This work also complements the work done by Franke et al. (2006). Later, stochastic variables of supply of used products and demand for remanufactured products are considered. Four possible destinations for returned product or its modules namely spare markets, remanufacturing factories, recycling centres and disposal sites are considered. Similar to the above authors, this research also includes an external procurement activity (suppliers) as it is practically impossible to reuse all components of a returned product. Hence to satisfy the market demand, OEMs may need to procure new components to make an 'as good as new' product. It is assumed that the remanufactured products cannot compete with new products in terms of its quality. Therefore, there would be a difference in pricing of new and remanufactured products. However, this factor is not considered explicitly in the model. As the spare parts, if any, can fetch a higher value compared to the finished products, the research also considers spare parts market as one of the potential avenue for returned products. The focus here is on deciding the number of facilities, their locations and allocation of corresponding goods flow at an optimal cost for a given market demand and return rate.

3. METHODOLOGY FOR MODEL FORMULATION

In this chapter, the methodology for formulating a RL network model for product recovery is proposed. The chapter describes the various assumptions made for formulating the model. The notations used in the model for the parameters and decision variables are also defined. The conceptual framework used for the development of the mathematical models involves 9 echelons which contribute actively in the respective functions of RL. The multi-layer RL chain includes retailers which act as collection points, warehouses (for storage and consolidation), reprocessing centres (RPC), remanufacturing factories, recycling centres, disposal sites, new module suppliers, spare part markets, and secondary markets. This chapter is divided in to two parts, one for the methodology for developing a deterministic model and the other for the methodology for a stochastic model.

The assumptions common to both models are given as follows:

1. As suggested by Savaskan et al. (2004) and Biehl (2007), the model assumes retailers as collecting points. These retailers are pre-specified by the OEMs. The goods collected in each retailer are transported to the warehouses as soon as possible so that they do not incur any holding costs.
2. Collection of reusable products is not considered for the design of network as those products are assumed to be resold by the retailers themselves.

3. The warehouse acts as a storage and consolidation centre and the cost for consolidation is assumed insignificant to its holding cost. This assumption is consistent with Lee and Dong (2007), Shih (2001), Krikke et al. (2001) and Dowlatshahi (2000).
4. The dismantling operations are carried out in the RPC, where the modules are dismantled, cleaned, tested and sorted for reuse, remanufacture, spare and recycle.
5. As a preference, spare market demands are met due to high value that it fetches from selling spare parts.
6. The warehouse, the RPC and the factory are considered to have a monthly fixed cost irrespective of the usage. Also, they incur different inventory holding costs.
7. All the returned products are not suitable for remanufacturing. Therefore some new modules may be required for remanufacturing of the products. The final assembly of the product with used and new modules, if any, is done inside the factory.
8. The factory has inventory holding costs only for the used modules while it operates on Just-In-Time (JIT) delivery of new modules.
9. Transport cost is calculated with respect to the distance and overhead costs assuming full truck loads (Bowersox and Closs, 1996; Louwers et al., 1999; Shih, 2001).
10. Consistent with the assumption made by Lieckens and Vandaele (2007) and Du and Evans (2008), it is assumed that remanufactured products are transported to distribution centres immediately after production.

11. Transportation costs do not vary with the change in the size or shape of the products.
12. Customers (for remanufactured products) are represented by demands at the distribution centre.
13. The returned products have a unique modular structure that is the module usage rate is 1.

3.1 DETERMINISTIC MODEL FORMULATION

The conceptual framework used for the development of the deterministic model is shown in Figure 3.1.

Figure 3.1: Proposed RL structure for deterministic model

Other assumptions are as follows:

1. An infinite source of used products is assumed.
2. If the number of modules are in excess of demand, then they are either recycled (incurring transport costs) or stored in the RPC (incurring inventory holding costs) till further demand is received.

The notations and description for parameters used in the model are given in Table 3.1 where as the description on decision variables are given in Table 3.2.

Table 3.1: Notation for Parameters (Deterministic Model)

Notation	Description
r	Set of retailers in the network, $r = 1, 2, 3, \dots, R$
w	Set of warehouses in the network, $w = 1, 2, 3, \dots, W$
j	Set of reprocessing centres (RPC's) in the network, $j = 1, 2, 3, \dots, J$
s	Set of markets for spare products, $s = 1, 2, 3, \dots, S$
u	Set of assembling factories in the network, $u = 1, 2, 3, \dots, U$
v	Set of possible disposal sites, $v = 1, 2, 3, \dots, V$
x	Set of possible recycling centres, $x = 1, 2, 3, \dots, X$
z	Set of new module suppliers for product p , $z = 1, 2, 3, \dots, Z$
h	Set of distribution centres (DC's) which serve as secondary markets, $h = 1, 2, 3, \dots, H$
n_p	Module 'n' of product 'p', $n = 1, 2, 3, \dots, N$
C_{pi_w}	Inventory carrying cost/product/time at warehouse w
C_{pi_j}	Inventory carrying cost/product/time at RPC j
$C_{in_p, j}$	Inventory carrying cost/module/time at RPC j
$C_{in_p, u}$	Inventory carrying cost/module/time at factory u
C_p	Unit cost of returned product 'p'
$C_{n_p, z}$	Unit cost of module 'n' of product 'p' from supplier z
C_{pA_u}	Assembly cost/product 'p' for factory u
$C_{d_{n_p}, v}$	Unit disposal fees for module 'n' of product 'p' at site v
$C_{R_{n_p}, j}$	Unit reprocessing cost for module 'n' of product 'p' at RPC j
C_u	Fixed cost of factory u
C_w	Fixed cost of warehouse w
C_j	Fixed cost of RPC j
T_p	Transport cost/product 'p' (for a given distance)
T_{n_p}	Transport cost/module n of product 'p' (for a given distance)
T_{pfg}	Transport cost/finished product 'p' (for a given distance)
V_{n_p}	Unit volume of module n of product 'p'
V_p	Unit volume of product 'p'
D	Total demand for all products at all distribution centres
D_{h_p}	Demand for product 'p' at distribution centre h
D_s	Demand at spare market s
D_u	Demand of factory u
E_x	Capacity of recycling centre x
E_v	Capacity of disposal site v
σ_{n_p}	Disposal fraction of module n of product p

ρ_{n_p}	Recyclability fraction of module n of product p
E_w	Storage capacity of warehouse w
E_j	Storage capacity of RPC j
$E_{Re j}$	Processing capacity of RPC j

Table 3.2: Notation for Decision Variables (Deterministic Model)

Notation	Description
Q	Total quantity of products returned by the customers
Q_p	Quantity of product 'p' returned by the customers
Q_{r_p}	Quantity of product 'p' with retailer r
Q_{w_p}	Quantity of product 'p' with warehouse w
Q_{j_p}	Quantity of product 'p' with RPC j
N^s	Quantity of module 'n' of product 'p' sent to spare market
N^u	Quantity of module 'n' of product 'p' sent to factory
N^x	Quantity of module 'n' of product 'p' sent for recycling
N^I	Quantity of module 'n' of product 'p' stored at RPC for future demand
N^v	Quantity of module 'n' of product 'p' to be disposed
N^B	Balance quantity of module 'n' of product 'p' available for manufacturing or storing
M_{n_p}	Quantity of returned module 'n' of product 'p'
$M_{n_p r}$	Quantity of product 'p' (in modular form) at retailer r
$M_{n_p w}$	Quantity of product 'p' (in modular form) at warehouse w
$M_{n_p j}$	Quantity of product 'p' (in modular form) at RPC j
$M_{n_p x}$	Quantity of module 'n' of product 'p' at recycling centre x
$M_{n_p f}$	Quantity of module 'n' of product 'p' at factory f
$M_{n_p v}$	Quantity of module 'n' of product 'p' at disposal site v
$M_{n_p z}$	Quantity of module 'n' of product 'p' procured from supplier z
$D_{n_p s}$	Demand for module 'n' of product 'p' at spare market s
N^ϕ	Quantity of new module 'n' of product 'p' ordered

3.2 STOCHASTIC MODEL FORMULATION

The conceptual framework used for the development of the stochastic model is shown in Figure 3.2.

Figure 3.2: Proposed RL structure for stochastic model

Other assumptions are as follows:

1. The supply of used products is assumed to be stochastic with the distribution $N(\mu_1, \sigma_1)$.
2. The demand for remanufactured products is assumed to be stochastic with the distribution $N(\mu_2, \sigma_2)$.
3. If the number of available modules is in excess of demand, they are disposed.
4. Demand for spare parts is deterministic. This type of assumption is also used by other researchers (Mabini and Christer, 2002; Diaz 2003).

The notations and description for parameters used in the model are given in Table 3.3 where as the description on decision variables are given in Table 3.4.

Table 3.3: Notation for parameters (Stochastic Model)

Notation	Description
r	Set of retailers in the network, $r = 1, 2, 3, \dots, R$
w	Set of warehouses in the network, $w = 1, 2, 3, \dots, W$
j	Set of reprocessing centres (RPC's) in the network, $j = 1, 2, 3, \dots, J$
s	Set of markets for spare products, $s = 1, 2, 3, \dots, S$
f	Set of assembling factories in the network, $f = 1, 2, 3, \dots, F$
v	Set of possible disposal sites, $v = 1, 2, 3, \dots, V$
x	Set of possible recycling centres, $x = 1, 2, 3, \dots, X$
z	Set of new module suppliers for product p , $z = 1, 2, 3, \dots, Z$
h	Set of distribution centres (DC's) for remanufactured products, $h=1, 2, 3, \dots, H$
n_p	Module 'n' of product 'p', $n = 1, 2, 3, \dots, N$
C_{pi_w}	Storage cost/product/time at warehouse w
C_{pi_j}	Material handling cost/product/time at RPC j
$C_{in_p, f}$	Material handling cost/module/time at factory f
C_p	Unit cost of returned product 'p'
$C_{n_p, z}$	Unit cost of module 'n' of product 'p' from supplier z
$C_{s_{n_p}}$	Cost for new module 'n' of product 'p' for spare market s
C_{pA_f}	Assembly cost/product 'p' for factory f
$C_{d_{n_p}, v}$	Unit disposal fees for module 'n' of product 'p' at site v
$C_{R_{n_p}, j}$	Unit reprocessing cost for module 'n' of product 'p' at RPC j
C_f	Annual fixed cost of factory f
C_w	Annual fixed cost of warehouse w
C_j	Annual fixed cost of RPC j
T_p	Transport cost/product 'p' (for a given distance)
T_{n_p}	Transport cost/module n of product 'p' (for a given distance)
V_{n_p}	Unit volume of module n of product 'p'
V_p	Unit volume of product 'p'
D_s	Demand at spare market s
E_x	Capacity of recycling centre x
E_v	Capacity of disposal site v
χ_{n_p}	Recyclability fraction of module n of product 'p'
E_w	Storage capacity of warehouse w
E_j	Storage capacity of RPC j
E_{Re_j}	Processing capacity of RPC j

Table 3.4: Notation for decision variables (Stochastic Model)

Notation	Description
Q	Stochastic quantity of products returned by the customers with density function $f(q)$ and distribution function $F(q)$
Q_p	Quantity of product 'p' returned by the customers
Q_{r_p}	Quantity of product 'p' with retailer r
Q_{w_p}	Quantity of product 'p' with warehouse w
Q_{j_p}	Quantity of product 'p' with RPC j
K	Stochastic demand for product 'p' at all distribution centres with density function $f(k)$ and distribution function $F(k)$
D_{h_p}	Stochastic demand for remanufactured product 'p' at distribution centre h
N^s	Quantity of module 'n' of product 'p' sent to spare market
N^f	Quantity of module 'n' of product 'p' sent to factory
N^x	Quantity of module 'n' of product 'p' sent for recycling
N^v	Quantity of module 'n' of product 'p' to be disposed
M_{n_p}	Quantity of returned module 'n' of product 'p'
$M_{n_p r}$	Quantity of product 'p' (in modular form) at retailer r
$M_{n_p w}$	Quantity of product 'p' (in modular form) at warehouse w
$M_{n_p j}$	Quantity of product 'p' (in modular form) at RPC j
$M_{n_p x}$	Quantity of module 'n' of product 'p' at recycling centre x
$M_{n_p f}$	Quantity of module 'n' of product 'p' at factory f
$M_{n_p v}$	Quantity of module 'n' of product 'p' at disposal site v
$M_{n_p z}$	Quantity of module 'n' of product 'p' procured from supplier z
$M_{n_p s}$	Quantity of module 'n' of product 'p' sent to spare market s
N^ϕ	Quantity of new module 'n' required for remanufacturing of product 'p'
N^ψ	Quantity of new module 'n' of product 'p' required to meet the spare market demand

Based on the notations in Tables 3.1 and 3.2 and the assumptions presented in this chapter, a deterministic model is proposed in Chapter 4 for the design of RL networks. The notations in Tables 3.3 and 3.4 and the assumptions are used to formulate a stochastic model for product recovery, as presented in Chapter 5. These models are implemented on a nine echelon network consisting of five retailers, four warehouses, three RPC's, five spare markets, three factories, one recycling centre, one disposal site, six new module suppliers and six distribution

centres are assumed to design a network for return handling of a single product for the purpose of implementation of the model. The assumed network is as shown in Figure 3.3

Figure 3.3: Assumed network structure

4. DETERMINISTIC MODEL AND ANALYSIS

In this chapter, a deterministic RL network model for product recovery is proposed. The model is formulated based on the assumption and notations presented in Chapter 3. In this chapter, the balance equations, cost terms, and constraints are developed. The model is implemented using simulated data.

4.1 BALANCE EQUATIONS

Total quantity of returned product 'p' be Q , which is given as

$$Q = \sum_{p=1}^P Q_p \quad (4.1)$$

$$\text{And, } Q_p = \sum_{r=1}^R Q_{p_r} \quad \forall p$$

Each product is made up of modules. The total number of modules is given as

$$Q_p = \sum_{n=1}^N M_{n_p} \quad \forall p \quad (4.2)$$

Also, total quantity of product 'p' can be written as

$$Q_p = \frac{\sum_{n=1}^N M_{n_p}}{\sum_{n=1}^N n_p} \quad \forall p \quad (4.3)$$

The total quantity of products (in modular form) collected at all retailers R is given as

$$Q_{r_p} = \sum_{n=1}^N \sum_{r=1}^R M_{n_p r} \quad \forall p \quad (4.4)$$

The total quantity of products consolidated at all warehouses W is given as

$$Q_{w_p} = \sum_{n=1}^N \sum_{w=1}^W M_{n_p w} \quad \forall p \quad (4.5)$$

The total quantity of products transported to all RPC's J for reprocessing is given as

$$Q_{j_p} = \sum_{n=1}^N \sum_{j=1}^J M_{n_p j} \quad \forall p \quad (4.6)$$

The balance of products between the retailers, warehouses and RPC's is given as

$$\sum_{n=1}^N \sum_{r=1}^R M_{n_p r} = \sum_{n=1}^N \sum_{w=1}^W M_{n_p w} = \sum_{n=1}^N \sum_{j=1}^J M_{n_p j} \quad \forall p \quad (4.7)$$

In the RPC, the products are dismantled to modules and certain pre-specified modules of each type of product are disposed as per their disposal fraction. The quantity of modules disposed at disposal sites V is given as

$$\sum_{n \in N^v} M_{n_p} = \sum_{n \in N^v} \sum_{v=1}^V \sum_{j=1}^J \sigma_{n_p} M_{n_p j v} \quad \forall p, \forall n \quad (4.8)$$

Similarly, modules which are not good for remanufacturing or sale, but are recyclable are sent for recycling. Certain pre-specified modules of each type of product are recycled as per their recyclability fraction. The quantity of modules sent for recycling at recycling sites X is given as

$$\sum_{n \in N^x} M_{n_p} = \sum_{n \in N^x} \sum_{x=1}^X \sum_{j=1}^J \rho_{n_p} M_{n_p j x} \quad \forall p, \forall n \quad (4.9)$$

The above two options could create a mismatch of the balance modules in the RPC. Thus, of the balance modules, the demand for the spare markets (D_s) and

remanufacturing factories (D_u) is catered in that preference. This is based on the logic that parts can fetch higher revenues to the OEM's.

The demand for modules in the spare markets S is given as

$$\sum_{n \in N^s} D_{n_p s} \leq \sum_{n=1}^N \sum_{j=1}^J M_{n_p j} - \sum_{n \in N^v} M_{n_p} - \sum_{n \in N^x} M_{n_p} \quad \forall p, \forall n, \forall s \quad (4.10)$$

If 10 unique modules ($m = 1, 2, 3, \dots, 10$) are returned to the RPC, of which module 1 and 2 are disposed and module 3, 4 and 5 are sent for recycling, the balance modules 6, 7, 8, 9 and 10 can be used to cater to the demand of spare markets and remanufacturing factories. Thus, if modules 6, 7 and 8 are sent to the spare market, only modules 9 and 10 will be left behind in the RPC. Now, if the demand at the remanufacturing factory is ≥ 1 , the modules 9 and 10 can be sent to cater the demand. Else, they will be stored in the RPC till the next period.

Thus, the balance of modules, available for remanufacturing or storing is given as

$$\sum_{n \in N^b} \sum_{j=1}^J M_{n_p b_j} = \sum_{n=1}^N \sum_{j=1}^J M_{n_p j} - \sum_{n \in N^v} M_{n_p} - \sum_{n \in N^x} M_{n_p} - \sum_{n \in N^s} \sum_{s=1}^S D_{n_p s} \quad \forall p, \forall n \quad (4.11)$$

The number of reprocessed modules sent to the factories is given as

$$\sum_{n \in N^u} M_{n_p u} \geq D_u \quad \forall p, \forall n, \forall u \quad (4.12)$$

Thus, of the balance quantity of modules (equation 12), the quantity of modules stored in the RPC is given as

$$\sum_{n \in N^l} \sum_{j=1}^J M_{n_p j} = \sum_{n \in N^b} \sum_{j=1}^J M_{n_p b_j} - \sum_{n \in N^u} \sum_{u=1}^U M_{n_p u} \quad \forall p, \forall n \quad (4.13)$$

Now, the demand of the remanufacturing factories can be met by the modules supplied by the RPC and by the modules procured from the new module suppliers. When the demand at the remanufacturing factories is less than the balance modules in the RPC, the required modules are supplied while the rest are stored. When the demand is higher than the quantity of modules supplied by the RPC, the factories need to procure the balance modules (for each product) from the new module suppliers. Thus, the balance quantity required to be procured from the new module suppliers Z is given as

$$N^\phi = D_u - N^u \quad \forall p, \forall n, \forall u \quad (4.14)$$

Thus, the total quantity of modules required by the remanufacturing factories to meet the market demand is the sum of the modules supplied by the RPC and that procured from the new module suppliers and is given as

$$\sum_{n=1}^N D_{n_p h} = \sum_{n \in N^u} \sum_{u=1}^U M_{n_p u} + \sum_{n \in N^\phi} \sum_{z=1}^Z M_{n_p z} \quad \forall p, \forall n, \forall h \quad (4.15)$$

This demand can be given in terms of products as

$$D_{h_p} = \frac{\sum_{n=1}^N \sum_{h=1}^H M_{n_p h}}{\sum_{n=1}^N n_p} \quad \forall p \quad (4.16)$$

4.2 COSTS ASSOCIATED WITH THE NETWORK

Various costs associated with the network are as follows

a. Transport costs

The total transportation cost includes the cost paid for transporting product between different supply chain echelons as given below

The cost of transporting product ‘ p ’ between retailer ‘ r ’ and warehouse ‘ w ’ is as

$$\sum_{w=1}^W \sum_{r=1}^R Q_{r_p} T_{p_{rw}} \quad \forall p \quad (4.17)$$

The cost of transporting product ‘ p ’ between warehouse ‘ w ’ and RPC ‘ j ’ is as

$$\sum_{j=1}^J \sum_{w=1}^W Q_{w_p} T_{p_{wj}} \quad \forall p \quad (4.18)$$

The cost of transporting modules between RPC ‘ j ’ and spare market ‘ s ’ is as

$$\sum_{n \in N^s} \sum_{j=1}^J \sum_{s=1}^S D_{n_p s} T_{n_p js} \quad \forall p, \forall n \quad (4.19)$$

The cost of transporting modules between RPC ‘ j ’ and factory ‘ u ’ is as

$$\sum_{n \in N^u} \sum_{j=1}^J \sum_{u=1}^U M_{n_p u} T_{n_p ju} \quad \forall p, \forall n \quad (4.20)$$

The cost of transporting modules between RPC ‘ j ’ and recycling site ‘ x ’ is as

$$\sum_{n \in N^x} \sum_{j=1}^J \sum_{x=1}^X M_{n_p} T_{n_p jx} \quad \forall p, \forall n \quad (4.21)$$

The cost of transporting modules between RPC ‘ j ’ and disposal site ‘ v ’ is as

$$\sum_{n \in N^v} \sum_{j=1}^J \sum_{v=1}^V M_{n_p} T_{n_p jv} \quad \forall p, \forall n \quad (4.22)$$

The cost of transporting remanufactured finished goods between factory ‘ u ’ and DC ‘ h ’ is as

$$\sum_{h=1}^H \sum_{u=1}^U D_{h_p} T_{pfg_{uh}} \quad \forall p \quad (4.23)$$

b. Inventory costs

Inventory costs at each facility could vary depending on the product/module.

The cost for acquiring Q_p quantity of product ‘ p ’ from the customers is as

$$\sum_{p=1}^P Q_p C_p \quad \forall p \quad (4.24)$$

The inventory cost of product 'p' at warehouse 'w' is given as

$$\sum_{w=1}^W Q_{w_p} C_{pi_w} \quad \forall p \quad (4.25)$$

The inventory cost of product 'p' at RPC 'j' is given as

$$\sum_{j=1}^J Q_{j_p} C_{pi_j} \quad \forall p \quad (4.26)$$

The inventory cost of module 'n' of returned product 'p' at RPC 'j' is given as

$$\sum_{n \in N^I} \sum_{j=1}^J M_{n_p j} C_{in_p j} \quad \forall p, \forall n \quad (4.27)$$

The inventory cost of module 'n' of returned product 'p' at factory 'u' is given as

$$\sum_{n \in N^u} \sum_{u=1}^U M_{n_p u} C_{in_p u} \quad \forall p, \forall n \quad (4.28)$$

c. Fixed Costs

Since we assume that the warehouse, the RPC and the factory are rented, these facilities incur fixed monthly charges. The total fixed cost for each facility is given as

$$\sum_{w=1}^W C_w \text{ - fixed cost of warehouse 'w'} \quad (4.29)$$

$$\sum_{j=1}^J C_j \text{ - fixed cost of RPC 'j'} \quad (4.30)$$

$$\sum_{u=1}^U C_u \text{ - fixed cost of factory 'u'} \quad (4.31)$$

d. New module costs

It is virtually impossible to reuse all the components/modules of a returned product. Hence, in order to meet the market demand, companies may require procuring new modules to produce ‘as good as new’ products. This quantity N^ϕ depends on the market demand ‘ D ’. The cost function can be written as

$$\sum_{n \in N^\phi} \sum_{z=1}^Z M_{n_p z} C_{n_p z} \quad \forall p, \forall n \quad (4.32)$$

e. Reprocessing costs

This is the cost incurred in reprocessing the module ‘ n ’ of returned product ‘ p ’ at RPC ‘ j ’. This includes,

cost for reprocessing the quantity of modules of product ‘ p ’ for spare market ‘ s ’

$$\sum_{n \in N^s} \sum_{j=1}^J \sum_{s=1}^S M_{n_p s} C_{R_{n_p} j} \quad \forall p, \forall n \quad (4.33)$$

and cost for reprocessing the quantity of modules of product ‘ p ’ for factory ‘ u ’

$$\sum_{n \in N^u} \sum_{j=1}^J \sum_{u=1}^U M_{n_p u} C_{R_{n_p} j} \quad \forall p, \forall n \quad (4.34)$$

f. Disposal costs

This is the cost incurred in disposing the modules at site ‘ v ’. They are mainly dependant on the legislative actions and is given as

$$\sum_{n \in N^v} \sum_{v=1}^V M_{n_p} C_{d_{n_p} v} \quad \forall p, \forall n \quad (4.35)$$

g. Assembly costs

This is the cost involved in assembling the modules at the factories to meet the market demand. Assembly cost can vary in different factory locations due to the variation in labor or resource costs. This cost is given as

$$\sum_{u=1}^U \left(\sum_{n \in N^u} \sum_{u=1}^U M_{n_p u} + \sum_{n \in N^\phi} \sum_{z=1}^z M_{n_p z} \right) \times C_{pA_u} \quad \forall p \quad (4.36)$$

The objective function here is to minimize the transportation costs, inventory costs, disposal costs and assembly costs as mentioned above.

$$\begin{aligned} \text{Min } & \sum_{w=1}^W \sum_{r=1}^R Q_{r_p} T_{p_{rw}} + \sum_{j=1}^J \sum_{w=1}^W Q_{w_p} T_{p_{wj}} + \sum_{n \in N^s} \sum_{j=1}^J \sum_{s=1}^S D_{n_p s} T_{n_p js} + \sum_{n \in N^u} \sum_{j=1}^J \sum_{u=1}^U M_{n_p u} T_{n_p ju} + \\ & \sum_{n \in N^x} \sum_{j=1}^J \sum_{x=1}^X M_{n_p} T_{n_p jx} + \sum_{n \in N^v} \sum_{j=1}^J \sum_{v=1}^V M_{n_p} T_{n_p jv} + \sum_{h=1}^H \sum_{u=1}^U D_{h_p} T_{pf_{uh}} + \sum_{p=1}^P Q_p C_p + \sum_{w=1}^W Q_{w_p} C_{pi_w} + \\ & \sum_{j=1}^J Q_{j_p} C_{pi_j} + \sum_{n \in N^t} \sum_{j=1}^J M_{n_p j} C_{in_{pj}} + \sum_{n \in N^u} \sum_{u=1}^U M_{n_p u} C_{in_{pu}} + \sum_{w=1}^W C_w + \sum_{j=1}^J C_j + \sum_{u=1}^U C_u + \\ & \sum_{n \in N^\phi} \sum_{z=1}^z M_{n_p z} C_{M_{n_p z}} + \sum_{n \in N^s} \sum_{j=1}^J \sum_{s=1}^S M_{n_p s} C_{R_{n_p j}} + \sum_{n \in N^u} \sum_{j=1}^J \sum_{u=1}^U M_{n_p u} C_{R_{n_p j}} + \sum_{n \in N^v} \sum_{v=1}^V M_{n_p} C_{d_{n_p v}} + \\ & \sum_{u=1}^U \left(\sum_{n \in N^u} \sum_{u=1}^U M_{n_p u} + \sum_{n \in N^\phi} \sum_{z=1}^z M_{n_p z} \right) \times C_{pA_u} \end{aligned} \quad (4.37)$$

Subject to the following constraints:

4.3 CAPACITY CONSTRAINTS

Each warehouse, RPC and factory has a limited capacity given as

$$E_w \geq \sum_{p=1}^P (V_p \times Q) \quad \forall w \quad (4.38)$$

$$E_j \geq \sum_{p=1}^P \sum_{n=1}^N \left(V_{pM_{n_p}} \times \sum_{p=1}^P \sum_{n=1}^N M_{n_p} \right) \quad \forall j \quad (4.39)$$

$$E_{\text{Re } j} \geq \left(\sum_{n \in N^s} \sum_{s=1}^S D_{n_p s} + \sum_{n \in N^u} \sum_{u=1}^U M_{n_p u} \right) \quad \forall p, \forall j \quad (4.40)$$

$$E_x \geq \sum_{n \in N^x} M_{n_p} \quad \forall x \quad (4.41)$$

$$E_v \geq \sum_{n \in N^v} M_{n_p} \quad \forall v \quad (4.42)$$

All the assigned product and module quantities are defined as non-negative integers.

4.4 ANALYSIS AND RESULT

Simulated data is used to illustrate the use of model. Consistent to earlier studies (Mabini et al., 1992; Mostard and Teunter, 2006; Salema et al., 2006; Mitra, 2007), a certain percentage (30% in this case) of returned modules of the returned products are assumed to be disposed. This may happen due to the age of the returned product or its quality. Of the recovered modules, the manufacturers would send maximum quantities to the spare markets as they would fetch higher price. Thus the quantity of remanufactured modules sent to the factory is uncertain. To meet the market demand the factories need to procure new modules from the suppliers. These quantities of purchase of new modules also become uncertain because of the uncertainty of supply of recovered modules from the RPC. Also, 10% of the returned modules are assumed to be sent for recycling. If there are mismatch of modules at the remanufacturer, additional new modules are purchased from pre-specified suppliers.

For simple illustration of the model a single returned product with ten modules are considered. Data used for the analysis are given in Appendix A. For the base case, it is assumed that the retailers receive about 25,000 used products on a monthly basis (cumulative sum of all inputs on the left of Figure 4.1). The model is solved using GAMS[®]. The resulting network with allocated and unallocated transportation routes and subsequent allocations of modules and products to different entities are shown in Figure 4.1.

The result shows that the optimal cost for this network would be around \$2,573,750 for acquisition, storing, processing and distributing per month. Further analysis of allocated data shows that the total logistics cost of the system (including transportation, inventory, and fixed and holding costs of warehouse and RPC) is around \$415,500. The transportation cost for the chosen network is about \$306,000. Sensitivity of transportation cost in the network was tested by increasing all transportation cost attributes by 50%. The analysis shows that this change would increase the optimal solution by less than one percent. Similarly, if the fixed and inventory costs associated with the warehouse and the RPC's are increased by 50%, the change in the optimal solution is less than half percent. Therefore, the assumed network is not sensitive towards transportation costs and fixed and inventory costs associated with the warehouse and RPC's. Therefore, given the strategic choice of the collection centre, warehouses and processing centers, transportation cost, fixed and inventory cost of the warehouses and RPC's is not an issue in the given network.

In the base case (when $Q = 25,000$ units), it was seen that none of the modules were sent for recycling. Rather, RPC_1 stored 4600 modules, RPC_2 stored 1000 modules and RPC_3 stored 3300 modules which could be used later on demand from the spare market or factory, but they incur an inventory carrying cost.

Scenario analysis shows that when the inventory costs of the RPC's are increased by 10%, the same quantity of modules is stored at each RPC and no modules are sent for recycling (incurring inventory costs). However, when the inventory costs are increased to 20%, the entire balance quantity of modules was sent for recycling i.e. 8,900 modules were sent for recycling and no modules were stored at either of the RPC's (reducing the inventory costs but incurring the transport cost for recycling). Thus, with a change in the inventory costs at the RPC's, the resultant overall inventory carrying cost and the network cost (Figure 4.2) also change. Change is also observed in the flow of modules from the RPC's to the recycling centres (Figure 4.3). This economic decision making is based on optimal costs of i) transport between the RPC's and the recycling centre; and ii) the inventory carrying cost at the RPC's.

Table 4.1: Variation in quantity of modules sent for recycling and stored at RPC due to change in inventory costs at RPC

Scenario	Base case	10% increase over base case (stage 1)	20% increase over base case (stage 2)
No. of modules sent for recycling	0	0	8900
No. of modules stored at RPC	8900	8900	0

Figure 4.1: Network structure when $Q = 25,000$ units (Dotted lines resemble unutilized transport routes)

Figure 4.2: Network and Inventory cost variation when inventory cost at RPC is varied (refer Table 4.1)

Figure 4.3: Distribution variation when inventory cost at RPC is varied (refer Table 4.1)

We carried out scenario analysis to understand possible changes in the network with variation in returned quantities with $Q = 20,000$ units (Figure 4.4) and $Q = 30,000$ units (Figure 4.5) while keeping all other attributes as constant. This is desired to simulate the effect of changes in the returned quantities on the optimality of the RL network. Low return rates are typically seen when customers return certain products after a long period after the product was discontinued by the company. Higher return rates are seen either when the product does not perform well in the market or the product sale is not as forecasted by the marketing departments or the products are recalled by the company due to technical failures. The analysis showed that when less number of products ($Q = 20,000$ units) are returned (compared with a base Q of 25,000), the system requires only three warehouses (see Figure 4.4 where warehouse W_3 has no allocations). However, due to lesser number of available modules from the used products, more new modules would be required to fulfill the demand

($N^\phi = 133,150$ units as compared to $N^\phi = 108,850$ units for the base case). With this, the cost of procuring new modules increases significantly from around \$815,000 in the base case to around \$1,002,000.

Similar to the above analysis, if more returned products are received in the collection centres (say $Q=30,000$ units) the flow of new modules from the suppliers reduces as the number of recovered modules also increase (from 71,150 units when $Q = 25,000$ to 88,200 units when $Q = 30,000$). The cost of procuring new modules also reduces (from \$ 815,000 when $Q = 25,000$ units to \$ 680,300 when $Q = 30,000$ units). It is seen from Figure 4.5 that factories ‘f1’ and ‘f2’ would require fewer new modules due to cost effective allocations. The new modules in this case can be supplied by five suppliers. However, for the third factory, although it would require more new modules, the supplies can come from only four suppliers.

Figure 4.4: Network structure when $Q = 20,000$ units

Figure 4.5: Network structure when $Q = 30,000$ units

Constraints in processing capacities at RPC can also cause changes in the flow of new and used modules. This situation can occur when there are sudden mechanical breakdowns or scheduled maintenance periods. Various scenarios of capacity reductions as shown in Table 4.2 were tested. For example, for the first scenario, a 10% reduction in capacity at RPC 1 is assumed while keeping the base case capacities for other RPC's. For the analysis all other factors are assumed as the same as in the base case.

Table 4.2: Processing Capacity reduction at RPC

Scenario	RPC 1	RPC 2	RPC 3
Base case	Base case	Base case	Base case
2	(-)10%	Base case	Base case
3	Base case	(-)10%	Base case
4	Base case	Base case	(-)10%
5	(-)10%	(-)10%	(-)10%

The analysis provides an insight to some of the key contributors to the overall network cost namely the new module cost (Figure 4.6) and the transportation and inventory costs (Figure 4.7). With a reduced capacity in a RPC, the cost of purchasing new module increases (Figure 4.2). In the base case, the number of recovered modules supplied to the factories by RPC_1 , RPC_2 and RPC_3 are 8,600; 47,550; and 15,000 respectively. In this case, the demand for new modules (N^ϕ) is 108,850 units. In scenario 1, the number of modules recovered and supplied to the factory by RPC_2 reduces to 45,000 (decrease of about 5.36%). However, the demand for new modules (N^ϕ) increased by only 2,550 (increase of about 2.34%). Also, the supply of modules for recycling decreases from RPC_1 by 2,500 modules (decrease of 14.29%) while it increases from RPC_1 to 10,000 modules (increase by 33.3%). In scenario 2, the number of modules recovered and supplied to the factory by RPC_1 is 10,640 (increase of about 23.7%) while the supply from RPC_3 is 10,600 (decrease of about 29.4%). In this scenario, the total number of modules recovered and supplied by all the RPC's is more than the cumulative supply in scenario 1, hence the demand for new modules (N^ϕ) decreases by 190 as compared to scenario 1. However, as compared to the base case, the demand for new modules (N^ϕ) increases by 2,360 (increase of about 2.16%). Also, the RPC_3 supplies 25,000 modules for recycling (total recycling demand). In scenario 3, the quantity of excess modules supplied by RPC_1 is equivalent to the shortage of supply from RPC_3 (9000 modules). The supply of recovered modules from RPC_2 also reduces of about 4.6% causing the demand for new modules (N^ϕ) to increase by about 2%. In scenario 4 the supply of recovered modules from RPC_1 increases by 6,640 (increase of about 77.2%). However, the supply from RPC_2 and RPC_3 decreases by 4,755 (decrease of about 10%) and 9,000 (decrease of

about 60%) respectively. Hence the demand for new modules increases significantly to 7,115 (increase of about 6.5%). Thus with a change of 10% in the RPC capacity, the new module cost changes by 2.27% in scenario 1, 2.16% in scenario 2, 1.96% in scenario 3, and about 6.37% in scenario 4. Also, a higher correlation between the network cost and the new module cost for the given scenarios is seen.

Figure 4.6: Network and New Module cost variation when $Q = 25,000$

Figure 4.7 shows the variation in transportation and inventory costs for the scenarios given in Table 4.2. The figure shows that for the base case in which 71,150 modules are recovered, the inventory cost is about \$51,800. For scenario 1, since only 68,600 usable modules are recovered, the inventory carrying cost decreases to about \$50,500. Similarly, the transport cost also reduces to about \$305,700 (as compared to the base case in which the transport cost was about \$306,200). In scenario 2, as seen from Figure 4.6, the number of recovered used

modules increases to 68,790 (since the number of new modules to be purchased decreases). Hence, the transport cost increases in scenario 2. However the inventory cost further reduces to about \$50,100. This is because, RPC_3 , which has a high average per module inventory cost, recovers 4,400 fewer modules than the base case. In scenario 3, a total of 68,945 usable modules are recovered from the returned products, hence the inventory carrying cost increases to about \$50,450. In scenario 4, the total number of recovered modules reduces drastically to 64,035. Hence, the inventory and transport costs reduce significantly to \$47,400 and \$304,900 respectively. When the processing capacities at the RPC's are constrained, the total quantity of recovered modules transported from the RPC's to the factories and spare markets reduces (as seen in Figure 4.6, the quantity of new modules procured increases). This results in a decrease in the transport costs. Hence, as there are fewer remanufactured modules at the factory, the inventory costs at the factories also reduce.

Similar patterns are observed for variation in network and new module procurement costs; and transport and inventory costs when the 20,000 units (Figure 4.8 and Figure 4.9) and 30,000 units (Figure 4.10 and Figure 4.11) are returned products.

Figure 4.7: Transportation and Inventory holding cost variation when $Q = 25,000$

Figures 4.8 & 4.9 show the variation in network & new module cost variation and variation in transportation and inventory costs for the scenarios given in Table 4.2 when $Q = 20,000$ respectively.

Figure 4.8: Network and New Module cost variation when $Q = 20,000$

Figure 4.9: Transportation and Inventory holding cost variation when $Q = 20,000$

Figures 4.10 & 4.11 show the variation in network and new module cost variation and variation in transportation and inventory costs for the scenarios given in Table 4.2 when $Q = 30,000$ respectively.

Figure 4.10: Network & New Module cost variation when $Q = 30,000$

Figure 4.11: Transportation and Inventory holding cost variation when $Q = 30,000$

Various legislations are forcing companies to manufacture products that have higher levels of recyclable materials and modules (WEEE Directive 2002/95/EC and 2002/96/EC; Yang, 1995). Hence, a higher percentage of recyclable modules and lower percentage of disposable modules are assumed for sensitivity analysis. The scenarios for recyclable and disposal percentage variations are given in Table 4.3. Assuming all other costs as constant, it is found that the total network cost decreases with an increase in the percentage of recyclable content of the product. This is because of reduction in disposal costs. Thus, companies may develop products with modules and materials that are highly recyclable.

Table 4.3: Variation in disposal and recycling percentage			
Scenario	Disposal %	Recycling %	Network Cost
0 (base case)	30	10	2573756
1	20	20	2406854
2	10	30	2240171

By using a nine echelon network, it is shown that the proposed model can be used for strategic decision making to design a RL network. Scenario analysis is given

to reflect the situation on changes in capacities at the processing centres and receipt of fewer or more returned products from the customer. By assuming inventory holding costs at the factories for unused products, real life situation when the demand are not met as expected or when factories are not able to process all the modules into products due to various constraints are reflected. Also, if the number of modules are in excess of demand, then they are either recycled (incurring transport cost) or stored in the RPC (incurring inventory carrying cost) till further demand is received. This economic decision making helps in further optimizing the network cost. Most of all, this research demonstrates that the model is useful to study network design for a RL situation.

5. STOCHASTIC MODEL AND ANALYSIS

As mentioned earlier, RL operations are complex and prone to high degree of uncertainty, affecting collection rates, the availability of reprocessing production inputs, and capacities of facilities in the reverse channel. The success of the RL system may also rely on appropriate used-product collection strategies like specifications of local used-product return points, collection frequencies for end customers' returns, and return promotions. When demand, prices, and acquired quantities differ, given a choice of capacities for the warehouses, remanufacturing facilities and other entities in a RL network, then the deterministic linear programming mentioned above does not work. One of the ways to deal with this type of situation is the use stochastic programming where probabilistic distribution of the events can be ascertained to some extent.

In this chapter, a stochastic RL network model for product recovery is proposed. The model is formulated based on the assumption and notations presented in Chapter 3. In this chapter, the balance equations, cost terms, and constraints are developed. The model is implemented using simulated data.

5.1 BALANCE EQUATIONS

Let there be ' p ' different products that are returned.

The total quantity of all products that are returned is given as Q , where

$$Q = \sum_{p=1}^P Q_p \quad (5.1)$$

The total quantity of returned product 'p' is given as Q_p , where

$$Q_p = \int_0^Q q_p f(q) dq \quad \forall p \quad (5.2)$$

Each product 'p' is made up of 'n' modules. The total number of modules is given as,

$$Q = \sum_{n=1}^N \int_0^Q M_{n_p} f(q) dq \quad \forall p \quad (\text{see Dasci and Verter, 2001 for this form of equations}) \quad (5.3)$$

The total quantity of product 'p' can be obtained from

$$Q_p = \frac{\sum_{n=1}^N \int_0^Q M_{n_p} f(q) dq}{\sum_{n=1}^N n_p} \quad \forall p \quad (5.4)$$

The total quantity of products (in modular form) collected at all retailers is given as

$$Q_{r_p} = \sum_{n=1}^N \sum_{r=1}^R \int_0^Q M_{n_p r} f(q) dq \quad \forall p \quad (5.5)$$

The total quantity of products consolidated at all warehouses is given as

$$Q_{w_p} = \sum_{n=1}^N \sum_{w=1}^W \int_0^Q M_{n_p w} f(q) dq \quad \forall p \quad (5.6)$$

The total quantity of products transported to all RPCs is given as

$$Q_{j_p} = \sum_{n=1}^N \sum_{j=1}^J \int_0^Q M_{n_p j} f(q) dq \quad \forall p \quad (5.7)$$

There is no loss of products in the transportation. Therefore

$$\sum_{n=1}^N \sum_{r=1}^R \int_0^Q M_{n_p r} f(q) dq = \sum_{n=1}^N \sum_{w=1}^W \int_0^Q M_{n_p w} f(q) dq = \sum_{n=1}^N \sum_{j=1}^J \int_0^Q M_{n_p j} f(q) dq \quad \forall p \quad (5.8)$$

In RPC 'j', the products are dismantled. As specified, recyclable modules of each product type is given as

$$\sum_{n \in N^x} M_{n_p x} = \sum_{n \in N^x} \sum_{x=1}^X \sum_{j=1}^J \chi_{n_p} M_{n_p j x} \quad \forall p, \forall n, \forall x \quad (5.9)$$

The demand for the spare markets (D_s) is catered from the remaining modules as spare parts generally fetch higher revenues. In case the demand can not be met by old modules alone, the excess demand is met by procuring new modules (N^ϕ) from pre-qualified suppliers. This demand is given as

$$\sum_{s=1}^S D_{n_p s} \leq \sum_{n=1}^N \sum_{j=1}^J \int_0^Q M_{n_p j} f(q) dq - \sum_{n \in N^x} M_{n_p} + \sum_{n \in N^\psi} M_{n_p} \quad \forall p, \forall n \quad (5.10)$$

The leftover modules are sent to the remanufacturing factories and is given as

$$\sum_{n \in N^f} M_{n_p f} \leq \sum_{n=1}^N \sum_{j=1}^J \int_0^Q M_{n_p j} f(q) dq - \sum_{n \in N^x} \sum_{x=1}^X M_{n_p x} - \sum_{n \in N^s} \sum_{s=1}^S D_{n_p s} \quad \forall p, \forall n, \forall f \quad (5.11)$$

The balance modules, if any, are disposed. This quantity is given as

$$\sum_{n \in N^v} M_{n_p v} = \sum_{n=1}^N \sum_{j=1}^J \int_0^Q M_{n_p j} f(q) dq - \sum_{n \in N^x} \sum_{x=1}^X M_{n_p x} - \sum_{n \in N^s} \sum_{s=1}^S D_{n_p s} - \sum_{n \in N^f} \sum_{f=1}^F M_{n_p f} \quad (5.12)$$

$$\forall p, \forall n, \forall v$$

Thus, from the RPC, the modules are sent for recycling, spare markets, remanufacturing factories and disposal. The balance between these is given as

$$\sum_{n=1}^N \sum_{j=1}^J \int_0^Q M_{n_p j} f(q) dq = \sum_{n \in N^x} \sum_{x=1}^X M_{n_p x} + \sum_{n \in N^s} \sum_{s=1}^S M_{n_p s} + \sum_{n \in N^f} \sum_{f=1}^F M_{n_p f} + \sum_{n \in N^v} \sum_{v=1}^V M_{n_p v} \quad (5.13)$$

The stochastic demand for remanufactured product ‘ p ’ can be written as

$$\sum_{h=1}^H D_{h_p} = \sum_{h=1}^H \int_0^K k_{h_p} f(k) dk \quad \forall p \quad (5.14)$$

The factories may need to procure new modules (for each product) to match the used module shortages. This is given as

$$N^\phi = \sum_{n=1}^N \sum_{z=1}^Z M_{n_p z} = \sum_{h=1}^H \int_0^K k_{h_p} f(k) dk - \sum_{n \in N^f} \sum_{f=1}^F M_{n_p f} \quad \forall p, \forall n \quad (5.15)$$

Thus, the total modules at the remanufacturing factory ‘ f ’ should meet the demand

$$\sum_{n \in N^f} M_{n_p f} + \sum_{z=1}^Z \int_0^K N_z^\phi f(k) dk = \sum_{h=1}^H D_{h_p} \quad \forall p, \forall n, \forall f \quad (5.16)$$

The demand, in product form is given as

$$K = \frac{\sum_{n=1}^N \int_0^K M_{n_p}}{\sum_{n=1}^N n_p} \quad \forall p, \forall n \quad (5.17)$$

5.2 COSTS ASSOCIATED WITH THE NETWORK

Various costs associated with the network are as follows

a. Transport costs

The total transportation cost includes the cost paid for transporting product between different supply chain echelons as given below.

The cost of transporting product ‘ p ’ between retailer ‘ r ’ and warehouse ‘ w ’ is as

$$\sum_{r=1}^R \sum_{w=1}^W \int_0^Q q_{p_r} T_{p_{rw}} f(q) dq \quad \forall p \quad (5.18)$$

The cost of transporting product ‘ p ’ between warehouse ‘ w ’ and RPC ‘ j ’ is as

$$\sum_{j=1}^J \sum_{w=1}^W \int_0^Q q_{p_w} T_{p_{wj}} f(q) dq \quad \forall p \quad (5.19)$$

The cost of transporting modules between RPC ‘ j ’ and spare market ‘ s ’ is as

$$\sum_{n \in N^s} \sum_{j=1}^J \sum_{s=1}^S M_{n_p s} T_{n_p j s} + \sum_{n \in N^w} \sum_{j=1}^J \sum_{s=1}^S M_{n_p s} T_{n_p j s} \quad \forall p, \forall n \quad (5.20)$$

The cost of transporting modules between RPC ‘ j ’ and factory ‘ f ’ is as

$$\sum_{n \in N^f} \sum_{j=1}^J \sum_{f=1}^F M_{n_p f} T_{n_p j f} \quad \forall p, \forall n \quad (5.21)$$

The cost of transporting modules between RPC ‘ j ’ and recycling site ‘ x ’ is as

$$\sum_{n \in N^x} \sum_{j=1}^J \sum_{x=1}^X M_{n_p x} T_{n_p j x} \quad \forall p, \forall n \quad (5.22)$$

The cost of transporting modules between RPC ‘j’ and disposal site ‘v’ is as

$$\sum_{n \in N^v} \sum_{j=1}^J \sum_{v=1}^V M_{n_p v} T_{n_p j v} \quad \forall p, \forall n \quad (5.23)$$

The cost of transporting remanufactured products between factory ‘f’ and DC ‘h’ is as

$$\sum_{h=1}^H \sum_{f=1}^F \int_0^Q k_{p_h} T_{p_{jh}} f(q) f(k) dq dk \quad \forall p, \text{ when } K \leq Q \quad (5.24)$$

$$\sum_{h=1}^H \sum_{f=1}^F \int_Q^\infty (N^f + N^\phi) T_{p_{jh}} f(q) f(k) dq dk \quad \forall p, \text{ when } Q \leq K \quad (5.25)$$

b. Storage and handling costs

Storage costs at each facility could vary depending on the product/module.

The cost for acquiring Q_p quantity of product ‘p’ from the customers is as

$$\sum_{p=1}^P \int_0^Q C_p q_p f(q) dq \quad \forall p \quad (5.26)$$

The cost of storing product ‘p’ at warehouse ‘w’ is given as

$$\sum_{w=1}^W \int_0^Q C_{p_i w} q_{w_p} f(q) dq \quad \forall p \quad (5.27)$$

The material handling cost for product ‘p’ at RPC ‘j’ is given as

$$\sum_{j=1}^J \int_0^Q C_{p_i j} q_{j_p} f(q) dq \quad \forall p \quad (5.28)$$

The material handling cost for module ‘n’ of returned product ‘p’ at factory ‘f’ is given as

$$\sum_{n \in N^f} \sum_{f=1}^F M_{n_p f} C_{in_p f} \quad \forall p, \forall n \quad (5.29)$$

c. Fixed Costs

Since we assume that the warehouse, the RPC and the factory are rented, these facilities incur fixed annual charges. The total fixed cost for each facility is given as

$$\sum_{w=1}^W C_w - \text{fixed cost of warehouse 'w'} \quad (5.30)$$

$$\sum_{j=1}^J C_j - \text{fixed cost of RPC 'j'} \quad (5.31)$$

$$\sum_{f=1}^F C_f - \text{fixed cost of factory 'f'} \quad (5.32)$$

d. New module costs

It is virtually impossible to reuse all the components/modules of a returned product. Hence, in order to meet the market demand, companies may require procuring new modules (N^ϕ) to remanufacture products. Sometimes, the demand from the spare market may also be too high to be met by the recovered modules alone. Hence, companies may need to procure new modules (N^ψ) to meet the demand. The cost of procuring these modules to meet the demand is given as:

$$\sum_{n \in N^\phi} \sum_{z=1}^Z \int_0^K N_z^\phi C_{n_p z} f(k) dk + \sum_{n \in N^\psi} \sum_{z=1}^Z \sum_{s=1}^S N_z^\psi C_{s_{n_p z}} \quad \forall p, \forall n \quad (5.33)$$

e. Reprocessing costs

This is the cost incurred in reprocessing the module ‘ n ’ of returned product ‘ p ’ at RPC ‘ j ’. This includes, cost for reprocessing the quantity of modules of product ‘ p ’ for spare market ‘ s ’, given as

$$\sum_{n \in N^s} \sum_{j=1}^J \sum_{s=1}^S M_{n_p s} C_{R_{n_p} j} \quad \forall p, \forall n \quad (5.34)$$

and cost for reprocessing the quantity of modules of product ‘ p ’ for factory ‘ f ’, given as

$$\sum_{n \in N^f} \sum_{j=1}^J \sum_{f=1}^F M_{n_p f} C_{R_{n_p} j} \quad \forall p, \forall n \quad (5.35)$$

f. Disposal costs

This is the cost incurred in disposing the modules at site ‘ v ’. This is given as

$$\sum_{n \in N^v} \sum_{v=1}^V M_{n_p v} C_{d_{n_p} v} \quad \forall p, \forall n \quad (5.36)$$

g. Assembly costs

This is the cost involved in assembling the modules at the factories to meet the market demand. Assembly cost can vary in different factory locations due to the variation in labor or resource costs. This cost is given as

$$\sum_{f=1}^F \left(\sum_{z=1}^Z \int_0^K (N_z^\phi)_u f(k) dk + \sum_{n \in N^f} M_{n_p f} \right) \times C_{pA_f} \quad \forall p \quad (5.37)$$

The objective function here is to minimize the transportation costs, inventory costs, disposal costs and assembly costs as mentioned above.

$$\begin{aligned}
& \text{Min} \sum_{p=1}^P \left\{ \sum_{r=1}^R \sum_{w=1}^W \int_0^Q q_{p_r} T_{p_{rw}} f(q) dq + \sum_{j=1}^J \sum_{w=1}^W \int_0^Q q_{p_w} T_{p_{wj}} f(q) dq + \sum_{n \in N^s} \sum_{j=1}^J \sum_{s=1}^S M_{n_p s} T_{n_p j s} \right. \\
& + \sum_{n \in N^w} \sum_{j=1}^J \sum_{s=1}^S M_{n_p s} T_{n_p j s} + \sum_{n \in N^f} \sum_{j=1}^J \sum_{f=1}^F M_{n_p f} T_{n_p j f} + \sum_{n \in N^x} \sum_{j=1}^J \sum_{x=1}^X M_{n_p x} T_{n_p j x} + \\
& \sum_{n \in N^v} \sum_{j=1}^J \sum_{v=1}^V M_{n_p v} T_{n_p j v} + \sum_{h=1}^H \sum_{f=1}^F \int_0^Q k_{p_h} T_{p_{fh}} f(q) f(k) dq dk + \\
& \sum_{h=1}^H \sum_{f=1}^F \int_0^Q (N^f + N^\phi) T_{p_{fh}} f(q) f(k) dq dk + \sum_{p=1}^P \int_0^Q C_p q_p f(q) dq + \sum_{w=1}^W \int_0^Q C_{p_i w} q_{w_p} f(q) dq + \\
& \sum_{j=1}^J \int_0^Q C_{p_i j} q_{j_p} f(q) dq + \sum_{n \in N^f} \sum_{f=1}^F M_{n_p f} C_{in_p f} + \sum_{w=1}^W C_w + \sum_{j=1}^J C_j + \sum_{f=1}^F C_f + \\
& \sum_{n \in N^\phi} \sum_{z=1}^Z \int_0^K N_z^\phi C_{n_p z} f(k) dk + \sum_{n \in N^w} \sum_{z=1}^Z \sum_{s=1}^S N_z^w C_{s_{n_p z}} + \sum_{n \in N^s} \sum_{j=1}^J \sum_{s=1}^S M_{n_p s} C_{R_{n_p} j} + \\
& \sum_{n \in N^f} \sum_{j=1}^J \sum_{f=1}^F M_{n_p f} C_{R_{n_p} j} + \sum_{n \in N^v} \sum_{v=1}^V M_{n_p v} C_{d_{n_p v}} + \\
& \left. \sum_{f=1}^F \left(\sum_{z=1}^Z \int_0^K (N_z^\phi)_f f(k) dk + \sum_{n \in N^f} M_{n_p f} \right) \times C_{p A_f} \right\} \tag{5.38}
\end{aligned}$$

Subject to the following constraints:

5.3 CAPACITY CONSTRAINTS

Each warehouse, RPC and factory has a limited capacity given as

$$E_w \geq \sum_{p=1}^P \int_0^Q q V_p f(p) dp \quad \forall w \tag{5.39}$$

$$E_j \geq \sum_{p=1}^P \sum_{n=1}^N \int_0^Q M_{n_p} V_{M_{n_p j}} f(q) dq \quad \forall j \quad (5.40)$$

$$E_{Re_j} \geq \left(\sum_{n \in N^s} \sum_{s=1}^S D_{n_p s} + \sum_{n \in N^f} \sum_{f=1}^F M_{n_p f} \right) \quad \forall p, \forall j \quad (5.41)$$

$$E_x \geq \sum_{n \in N^x} \sum_{p=1}^P M_{n_p} \quad \forall x \quad (5.42)$$

$$E_v \geq \sum_{n \in N^v} \sum_{p=1}^P M_{n_p} \quad \forall v \quad (5.43)$$

All the assigned product and module quantities are defined as non-negative integers.

5.4 ANALYSIS AND RESULT

For simple illustration of the model a single returned product with ten modules are considered. Data used for the analysis are given in Appendix B. Also, as assumed by Inderfurth (2004), the balance of modules, if any, is assumed to be disposed at a cost. For the base case, the supply of used products is assumed to be stochastic with the distribution $N(21000, 1800)$ and the demand for remanufactured products to be stochastic with the distribution $N(15000, 450)$. The model is solved using GAMS[®] software.

The analysis from the model shows that the optimal cost for the network would be around \$954,450 for acquisition, storing, processing and distributing per year. The allocation for the network is shown in Figure 5.1, which gives the total transport

cost of the system as \$169,600. The cost of disposing the extra modules is \$7,900. It is also seen that for the given supply and demand distributions, only 554 new modules are required which are catered by suppliers, S_1 and S_2 . The cost of procuring these new modules is \$6,500.

Figure 5.1: Network structure when $Q = N(21000, 1800)$ and $D = N(15000, 450)$

Scenario analysis with base case demand but reduced supply is shown in Figure 5.2. In this case, the supply is assumed to be stochastic with the distribution $N(16000, 1800)$. The analysis showed that when less number of products are returned, less number of warehouses are required. However, this would require more new modules to satisfy the demand for remanufactured products ($N^\phi = 39,655$ units as compared to $N^\phi = 554$ units for the base case). As a result, the total cost of procuring new modules also increases significantly (from about \$6,500 in the base case to about \$304,300). The total network cost also increases

to about \$1,048,000. However, the transport cost decreases to \$127,850. Also, no usable modules need to be disposed. Therefore, when the return rate is less for a network, it does not necessarily decrease the total cost of network.

Figure 5.2: Network structure when $Q = N(16000, 1800)$ and $D = N(15000, 450)$

The network structure is also analyzed by fixing supply to the base case and assuming demand for the remanufactured products as stochastic with the distribution $N(10000, 450)$. The resulting network is shown in Figure 5.3. In this scenario, more modules from the returned products need to be disposed (54,345 modules as compared to 5,899 in the base case). Also, due to decreased demand, remanufacturing facility (F_2) is not required. The transport cost and disposal cost increase to \$256,430 and \$94,300 respectively, due to higher disposal of excess modules. The network cost in this scenario is increased to \$1,045,560.

Figure 5.3: Network structure when $Q = N(21000, 1800)$ and $D = N(10000, 450)$

The key cost components under the different scenarios of supply and demand are summarized in Table 5.1.

Table 5.1: Key cost components under various scenarios

Scenario	Supply	Demand	Optimal Network Cost (\$)	Transport Cost (\$)	New Module Cost (\$)	Disposal Cost (\$)
Base Case	N(21000,1800)	N(15000,450)	954446	169627	6506	7869
Low Supply	N(16000,1800)	N(15000,450)	1048351	127847	304651	0
Low Demand	N(21000,1800)	N(10000,450)	1045560	256431	0	94326
High Supply	N(26000,1800)	N(15000,450)	1250246	286126	0	85541
High Demand	N(21000,1800)	N(18000,450)	1144441	163790	194288	0

In order to understand the impact of the changes in demand and supply in the designed network (base case), various other scenarios are examined. Table 5.2 shows the scenarios under constant supply and Table 5.3 shows the scenarios under constant demand.

Table 5.2: Network cost variation under varying demand and constant supply [$N(15000,450)$]

Scenario	Demand	Optimal Network Cost (\$)	New Module Quantity (units)	Disposed Quantity (units)
1	N(12000,450)	1005203	0	35348
2	N(13000,450)	985345	0	25348
3	N(14000,450)	965887	0	15348
4	N(15000,450)	954446	554	5901
5	N(16000,450)	993945	5556	904
6	N(17000,450)	1065835	14652	0
7	N(18000,450)	1144441	24652	0

Table 5.2 gives the variation in the network cost and the quantity of modules disposed and procured for various demand scenarios. It is seen that the network cost decreases with increase in demand till the demand reaches the base case demand (scenario 4) (see Figure 5.4). This is because fewer modules need to be disposed with increase in demand. However, when the demand increases above the base case, the network cost increases significantly because more new modules need to be procured to meet the demand. Also, when demand increases, the transportation cost increases marginally. Also, when demand increases, associated network and transportation cost would also increase. The transport cost also increases marginally.

Figure 5.4: Network and Transport cost variation due to variation in demand but constant supply

Figure 5.5 represents the variation in the new module procurement cost and the disposal cost for various demand scenarios. It is seen that when the demand is lower than the base case (scenario 4), no new modules need to be procured. At the same time, the supply of used products is excess to the demand, hence some modules need to be disposed, incurring disposal cost.

Figure 5.5: New module and disposal cost variation due to variation in demand but constant supply

Table 5.3 shows the scenarios under constant demand.

Table 5.3: Network cost variation under varying supply and constant demand [N(21000,1800)]

Scenario	Supply	Optimal Network Cost (\$)	New Module Quantity (units)	Disposed Quantity (units)
1	N(18000,1800)	991756	21652	0
2	N(19000,1800)	963866	12652	0
3	N(20000,1800)	945922	4956	1304
4 (base case)	N(21000,1800)	954446	554	5901
5	N(22000,1800)	1007115	0	14348
6	N(23000,1800)	1067826	0	23348
7	N(24000,1800)	1128565	0	32348

Table 5.3 represents the change in the network cost and the quantity of modules disposed and procured under various supply scenarios. It is seen that when the supply increases from scenario 1 to scenario 3, the network cost decreases (see Figure 5.6). This is because, as the supply increases, more of recovered can be used to meet the demand. This also reduces the cost of procuring new modules.

However, the transport cost increases due to the excess products and modules. It is also seen that, when supply increases (scenario 3) in excess of demand; more modules need to be disposed.

Figure 5.6: Network and Transport cost variation due to variation in supply but constant demand

Figure 5.7 represents the change in the new module procurement and disposal costs for various supply scenarios. It is seen that, when supply increases (scenario 3) in excess of demand; more modules need to be disposed. Also, the cost of acquiring used products also increases with increase in supply, thus increasing the overall network cost.

Figure 5.7: New module and disposal cost variation due to variation in supply but constant demand

The scenario analysis provided above can reflect the situation of uncertainty in the receipt of used products and demand of remanufactured products. The analysis shows that the establishment of RL network and allocations to each echelon should be carefully designed in order to avoid significant cost to RL operations. If not, the increased costs have to be passed on to the customer, which can make the remanufactured product non-competitive. Similarly, if the price of remanufactured products cannot be increased, acquisition costs have to be decreased, which might not prompt the customers to return their used products. Therefore, the model presented here is useful to understand the optimal allocation in the face of stochastic demand and supply and then to analyze the effect of changes in demand and supply in a RL network.

6. CONCLUSIONS AND FUTURE WORKS

In this chapter, the findings of this research on RL network design are presented. The limitations of this research and potential research areas are also identified in this chapter.

6.1 CONCLUSIONS

Establishing networks to cater to reverse logistics would be the mainstream activities of OEMs in the coming days due to pressures to take back the products sold to the customers at various places. The past decade has witnessed the development of supply chains consisting of a large number of specialized parties located all over the world. Intuitively, one may doubt whether such a globalization is equally attractive for the reverse channel. What matters most is the spatial distribution of the customers all around the world. Therefore, companies have to understand the customer distribution and establish centres at various locations for collections, storage, dismantling, inspection and further processing. Further processing could be sending the unusable materials to recycling or disposal sites and sending the usable materials to the spare markets or remanufacturing units. It is the total cost that has an impact on establishment of RL network.

In this research, logistics network design for product recovery environment is analyzed. As a starting point, generic steps of activities carried out in product recovery networks and processes are identified. It is seen that a typical network

structure includes a convergent part concerned with collection from a disposer market to recovery facilities, a divergent part for distribution to a re-use market, and an intermediate part related with the recovery processing. From the review of the various case studies presented and considering recovery situations in more detail, it is seen that product recovery networks can be subdivided into number of classes. Remanufacturing networks, recycling networks, product recovery networks, and hazardous waste reprocessing networks each appear to have their own typical characteristics.

Initially, a deterministic model is proposed for recovery of multi-product modular structured products. This model allows capacity constraints in warehouses, RPC's and factories. This simulates current pattern used by some of the industries to use existing warehouses, dismantling centres and factory lines for returned products. Due to the difficulty in establishing whole new entities to cater to the needs for RL, some companies segregate their capacities to handle new products and returned products. This way, companies will have flexibility to produce new or remanufactured products as per the demand.

Later, the deterministic model is modified to incorporate stochastic supply and demand situations. The model considers stochastic supply of used products and stochastic demand for remanufactured products. Due to varied usage patterns, varied demand and location of customers, it is difficult to estimate the timing and quantity of returned products. Such a model represents the real situation of the industry. Companies are faced by problems in establishing warehouses, dismantling centres and processing lines for returned products under uncertainty.

The models assume a product with interchangeable modules so that products of various models can be developed through a single remanufacturing process. This assumption is made for the simplification in terms of application of the model for numerical analysis. This type of process of using a single assembly line and machine setup can be found in various automobile, mobile phone, and computer manufacturing industries to produce various models in different numbers from a single production line as the basic manufacturing process for producing various models is similar. Therefore, when a family of products is considered, this type of remanufacturing would be a feasible option. From the implementation of the model in a simulated scenario, it can be concluded that the model can help to obtain various scenarios for the design of a cost effective network.

The model brings out an important conclusion in the forefront. That is, transportation and other logistics costs may not be an important factor in the design of a network. Rather, the cost of reprocessing, remanufacturing, and the cost of new modules can be the driving factor for the choice of a reverse logistics network. Through the analysis with different quantities of returned products, the cost of new module is seen as an important factor in network cost. Therefore, it might be beneficial for the decision makers to locate reprocessing centre at a location where resources (like labour, energy, land) are cheaper and to locate remanufacturing centres at places where new modules of the remanufactured products can be obtained at a cheaper rate.

In general, it is seen that most remanufacturing models consider remanufacturing of the products with all used parts. It is believed that when the demand for remanufactured products increase in emerging markets there would be a need to mix and match old and new modules instead of reworking only on the used products. Therefore, these models also reflect the real situation in terms of purchasing the new modules to develop the final remanufactured products. With practices such as just in time and vendor managed inventory, the inventory cost of such new modules can be eliminated at the factory level. However, as those suppliers are world wide and need to be competitive in terms of costs, a differential cost for the same modules supplied by each supplier to each of the factories is assumed.

The models also consider the demand of modules in the spare market as it would generally fetch a higher value (compared to the final product) per module for the companies. It is very difficult to consider the quantities that could go to disposal sites as it depends on various factors, like life of returned period, the pattern of product use and so on. However, with the advancement in technology and design processes, it is possible to estimate the number and type of modules that might have to be disposed.

6.2 LIMITATIONS AND FUTURE WORKS

Though this research proposes a strategic decision making model for the design of RL networks, it has certain limitations. The above research does not consider lead times for supply of cores and is used for single period returns only. Also, various

modes of transport may be available between various nodes; however, the model assumes only a single mode of transport. Commonality of modules is another feature which this research has not considered.

Arising from the research limitations mentioned above, the models can be further extended in terms of the following:

1. Discount pricing

The research assumes a differential cost for the same module supplied by different suppliers. However, an important extension could be to model the new module costs with respect to required quantities to represent discount pricing. Obviously, suppliers would not be able to offer a discount on modules when demand quantities are lower.

2. Product obsolescence

Product obsolescence is another feature which can be incorporated in the model. This becomes challenging especially to those products which have a short shelf life. Thus, remanufacturing the used product as soon as it is returned can significantly alter the facility location and transport requirements.

3. Part commonality

This research assumes a unique modular structure that is module usage rate is 1. However, this may not be the case in reality. Products such as computers, automobiles, and machinery have many multiple module usages. Hence, the model needs to be extended to handle such multi-usage rates.

4. Inventory costs

The proposed stochastic model assumes the disposal of excess modules from RPC. This assumption is consistent with that made by Inderfurth (2004) and Inderfurth and Langella (2006). However, this may not happen in practice. Due to high raw material costs, processing costs and higher lead times, companies may desire to store the excess usable modules for use in the next period. This requires incorporation of inventory costs at different facilities.

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GLOSSARY OF TERMS

This section provides a brief description of the various terms associated with reverse logistics, more specifically, with this thesis. The terms are as listed below:

Cannibalization Cannibalization usually commands low economic benefits. In this, only a limited set of reusable parts are recovered and sold ‘as it is’, while other parts are disposed

Closed Loop Supply Chain (CLSC) A system which utilizes waste or scrap from one stage of production as inputs to other stages of production is referred to as a closed loop supply chain. In CLSC, the traditional supply chain is extended to include supply flow of returns and recyclables.

Disposal Products or parts that cannot be reused for technical or economical reasons are disposed. Such parts are either land-filled or incinerated.

Extended Producer Responsibility (EPR) EPR is a strategy designed to impose accountability over the entire life cycle of products and packaging introduced on the market. This means that firms, which manufacture, import and/or sell products and packaging, must either take back spent products and manage them through reuse, recycling or in energy production, or delegate this responsibility to a third party.

Green Manufacturing Green manufacturing is a strategy aimed to minimize the deleterious impacts resulting from industrial activity by using the appropriate material and technologies.

Recycling Recycling refers to the process in which the products and/or its modules and components lose their shape, size, identity, usability and

functionality. They are processed to form basic ‘materials’ which can be reused in the production of new parts and products.

Refurbish The process of disassembling the product and inspecting and replacing all critical modules to get the product to a specified quality standard is known as refurbishment. In this, some working modules may be replaced with technologically superior ones for upgrading the product.

Remanufacturing A remanufacturing process uses the disassembled quality modules of used products to produce ‘as new’ products through a manufacturing process. The reusable components are reprocessed and tested to ensure that they meet the company standards.

Repair When a product is repaired, it is restored to working condition. In this certain worn out parts may be replaced.

Resell Remanufactured parts are generally sold to serve as inputs to other technological industries. For example, printed circuit boards recovered from discarded computers may be used in making high-tech toys.

Reuse In reuse, used products are used again for the same or a different purpose without major treatment. Generally, the product as a whole is kept in the economic cycle. For example, containers, pallets and glass bottles are reused.

Waste of Electronic and Electrical Equipment (WEEE) Directive The WEEE Directive is the European Community directive 2002/96/EC on waste electrical and electronic equipment which became European Law in February 2003, setting collection, recycling and recovery targets for all types of electrical goods. The directive compels the manufacturer to use the collected waste in an ecological-friendly manner, either by ecological disposal or by reuse/refurbishment.

APPENDIX A

DATA FOR DETERMINISTIC MODEL

Input data used for the analysis of the network based on the deterministic model are given in Tables A.1-A.6. A product made up of ten unique modules is assumed for return. The cost of transporting the product and its modules between the several nodes of the network are given in Table A.1. The inventory carrying cost of the modules and products incurred at the facilities is given in Table A.2. Fixed costs of the facilities and the product acquisition costs are given in Table A.3. Table A.4 gives the monthly capacity constraint of the suppliers (Z) to supply new modules and the cost of the new modules from each supplier to each factory. The products are dismantled into modules at the RPC's. These modules are then reprocessed for recovery. The modules which are remanufactured may be sent to the factories for assembly to produce a remanufactured product. The modules which cannot be recovered and recycled need to be disposed. The data on the total quantity of products supplied by the retailers (Q) and the storage capacity of the warehouse and RPC is given in Table A.5. This table also gives the demand of remanufactured modules in the spare market, the demand for remanufactured products at the distribution centres and the production capacity of each factory. Table A.6 gives the costs associated with the reprocessing, assembling and disposal activities.

Table A.1: Input Data on transportation costs

Retailer to warehouse (\$rw/prod)	Warehouse to RPC (\$wj/prod)	RPC to factory (\$ju/mod)	RPC to spare market (\$js/mod)	RPC to disposal (\$jv/mod)	RPC to recycling (\$jx/mod)	Factory to DC (\$uh/prod)
(0.3,0.54,0.33, 0.38,0.26,0.42, 0.29,0.36,0.3, 0.5,0.39,0.42, 0.33,0.3,0.36, 0.33,0.42,0.44, 0.3,0.35)	(0.95,0.83, 0.90,1.11, 1.05,1.02, 1.16,1.19, 1.23,0.87, 0.77,0.83)	(0.24,0.23, 0.24,0.21, 0.24,0.23, 0.24,0.22, 0.23)	(0.9,0.75,0.89, 0.78,0.81,0.86, 0.84,0.86,0.75, 0.78,0.89,0.8, 0.87,0.78,0.78)	(2.25,2.75, 2.20)	(4.65, 2.80,3.35)	U ₁ (1.59, 3.18,2.85, 0.78,1.71, 2.43,2.52, 2.40,2.28, 0.75,1.47, 2.73,2.10, 2.07,2.58, 0.78,1.89, 2.79)

Table A.2: Input Data on inventory carrying cost (ICC)

ICC at warehouse w (\$/prod/month)	ICC at RPC j (\$/prod/month)	ICC at factory f (\$/prod/month)	ICC at RPC j (\$/module/month)
(716.75,645.00, 403.25,537.50)	(1875,2100, 1600)	U ₁ (0.28,0.52,0.83,0.42,0.48, 0.57,1.0,0.47,0.45,0.30) U ₂ (0.35,0.58,1.03,0.65,0.53, 0.90,1.3,0.75,0.63,0.57) U ₃ (0.32,0.55,0.92,0.50,0.50, 0.73,1.13,0.62,0.55,0.43)	J ₁ (2.18,1.16,0.80,0.22,0.68, 1.16,0.60,0.76,0.46,1.20) J ₂ (1.56,1.38,0.84,0.26,0.94, 1.30,0.70,0.70,0.50,1.16 J ₃ (1.20,1.36,0.72,0.30,1.10, 1.34,0.66,0.82,0.56,1.12)

Table A.3: Input Data on fixed cost

Fixed cost of warehouse w (\$w/month)	Fixed cost of RPC j (\$j/month)	Fixed cost of factory u (\$u/month)	Product acquisition cost (\$/product)
(5750,5500,4900,6900)	(9350,6700,5500)	(4850,4550,4600)	21.5

Table A.4: Input Data on monthly supply constraint and cost of new modules

Monthly supply constraint $z(M_i, \dots, M_n)$ (modules)	Total Cost of new module (\$zf/Mi)
$z_1(1900, 1800, 2580, 1800, 1300, 1800, 1800, 1260, 1500, 2260)$	\$11(3.6, 25, 11.25, 5.3, 6.6, 6.85, 13.3, 7.45, 5.75, 8.25) \$12(3.3, 6.5, 11.5, 5.6, 6.8, 7.05, 13.5, 7.65, 6.8, 7.5)
$z_2(1700, 2000, 1660, 1500, 2500, 2200, 2100, 1540, 1000, 1800)$	\$13(3.2, 6.4, 11.35, 5.75, 6.25, 6.5, 13.35, 7.5, 5.6, 8.25) \$21(2.9, 6.5, 11.2, 5.25, 6.45, 6.9, 13.3, 7.35, 5.8, 8.2)
$z_3(2700, 1500, 1740, 1500, 1700, 2000, 2500, 1280, 1800, 1600)$	\$22(3.25, 6.6, 11.6, 5.65, 6.75, 7.15, 13.55, 7.8, 6.25, 8.5) \$23(3.15, 6.5, 11.3, 5.65, 6.5, 6.65, 13.3, 7.15, 5.8, 8.4)
$z_4(2360, 1900, 1500, 1680, 1800, 2300, 2000, 1100, 1300, 1800)$	\$31(3.15, 6.6, 11.35, 5.3, 6.5, 6.95, 13.4, 7.5, 5.8, 8.5) \$32(3.15, 6.6, 11.55, 5.5, 6.6, 6.95, 13.4, 7.7, 6.15, 8.75)
$z_5(1800, 2100, 1600, 1100, 2100, 2400, 1600, 1200, 1000, 2100)$	\$33(3.15, 6.35, 11.35, 5.5, 6.35, 6.7, 13.45, 7.25, 5.65, 8.6) \$41(2.9, 6.35, 11.15, 5.2, 6.55, 6.95, 13.35, 7.4, 5.75, 8.2)
$z_6(1540, 2000, 1400, 900, 2600, 1700, 2000, 1620, 1800, 2400)$	\$42(3.2, 6.55, 11.45, 5.6, 6.65, 7, 13.35, 7.75, 6.1, 8.65) \$43(3.2, 6.35, 11.4, 5.6, 6.3, 6.55, 13.35, 7.35, 5.75, 8.5)
	\$51(3.05, 6.25, 11.15, 5.2, 6.5, 6.85, 13.45, 7.35, 5.9, 8.45) \$52(3.15, 6.5, 11.45, 5.75, 6.7, 6.95, 13.45, 7.65, 6.05, 8.6) \$53(3.25, 6.45, 11.45, 5.7, 6.4, 6.85, 13.45, 7.2, 5.7, 8.45) \$61(3.1, 6.45, 11.3, 5.25, 6.45, 7.05, 13.5, 7.4, 5.75, 8.35) \$62(3.25, 6.65, 11.4, 5.5, 6.6, 7.05, 13.5, 7.8, 6.8, 7) \$63(3.3, 6.45, 11.3, 5.55, 6.35, 6.6, 13.5, 7.4, 5.75, 8.35)

Table A.5: Data on supply, storage capacity, demand at DC and capacity constraint at factory

Supply from retailer r (units)	Storage capacity at warehouse w (prod)	Storage capacity at RPC J (prod)	Demand for modules in Spare market $s(m_1, \dots, m_n)$ (units)	Demand at DC h (prod)	Capacity constraint at factory u (prod)
(5750, 6000, 4250, 5000, 4000)	(8000, 9000, 7000, 8500)	(10000, 12000, 9000)	S1(3300,600,1000, 3500,1200,7500, 100,0,500,2300) S2(0,4500,2500, 0,5500,1900, 0,2000,600,0) S3(2500,2500,2400, 1500,2000,800,1500,2500, 900,3900) S4(2000,550,1800, 2700,800,1000, 1800,1500, 4000,1850) S5(0,1850,1500, 0,800,800, 4100, 500,1500,950)	(3500, 3500, 2500, 3500, 2500, 2500)	(6500, 5500, 6000)

Table A.6: Input Data on reprocessing, disposal and assembly costs

Reprocessing cost at RPC j (\$j/mod)	Disposal cost at site v (\$v/mod)	Assembly cost at factory u (\$u/mod)
J ₁ (0.64,0.58,0.16, 0.36,0.30,0.48, 0.50, 0.58,1.04, 1.00) J ₂ (0.68,0.64,0.24, 0.29,0.29,0.48, 0.60,0.52,0.88, 0.76) J ₃ (0.66,0.62,0.2, 0.31,0.28,0.45, 0.55,0.55,0.92, 0.84)	(0.99,1.08,1.64,0.86, 2.27,3.58,2.25,1.03, 2.09,1.78)	U ₁ (0.28,0.73,0.05, 0.25,0.18,0.56, 0.46,0.52,0.12,0.25) U ₂ (0.35,0.71,0.08, 0.22,0.16,0.60, 0.50,0.56,0.09,0.29) U ₃ (0.32,0.72,0.06, 0.23,0.17,0.58, 0.48,0.54,0.11,0.27)

APPENDIX B

DATA FOR STOCHASTIC MODEL

Input data used for the analysis of the network based on the stochastic model are given in Tables B.1-B.6. A product made up of ten unique modules is assumed for return. The cost of transporting the products and its modules between the several nodes of the network are given in Table B.1. The inventory carrying cost (ICC) and the handling cost are given in Table B.2. The costs associated with reprocessing, assembling and disposal are given in Table B.3. Fixed costs of the facilities and the product acquisition costs are given in Table B.4. The data on the total quantity of products supplied by the retailers (Q), the storage capacity of the warehouse and RPC, the production capacity of each factory and demand (K) are given in Table B.5. The capacity constraint of the suppliers and the cost of new modules from each supplier to each factory are given in Table B.6.

Table B.1: Data on transportation costs

Retailer to warehouse (\$rw/prod)	Warehouse to RPC (\$wj/prod)	RPC to factory (\$jf/mod)	RPC to spare market (\$js/mod)	RPC to disposal (\$jv/mod)	RPC to recycling (\$jx/mod)	Factory to DC (\$fh/prod)
(0.3,0.54,0.33, 0.38,0.26,0.42, 0.29,0.36,0.3, 0.5,0.39,0.42, 0.33,0.3,0.36, 0.33,0.42,0.44, 0.3,0.35)	(0.95,0.83, 0.90,1.11, 1.05,1.02, 1.16,1.19, 1.23,0.87, 0.77,0.83)	(0.27,0.23, 0.21,0.25, 0.18,0.23, 0.30,0.19, 0.20)	(0.9,0.75,0.89, 0.78,0.81,0.86, 0.84,0.86,0.75, 0.78,0.89,0.8, 0.87,0.78,0.78)	(2.25,2.15, 2.20)	(2.65, 2.80, 3.35)	(1.59, 3.18,2.85, 0.78,1.71, 2.43,2.52, 2.40,2.28, 0.75,1.47, 2.73,2.10, 2.07,2.58, 0.78,1.89,2.79)

Table B.2: Data on inventory carrying cost (ICC)

ICC at warehouse w (\$/prod/year)	Material handling cost at factory f (\$/module/year)	Material handling cost at RPC j (\$/prod/year)
(716.75,645.00, 403.25,537.50)	U1(0.28,0.52,0.83,0.42,0.48, 0.57,1.0,0.47,0.45,0.30) U2(0.35,0.58,1.03,0.65,0.53, 0.90,1.3,0.75,0.63,0.57) U3(0.32,0.55,0.92,0.50,0.50, 0.73,1.13,0.62,0.55,0.43)	J1(2.18,1.16,0.80,0.22,0.68, 1.16,0.60,0.76,0.46,1.20) J2(1.56,1.38,0.84,0.26,0.94, 1.30,0.70,0.70,0.50,1.16 J3(1.20,1.36,0.72,0.30,1.10, 1.34,0.66,0.82,0.56,1.12)

Table B.3: Data on reprocessing, disposal and assembly costs

Reprocessing cost at RPC j (\$j/module)	Disposal cost at site v (\$v/module)	Assembly cost at factory f (\$f/module)
J1(0.64,0.58,0.16, 0.36,0.30,0.48, 0.50, 0.58,1.04, 1.00) J2(0.68,0.64,0.24, 0.29,0.29,0.48, 0.60,0.52,0.88, 0.76) J3(0.66,0.62,0.2, 0.31,0.28,0.45, 0.55,0.55,0.92, 0.84)	(0.99,1.08,1.64,0.86, 2.27,3.58,2.25,1.03, 2.09,1.78)	U1 (0.28,0.73,0.05, 0.25,0.18,0.56, 0.46,0.52,0.12,0.25) U2 (0.35,0.71,0.08, 0.22,0.16,0.60, 0.50,0.56,0.09,0.29) U3 (0.32,0.72,0.06, 0.23,0.17,0.58, 0.48,0.54,0.11,0.27)

Table B.4: Data on fixed cost

Fixed cost of warehouse w (\$w/year)	Fixed cost of RPC j (\$j/year)	Fixed cost of factory f (\$f/year)	Product acquisition cost (\$/product)
(5750,5500,4900,6900)	(9350,6700,5500)	(4850,4550,4600)	21.5

Table B.5: Data on supply, storage capacity, demand at DC and capacity constraint at factory

Supply (Q) from retailer r (units)	storage capacity at warehouse w (prod)	Storage capacity at RPC J (prod)	Demand for modules in Spare market s (mi...mn) (units)	Demand at DC h (prod)	Capacity constraint at factory f (prod)
N(21000, 1800)	(8000, 7000, 7000, 8000)	(10000, 12000, 9000)	S1(300,100,100, 500,300,500, 1100,400,500,200) S2(100,500,600, 525,500,200, 700,200,800,100) S3(250,200,1250, 150,200,800,1000,500, 400,1450) S4(800,550,800, 200,500,1200, 800,500, 600,850) S5(850,850,500,450,800,800, 200,1500,500,800)	N(15000, 450)	(6500, 5500, 6000)

Table B.6: Data on annual supply constraint and cost of new modules

Supply capacity/year z(Mi....Mn) (modules)	Total cost of new module (\$zf/Mi)
z1(900,1800,2500,2800,2300,3800, 4800, 4260,2800,2260) z2(700,2900,1700,3500,5500,4200, 4100, 3540,3500,4800) z3(700,6500,6800,1500,4700,3500, 3500, 2280,2400,3600) z4(350,5900,2000,4680,3800,4300, 3000,5100,4800,2800) z5(800,2100,5800,2100,2100,3400, 3600,4200,5500,3700) z6(550,2000,6600,4900,2600,4700, 3000,3600,2200,7400)	\$11(3,6.25,11.25,5.3 ,6.6,6.85,13.3,7.45,5.75 ,8.25)
	\$12(3.3,6.5,11.5,5.6,6.8,7.05,13.5,7.65,6,8.75)
	\$13(3.2,6.4,11.35,5.75,6.25,6.5,13.35,7.5,5.6,8.25)
	\$21(2.9,6.5,11.2,5.25,6.45,6.9,13.3,7.35,5.8,8.2)
	\$22(3.25,6.6,11.6,5.65,6.75,7.15,13.55,7.8,6.25,8.5)
	\$23(3.15,6.5,11.3,5.65,6.5,6.65,13.3,7.15,5.8,8.4)
	\$31(3.15,6.6,11.35,5.3,6.5,6.95,13.4,7.5,5.8,8.5)
	\$32(3.15,6.6,11.55,5.5,6.6,6.95,13.4,7.7,6.15,8.75)
	\$33(3.15,6.35,11.35,5.5,6.35,6.7,13.45,7.25,5.65,8.6)
	\$41(2.9,6.35,11.15,5.2,6.55,6.95,13.35,7.4,5.75,8.2)
	\$42(3.2,6.55,11.45,5.6,6.65,7,13.35,7.75,6.1,8.65)
	\$43(3.2,6.35,11.4,5.6,6.3,6.55,13.35,7.35,5.75,8.5)
	\$51(3.05,6.25,11.15,5.2,6.5,6.85,13.45,7.35,5.9,8.45)
	\$52(3.15,6.5,11.45,5.75,6.7,6.95,13.45,7.65,6.05,8.6)
	\$53(3.25,6.45,11.45,5.7,6.4,6.85,13.45,7.2,5.7,8.45)
	\$61(3.1,6.45,11.3,5.25,6.45,7.05,13.5,7.4,5.75,8.35)
	\$62(3.25,6.65,11.4,5.5,6.6,7.05,13.5,7.8,6,8.7)
	\$63(3.3,6.45,11.3,5.55,6.35,6.6,13.5,7.4,5.75,8.35)