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VALUE ANALYSIS IN REMANUFACTURING

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A thesis submitted to the Nanyang Technological University
in fulfillment of the requirement for the degree of
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Abstract

Remanufacturing of used products is an important option for companies and society as it promotes sustainable use of resources and conserves energy and material. By way of remanufacturing, companies extract the economic value from used products as well.

Remanufacturing requires adequate supply of used products (called cores in this thesis to be consistent with the literature). Due to the use pattern, cores returned by customers would be in different quality levels. While a core with lowest quality can only be recycled and disposed, cores with highest quality can be sent back to the market after minimum processing/packaging. All cores in between these two qualities can be classified within various quality levels as designated by the remanufacturer. Therefore, it is not only the quantity of cores, but also their quality, which determines the feasibility of remanufacturing.

Cores are located at the customers' place, which are sparsely located. Cores are collected by remanufacturer itself or through outsourced companies. Customers are provided with certain incentive (money) for return of cores. If the incentive is not enough, the customers may not return cores and remanufacturing cannot take place. Even if the incentive is attractive, the number of cores and their quality would be stochastic.

Remanufactured products compete with the original product of same or equivalent type. Therefore, if there are no price differences between these products, customers would not be attracted towards the purchase of remanufactured products. Also, the demand for

remanufactured products can be stochastic and it can be challenging to fix incentives and supply quantities.

The purpose of this research is to investigate the issue of supply of cores in order to meet demand for remanufactured products. The research focuses on: i) the flow of cores from the collection centers (as the drop point for cores by the customers) to the consolidation center (as a consolidator of cores obtained from various collection centers) and finally to the remanufacturer (to obtain the requisite number of cores); ii) on obtaining demand profile from the retailers, devising a pricing and quantity schedule (with various prices based on quality of cores) and providing that information to the consolidation center and providing the funds for the cores supplied by the consolidation center, and; iii) the consolidation center developing incentive profile and quantities for the collection centers so that cores collection can be initiated.

In order to investigate the three aspects mentioned above, this thesis employs the development of models: i) for the transaction between the collection centers and the consolidation center, and the consolidation center and the remanufacturer as single period models, and; ii) the transaction of cores in terms of an integrated model in a multi-period setting.

The models have been tested with numerical study and the results show that optimal quantity of cores (of different quality) and the acquisition price (for different quality cores) can be developed jointly to assist the decision makers. The results also shows that

when there is a change in the price of the remanufactured product, and when there is a stochastic supply and demand, the price to be paid for the cores changes significantly. The analysis shows that when a too low price is set for the remanufactured product, it may sell in the market, but it may lead to lower incentive for cores thus not attracting enough cores to meet the demand for products. Therefore, a balanced pricing mechanism becomes necessary. Also, when there are inventories, they can only be carried to a certain time horizon to avoid their obsolescence. Therefore, if the pricing mechanism does not balance the attraction of remanufactured product and the return of cores, remanufacturing cannot take place.

The models proposed in this thesis provide basic analytical mechanism to adjust core price and quantities. The contribution in this thesis is in terms of first development of such analytical models that can be used by the decision makers. It is hoped that researchers can build onto this concept of using intertwining quantity, quality and price to develop specific pricing and supply models for a particular industry.

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CHAPTER 1

Introduction

Implementation of legislation, need to fulfill social responsibilities and project corporate images, concern on environment, opportunity for economic benefits and increased customer awareness are the factors that are leading companies not only to provide more environmentally friendly products but also to take back the products after their use. Original equipment manufacturers (OEMs) have adopted two main approaches to respond to this situation. The first approach is to redesign the products and the manufacturing processes in order to use more and more environmentally friendly materials. This is also known as extended producer responsibility (EPR). The second approach is to retrieve the materials, parts, modules for recovery (Thierry et al., 1995; Carter and Ellram, 1998). The second approach encompasses all activities used for handling the used and discarded products in order to capture the latent economic and ecological value embedded in them and to ultimately reduce the waste. Most companies use various combinations of these two approaches in a bid to promote their environmentally friendly products to the customers and fulfill legislative requirements and social responsibilities.

Legislation and social responsibilities for end-of-life and end-of-use products encourage sustainability of materials, parts and products and address environmental concerns such as waste reduction and resource conservation (Ayres et al., 1997; Ferrer

and Ayres, 2000; Ravi et al., 2005). This awareness, coupled with the ability to extract value from used products through remanufacturing, make much sense to remanufacturing. Cohen (1988), Heeb (1989) and Toensmeier (1992) reported that companies' remanufacturing practices could potentially save about 40%-60% costs if they were using recovered materials or modules and it would promote greener industrial ethics as well (Bloemhof-Ruwaard et al., 1995; Bloemhof-Ruwaard and van Nunen, 2005). Thus, remanufacturing is both a 'waste stream driven' system and a 'market driven' system (Guide and van Wassenhove, 2001). The increasing emphasis on product take-back and product recovery by remanufacturing has led to a great deal of research in the area of moving and handling returns, i.e., reverse logistics (RL) and product recovery. In the following sections, various aspects of reverse logistics and product recovery with relation to remanufacturing have been discussed.

1.1 Reverse Logistics

Reverse logistics relates to the logistics of collecting and disassembly of used products (called cores), and processing of parts and materials from such products. The main sources of reverse flow of cores are customers themselves (Rogers and Tibben-Lembke, 1999; Tibben-Lembke, 2002). The customers would return their products for the following reasons:

- defective products;
- unwanted products and unsatisfied customers;

- warranty returns;
- product recalls;
- product upgrades or trade-ins; and
- environmental and disposal issues.

Guide et al. (2000) and Flapper (1995) have discussed differences between forward and reverse supply chains in terms of the difficulties in forecasting product returns as the supply sources. Compared to forward supply chain, the uncertainty in quantity, quality and timing of cores returns makes the planning of incoming cores more complicated. Other than this uncertainty, the demand for reprocessed products is also stochastic. Another difference is the number of origin and destination points in reverse supply chains. A forward supply chain generally has a few suppliers and a large number of customers, a reverse supply chain involves a large number of suppliers and a small number of customers (Fleischmann et al. 1997).

1.2. Product Recovery

Product recovery accounts for total sales in excess of USD 53 billion per year in the United States (Guide et al., 2000). Various forms of product recovery are: repair, refurbish, remanufacturing, resell, cannibalization and recycling.

In the repair process, the returned products are restored to working condition. In this process, certain worn-out parts of the products are replaced while those in good working condition are retained. The products become the so-called 'as new' or 'equivalent to new' product (Jorjani et al., 2004).

In the refurbishment process, cores are disassembled and all the broken modules are either fixed or replaced. In this option, some existing modules may be replaced with upgraded modules.

In the remanufacturing process, the disassembled qualified modules of cores are used to produce 'as new' products (Ferrer, 2001). The remanufacturing process is similar to repair or refurbishment options but the scales and activities involved are different.

In the reselling process, the valuable parts are recovered from the cores and are sold separately for use by same and other industries in the market. For instance, printed circuit boards recovered from discarded computers may be used in making high-tech toys, a concept popularly known as de-manufacturing (White et al., 2003).

In the cannibalization process, certain parts extracted from cores are kept as usable parts. However, only a limited set of such parts can be sold 'as it is'. In some industries, the cannibalization is regarded as a good solution for service parts, especially for some old models, which are not currently under production.

Recycling is another important recovery activity, in which cores 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.

1.3 Remanufacturing

Remanufacturing is another option, the most important one, supported by reverse logistics. Product recovery focuses on the processing of cores and other supporting activities, such as the collection and inspection of cores, disposal of cores or their parts and redistribution of recovered products.

Guide et al (2000) highlight that due to the nature of recovery operations, there are many uncertainties that challenge the management of recovery process, and they are

- uncertainty of time and quantity returns;
- uncertainty in materials recovery from returns;
- complicated materials matching, and;
- stochastic routing and processing time.

As core returns are initiated by different end users, it is difficult to predict the quality, quantity and timing of such returns. The demands of remanufactured products are also stochastic. Unfortunately, the match between demands and returns is necessary for

certain scale of systematic remanufacturing. Moreover, the demand for replacement parts or materials to be used for remanufacturing cannot be forecasted in advance as both the quality and quantity of cores are stochastic. Therefore, attracting cores becomes primary focus for remanufacturing for which the remanufacturers or decision makers of reverse logistics supply chain should use the historical information on the supply, product characteristics in terms of quality during the usage and the demand for remanufactured products.

Dyckhoff et al. (2004) developed a conceptual framework of closed loop supply chain (CLSC) for German automobile industry (Figure 1.1). According to German Closed Substance Cycle and Waste Management Act, the automobile manufacturers are responsible for the entire life cycle of their automobiles, not only during automobiles' stewardship but also after their stewardship. Therefore, the competency to manage end-of-life vehicles (ELV) becomes an enterprise-wide assignment. Germany is a leading country that considers the sustainability of industries and society and enforces automobile industry to adopt options to promote reverse logistics.

Figure 1.1 shows a 'double-layer model' for automobile CLSC as studied by Dyckhoff et al. (2004). One layer is for all transactions by actors and the other layer is for the material flow and its transformations. In the actors/transactions layer, disposers join this CLSC to manage the transactions and operations between POR (point of return) and POE (point of entry or re-entry). In the material

flow/transformations layer, collection, reduction and induction operations are added. Management of the material flow and transformations over the transactions among actors is a critical task. At the POR, ELV are collected by car collectors, while dismantlers disassemble the cars into recoverable materials and reusable parts. These recoverable materials and reusable parts are sent to the shredder plants and reprocessing plants to obtain recycled materials and reprocessed parts. These materials or parts can re-enter the production at the POE. As more and more players are involved in CLSC, the control policies of transactions become necessary.

Fig 1.1 A basic double-layer closed loop model (Dyckhoff et al., 2004)

Similar to ELV, networks have been developed for waste electrical and electronic equipment (WEEE) in Europe (Krikke et al., 2002). According to the WEEE Directive and the Directive of the European Parliament and Council on the Restriction of the Use of Certain Hazardous Substance (RoHS-Directive), the producers of such equipments have financial responsibility for the treatment, recovery and final disposal of waste electrical and electronic equipment (http://ec.europa.eu/environment/waste/weee/index_en.htm). As shown in Figure 1.2, recovered WEEE re-enter the forward supply chains in the form of reusable products, remanufactured products, remanufactured parts, reprocessed materials and recycled materials. Therefore different financial results are obtained at different re-entry points. In terms of incomes, compared with other options such as reprocessing and recycling, remanufacturing contributes the highest value in the closed loop supply chain for WEEE.

Fig 1.2 Generic closed loop supply chain for WEEE

1.4 Transaction Management for Remanufacturing

The transactions among players include not only the acquisition of recoverable products but also the distribution of recovered materials, parts and products. Transaction management (TM) is a critical step in remanufacturing. Acquiring recoverable products (either new/used or end-of-life/end-of-use) is the first step in remanufacturing.

1.4.1 Acquisition of Cores

The acquisition of cores for remanufacturing is a unique process as the origin of main material (that is, core) is at the customers' place. Therefore, acquiring cores becomes a difficult task for remanufacturers Guide and Jayaraman (2000) point that there are five categories of product acquisition management (PrAM),

- Cores acquisition,
- Forecasting and balancing,
- Returns with demands,
- Resource planning and,
- Strategies to reduce uncertainties in returns.

Figure 1.3 shows the roles of PrAM is to coordinate purchasing, production and marketing functions in a remanufacturing system. The information on quantity and

quality of cores is important for reprocessing them. Information on quality helps to identify the need for replacement parts and inventory of cores for recovery production. Information on quantity helps to balance the supply and demand, and eventually the remanufacturing quantity and the demand for remanufactured products. Therefore, PrAM becomes the key concern of the remanufacturing processes and activities. Guide and Jayaraman (2000) pointed out that there is a need to develop economic models for potential benefit of each of PrAM activities, especially for purchasing transactions.

Fig 1.3 PrAM interfaces (Guide and Jayaraman, 2000)

1.4.2 Sale of Remanufactured Products

The management of sale of remanufactured products generally involves retailer level transactions between retailers and customers, the remanufacturing and manufacturing level transactions for material flows and product transformations.

In Europe, the legislative regulations permit the returned new products to be reused directly after confirmation of their quality. Of the total mail/catalog sales in Europe, as high as 40% of items are returned during the selling season itself. If these returns cannot be resold or treated properly within a specific period, then they would become dead inventory leading to big losses. However, in the United States, direct sale of returned new products is not allowed. Outlets are employed here to sell returned new products at competitive prices, which are definitely lower than those of new products. Since most returned products only require minor recovery, like either package replacement or minor cleaning.

1.4.3 Transactions methods in Remanufacturing

There are mainly two kinds of products remanufacturing:

- Refillable container remanufacturing
- Industrial remanufacturing

The good example of refillable containers remanufacturing is the cartridge remanufacturing by Xerox. The acquisition of empty cartridges is through prepaid

mailers or a periodic collection mechanism. A prepaid mailer is provided to individual customers along with the cartridge. The empty cartridge is sent directly to Xerox by individual customers through the Post. For high volume users, Xerox uses a private network and courier service providers. This way, the acquisition of empty refillable containers becomes controllable and the cost of acquisition can be forecasted.

The case of Kodak single-use cameras is another example of refillable containers remanufacturing. Customers get new single-use cameras from retail stores or supermarkets and return them after their use to film developers for processing of photographs. The acquisition of the used camera from the film developers can be difficult due to the sparse locations of film developers. Therefore, Kodak has to employ consolidation centers in order to collect used cameras and send them to designated remanufacturing sites.

Industrial remanufacturing refers to the remanufacturing of functional industrial products (through disassembly and reassembly) and it accounts for the majority of remanufacturing operations (Guide et al., 2000).

Caterpillar (CAT) Inc., the world's largest manufacturer of construction and mining equipment, diesel and natural gas engines, and industrial gas turbines, is one of companies, which adopt industrial remanufacturing for their products. In 2006, CAT acquired Progress Rail Services Corporation, a provider of remanufactured

locomotive, railcar products and services to the North American railroad industry. In 2007, it acquired Eurenov S.A.S., a remanufacturer of engines, transmissions and components for leading European automotive manufacturers. These two acquired companies receive used diesel engines collected by CAT and remanufacture them for CAT as outsourced companies. The remanufactured engines are sold through CAT's own marketing channel.

In other instance, third party remanufacturer may be employed by the original equipment manufacturer in order to segregate remanufacturing with manufacturing process. In other cases, part of remanufacturing chain such as the collection and inspection of cores can be outsourced such that the remanufacturers can put more focus on their main activities such as remanufacturing and analyzing the markets for remanufactured products. Therefore, there could be various structures for remanufacturing of cores, however, the most important part is making the return of cores and purchase of remanufactured product as attractive options for the customers.

1.5 Research Objectives

The objective of this research is to develop the control policies for remanufacturing, which are influenced by stochastic demand and supply, specifically the price, quantity and quality of cores and remanufactured products. The following are the specific objectives addressed in this thesis:

- Review of current literature on reverse logistics, remanufacturing, price and order quantity joint optimization
- Analyse transactions in remanufacturing and development of the framework for explanation of players roles
- Develop models for price and quantity for transactions of cores and remanufactured products among various actors in remanufacturing;
- Conduct numerical studies to implement to show the applicability of models .

1.6 Research Scope

The acquisition of cores and redistribution of remanufactured products are both challenging fields for the researchers and practitioners in remanufacturing, especially, when these two transactions are integrated.

This research focuses on the development of quantitative models of price and quantity policies for transactions in order to facilitate remanufacturing. Two transactions are established here: one is the transaction of cores and the other is the transaction of remanufactured products.

1.7 Contributions

The contributions of this research are as follows:

- Development of single period transaction model for cores from the collection centers;
- Development of single period transaction model for remanufacturing and redistributing remanufactured products, and;
- Development of multiple period transaction model for handling cores and remanufactured products.

1.8 Thesis Organization

This thesis is organized as follows:

- Chapter 1 introduces the basis on RL and product recovery process.
- Chapter 2 provides literature review reverse logistics and remanufacturing structure and networks and joint pricing and quantity models and economic analysis of remanufacturing. Research gap is presented at the end of the chapter.
- Chapter 3 presents the basis and the background for modeling framework.
- Chapter 4 presents a single period model for cores acquisition transaction between collection centers and the consolidation center.
- Chapter 5 presents a single period model for remanufactured products transactions between consolidation centers and the remanufacturing company.
- Chapter 6 presents an integrated, multiple-period model of transaction for cores and remanufactured products.

Chapter One: Introduction

- Chapter 7 provides the conclusions and future work.

CHAPTER 2

Literature Review

This chapter provides literature review pertaining to remanufacturing structures and networks, inventory management, and the transactions of cores and remanufactured products, price and order quantity joint optimization in forward supply chains, and economics of remanufacturing.

2.1 Structures and Networks

Geyer and Jackson (2004) identified that there are three key constraints faced in remanufacturing related reverse process:

- limited access to end-of-life products leaving the use phase;
- limited feasibility of end-of-life product reprocessing; and
- limited market demand for the secondary outputs from reprocessing.

The reverse logistics and forward supply chain structure, shown in Figure 2.1, classifies three levels of cores recovery according to the available reprocessing options. They are direct resale of reusable returns, economic reuse of recoverable returns, and recycle of end-of-life returns. The development of this type of structure helps in the design of network based on the implementations of different recoveries.

Fig 2.1 The structure of forward and reverse supply chain (Krikke et al., 2004)

Maslennikova and Foley (2000) presented the structure of Xerox to facilitate remanufacturing. Figure 2.2 gives the example of Xerox photocopy machine recycling, remanufacturing and disposal.

Fig 2.2 Xerox structures for the remanufacturing (Maslennikova and Foley, 2000)

The figure highlights that remanufacturing is done with strict quality control using certified reprocessing and pre-specified dismantling processes. Establishment of this type of structure helps company to work on network that support various processes such as delivering, remanufacturing, returning and disposing of cores.

Barros et al. (1998) presented the structure and network for recycling construction wastes in The Netherlands. The construction industry in The Netherlands produced 14 million tons of construction wastes per annum. The authors proposed a MILP model for the location of cleaning facilities and depots, their capacities and the material

flows based on stochastic demand for clean sands and stochastic supply of polluted sands.

Listes and Dekker (2005) extended the work of Barros et al. (1998) by considering uncertainties of demand locations and supply locations. The authors suggest that structures and networks should have flexibilities in order to cater for the balance of supply and demand.

Krikke et al. (1999a) studied the economics of network design for a type of photocopying machine in order to assess the feasibility of moving remanufacturing activities to a new location with low labor cost. The authors concluded that there may be no economic motivation (cost reduction) for location transformations as these may be other factors that influence the total cost of network and remanufacturing.

Guide et al. (2006) presented a study on the returns of HP inkjet printers and Bosch power tools. Although the planning time horizon was not limited to a single period, time value was considered as important to returns, since the product could lose as high as 30% of its price value on its way to the market. The authors found that centralized reverse logistics structures and networks could provide economics of scales while decentralization and small lots are better for quick response to demand for products like laptops and printers.

2.2 Planning and Control and Inventory Management for Remanufacturing

As per de Brito et al. (2003), there are five important aspects of reverse logistics: reverse logistics network structures, reverse logistics relationships, inventory management, planning & control of recovery activities, and IT for reverse logistics. Therefore, not only the structure but also the relationship to establish transactions for acquiring used products and distributing the recovered products are important to fulfill the objectives of reverse logistics.

Pokharel and Mutha (2009) provided a complete review of reverse logistics literature. The authors presented almost all existing literature on planning and control and inventory management for remanufacturing. The authors show that planning and control and inventory management for remanufacturing are the most difficult research topics and continuous efforts are required in the future.

In the next two sub-sections, the literature on planning and control and inventory management for remanufacturing are reviewed.

2.2.1 Planning and Control in Remanufacturing

Many researchers found that cores acquisition as a critical activity in remanufacturing (Jayaraman et al., 1999; Guide et al., 2003; and Guide et al., 2006). Guide and

Jayaraman (2000) proposed six important responsibilities of the acquisition of used products, which are:

- Identify and rate sources of cores;
- Forecast core availability;
- Start programs that balance return rates with demand rates;
- Track, forecast and use material recovery rates in determining purchase lot sizes;
- Forecast core availability and the associated material recovery rates, and; .
- Reduce the uncertainties in the timing of returns and the quantities of returns.

Maslennikova and Foley (2000) pointed out that the easiest way to acquire the returns is to get them around you. Xerox uses methods to take them back so that it prevents used products and cartridges from going out of its control. For example, using rental contracts instead of sales contracts and using prepaid envelopes, Xerox keeps the used photocopy machines and cartridges within its networks. Thus, Xerox does not need to worry too much about the acquisition of cores.

2.2.2 Inventory Management

Inventory management for remanufacturing and reverse logistics can be very much different from that for forward supply chain because the market for remanufactured

products is still growing. Both sides of remanufacturing, inbound and outbound transactions are characterized by uncertainties (Toktay et al., 2000). Inventory decisions balance the remanufacturing with stochastic demand. The literature on inventory management for remanufacturing is limited due to limited practice and theoretical studies for this topic.

Kelle and Silver (1989) discusses the return of reusable containers. As companies take back the containers and use them to satisfy future demand (put the new products into usable containers), these companies care about the return rate and return probability of these containers. The authors used the optimal method to plan the inventory of containers.

Many authors (such as Silver and Moon, 2001; Vlachos and Dekker, 2003; Mostard et al., 2005; Mostard and Teunter, 2006) have studied single period situation by combining new and old inventories for remanufacturing or recovery. However, remanufacturing generally happens on a multi-period context and therefore, inventories are accumulated in the logistics chain. In a multiple transaction situation, if there is an overflow of inventory, then the used products can be disposed to avoid the cost of obsolescence, while, if the inventory is lower than the expected demand, inventory cannot be disposed but new parts have to be procured in order to meet the demand.

Van der Laan et al. (1999) considered inventory control of hybrid systems (remanufacturing and manufacturing) for a single component durable product. The authors found that due to return uncertainty of cores and system interactions between manufacturing and remanufacturing, such a hybrid system becomes more difficult to control. Therefore, the valuation of inventories is important in adopting an inventory control policy in such cases.

Fleischmann et al. (2002) considered a single item inventory model for industrial reuse opportunities. The demand for recovered products and supply of returns were defined by Poisson distributions. The authors developed an optimal (s, Q) control policy based on demand and supply assumptions. The model was assumed as a first step toward systematic analysis of inventory management in reuse context.

Mahadevan et al. (2003) analyzed an inventory system with remanufacturing and manufacturing. They assumed demand for remanufactured products and supply of returned products as the Poisson processes. The model uses return rates, backorder costs and manufacturing and remanufacturing lead times. The authors developed bounds on the objective function, which was to minimize the total costs and these bounds were important constraints for heuristic solutions.

Teunter et al. (2002) defined the inventory decision for final phase of the product. As a products' life cycle might be over sometime, serviceable parts inventory was

required to be planned before the end of life (EOL). It was to estimate the return rate after EOL. The authors used a fixed planning time horizon and advised a decreasing order-up-to inventory decision for various intervals in the planning horizon. Moreover, they predicted the returns by using such a method, decreasing order-up-to inventory decision, companies are able to increase service levels for service parts in the final phase.

de Brito and Dekker (2003) analyzed return and demand distribution effort on the inventory control policy. The authors assumed the demand and return to follow homogeneous compound Poisson processes (HCCP) and assumed a negative exponential distribution of time lapse between return and demand occurrence. Their analysis shows that in case of short and long lag mixture returns and a dynamic environment, the general assumption of HCCP and negative exponential distribution may be rejected. In practice, the time lag should be noticed since environmental regulations and concerns do not permit the time lag when the general assumption is applied to the inventory control policy.

The review on inventory management shows that like in forward logistics, inventories are important in reverse logistics situations as well in order to cushion fluctuation in demand. However, inventory in a reverse logistics situation can become obsolete faster and may have to be disposed for recycling after a few period of transactions. This concept of inventory would be used in the development of multi-period model

presented in the thesis.

2.3 Price and Order Quantity Joint Optimization

Price and order quantity generally are viewed as separate decision variables in forward supply chains. Also, some authors only optimize either of them in order to achieve profit maximization. However, both price and order quantity decisions can be linked with each other for profit maximization simultaneously. In a remanufacturing situation, joint optimization of quantity and price for acquisition is more important as prices can reflect not only the quantity decision but also the stochastic nature of supply and demand. The research presented here aims at the joint price and quantity decisions for used products and remanufactured products transactions in remanufacturing environment. Joint price and quantity decisions for forward supply chain are reviewed here as the references of joint optimizations.

Whitin (1955) proposed one of the first models to combine inventory lot size (order quantity) problems with its price in order to obtain a higher profit. As demand for the product is a function of price of the product, the combination of price and lot size for profits maximization would depend on the demand function. The results showed that the maximized profit is decided by both price and lot size of products. Mills (1959) recognized that there should be a difference in decision making for profit maximization with or without uncertainty. The author analyzed the expected profit

maximization problem for a monopolist, who produced a single commodity and needed to make short run pricing and output decisions. The author found that if the marginal cost was constant then the equilibrium price of the commodity with demand uncertainty would be lower than that with a deterministic demand. The author also concluded that the uncertainty in demand was likely to induce an increase in price above the riskless level when a firm was producing the products near its capacity. These works of Whitin (1955) and Mills (1959) essentially started the realization that marketing considerations have to be combined with operational models and they need to be jointly optimized in order to achieve better performance of a supply chain.

Different kinds of uncertainties have been analyzed in joint optimization problems. Abad (1988) analyzed the uncertainty of a supplier offering all-unit quantity discounts. The author assumed demand as a decreasing function of price. The author used the EOQ model to find the optimal quantity and optimal price for either discrete or continuous discount plans.

Abad (1996) described another uncertainty problem, where backorder became necessary to avoid salvaging of unsold products. The author developed a dynamic model for pricing policy and lot size determination for such kinds of transactions. This model was extended further by Abad (1997) by considering temporary discount offered by a supplier to a powerful reseller (customer of the supplier). The author showed that forward buying by the reseller could be an option for maximizing profit.

Khouja and Park (2003) considered the price and order quantity for hi-tech products. Due to continuous launches of new generation products, the prices of hi-tech products tended to decrease gradually. They assumed that prices were decreased at the beginning of each period by a stable pattern and developed the EOQ model extension for continuous price decrease.

Khouja (1995, 2000) presented single period liquidation models for a single product in a single period with the possibility of changing the price within the period. Khouja (1995) assumed a predefined price change while Khouja (2000) assumed a demand driven price change. For either predefined or demand driven price change, the corresponding pricing and inventory policies were derived in these two papers.

Khouja and Mehrez (1996) considered the case of multi-product liquidation in a single period with changeable price within a period by using predefined price discounts. Similarly, Khouja (1999) reviewed the single period newsboy model and its extensions and concluded that the quantity and price decisions of the newsboy model should be coordinated for a maximized profit.

Petruzzi and Dada (2004) reviewed single period (newsboy) and pricing policies. This review was different from the last one because the authors focused on the explanations of additive and multiplicative demand and advised corresponding pricing methods. They presented structural results of optimal pricing policies rather than

technical improvement on computations. Both single and multi period models were shown in the paper, which could be viewed as an important complementary to other single period inventory models reviewed.

Khouja (2006) presented a single period promotion planning problem. As decision makers, retailers were required to plan the optimal price, rebate face value and order quantity for mail-in promotion. Rebate face value was taken as a new independent variable in the demand function. Two kinds of effects were considered in demand function, one with linear increase in demand with rebate value and the other with diminishing rebate effect. This paper provided instructive hints for rebate program for retailers and manufacturers. Decision makers were able to forecast the order (production) quantity when price rebate program was conducted.

Pricing policy is a key mechanism for dealing with demand and supply coordination. Literature provides different insights because of different assumptions for demand and supply, such as discount or rebate. For single period, the newsboy model is mostly utilized since the companies worry about the oversupply in single period, which can be much less value or even zero value at the end of period. Meanwhile, for multiple periods, EOQ and dynamic programming are very common as the balance of inventory cost and ordering cost is main concern over the periods. In this thesis, the development of models for remanufacturing environment take the pricing policies as the tool to control the transactions of used products and remanufactured products in

order to drive the demand for remanufactured products and the supply of used products. Furthermore, other than the balance of demand and supply by pricing and quantity mechanism in remanufacturing, value analysis of the economics of remanufacturing becomes the other objective of this thesis. In the following, literature on the economics of remanufacturing and reverse logistics is reviewed.

2.4 Economics of Remanufacturing and Reverse Logistics

Guide and van Wassenhove (2001) analyzed the management of product returns for remanufacturing by using Economic Value Added (EVA) model as shown in Figure 2.3. Analysis of economic value helps to understand the viability of remanufacturing or recycling of a particular product. EVA is not a new tool but the implementation for recovery business is a new field.

Guide and van Wassenhove (2001) studied cellular phone remanufacturing as an example illustrating the importance of product returns management. The impact of acquisition price on various parts of an organization is shown in Figure 2.4. The acquisition costs for remanufacturing and manufacturing are totally different due to different acquisition methods. The authors mention that there is a need for economic models for product acquisition management as most remanufacturing operations nowadays are still using traditional economic models.

Fig. 2.3 EVA calculations (Guide and van Wassenhove, 2001)

Guide and Pentico (2003) emphasized the importance of product acquisition, cost of acquisition and associated costs in remanufacturing. In any kind of take-back programs, the quality of returned products is also important if remanufacturing is to be considered (Inderfurth, 2001). Therefore, A quality based pricing policy for returned products is necessary because there is a need to establish the connections between quality and remanufacturing casts. Furthermore, core acquisition price is also related to expected demand for a remanufactured product with a particular selling price. Therefore, all these factors make used product acquisition the key to successful remanufacturing. The authors have proposed financial incentives as a driver to control quantity and quality of incoming used products for remanufacturing. However,

models for establishing such incentives have not been considered in literature. Therefore, in this thesis, various models are developed to assist in decision making for transactions of cores and remanufactured products.

Fig. 2.4 A simple view of the impact of acquisition price (Guide and van Wassenhove, 2001)

The literature in the last section on the joint optimization of price and inventory decisions for the forward supply chain highlights the fact that pricing and inventory contribute to the profitability of a production process. Thus, values along forward supply chain can be captured. However, in remanufacturing and reverse logistics, captured value is decided mainly by the pricing and quantity decisions of the transactions of used products and remanufactured products.

Ferrer (1997a) discussed the problem of used computer components reuse and tried to

identify the economic value of computer remanufacturing. The author described and analyzed the value of each component in used computers to model the cost structure of a remanufactured computer. The price of remanufactured computer was derived through an ordinary least square (OLS) regression model. The author did not consider the transactions of used computers and remanufactured computers. The purely mathematical cost model provided a way to value the used parts and cost the remanufactured computers.

Ferrer (1997b) presented tire remanufacturing as an example of capturing economic value from used products. Each activity associated with tire remanufacturing was analyzed and the associated costs were taken into consideration for calculating the profits of tire remanufacturing. The author concluded that tire remanufacturing was a feasible recovery option that could lead to cost savings and resource conservation.

Klausner and Hendrickson (2000) also analyzed the economic feasibilities of remanufacturing and recycling power tools. Because decision makers wanted to control the returns in terms of their return time, quantity and quality in order to balance the revenue and cost, a buy-back plan was designed. Such buy-back plans could be designed to provide discounts for new purchases or to provide a direct cash rebate. The authors looked at the remanufacturing cost and buy-back cost so that the feasible buy-back plan can achieve the objective of conserving the resources and earning the profits under the return probability and market demand for the

remanufactured power tools.

Teunter et al. (2000) analyzed the effects of different holding costs of inventory management when forward and reverse logistics situations coexist. Traditionally researchers set the inventory holding cost as a fixed rate regardless of the remanufactured, manufactured or returned non-serviceable items. This research included the opportunity cost rate for holding a returned non-serviceable item. The authors compared five traditional average cost methods by using different opportunity cost rates. In their analysis, holding cost of non-serviceable items is a function of the out-of-pocket holding cost, interest rate, and marginal cost of manufactured and remanufactured items. The authors concluded that their method can be a near-optimal discounted cash flow (DCF) solution.

Guide et al. (2003) provided probably the first published work that considered the prices of cores and modeled the corresponding quantities for different quality level used products. The authors used a production function and derived the first order conditions for optimal acquisition prices and quantities for used products. They assumed an unlimited return supply, remanufacturing capacity and market demand and encouraged the model extensions to relax these assumptions. Economic value of used cellular phone remanufacturing was presented in this paper as a case study with numerical validation of the model.

2.5 Summary and Research Gaps

The literature review shows that remanufacturing is an increasing phenomenon for both industrial and consumer products. Acquisition of cores and redistribution of remanufactured products eventually become two important transactions in remanufacturing. Structure and network are provided to support the infrastructure for acquisition and redistribution. Planning and control and inventory management of cores and outgoing remanufactured products support the material flows with suitable cost structure in terms of acquisition decision and redistribution decision. Joint pricing and quantity models are the good reference for the transactions management of acquisition and redistribution. Literature on economics of remanufacturing is dedicated to the value analysis of remanufacturing by mainly considering the transactions of acquisition and redistribution.

Specifically, there are still a lot of undeveloped areas of transactions in remanufacturing. This literature review presents that joint optimization of quantity and prices could be one of the ways to tackle the problem of pricing decisions under stochastic demand and supply. Although joint models have been developed for forward logistics situation, its suitability for remanufacturing situations has not been adequately studied. Furthermore, inventory of cores, parts and remanufactured products is another issue which will have profound impact on pricing decisions. In the cases of single period transaction, the inventory is salvaged or skipped at the end of

the period; while the case of multiple periods, the inventory is kept over periods. Especially, the inventory may include serviceable or non-serviceable. Therefore, multiple periods of transactions should consider demand, supply and inventory. In all above cases, they will all have an impact on pricing, which have been missed in the literature and need to be developed.

The above literature review identifies the gaps in remanufacturing situations in terms of the absence of generic economic models that jointly cater for the pricing of cores in the face of stochastic nature of cores return, stochastic quantity and quality of supply, and also the stochastic nature of demand for remanufactured products. As the demand for remanufactured products and cores vary from period to period, there is a need to establish a good acquisition and redistribution policy. Therefore, this research fills in the gaps in the area of transactions management for remanufacturing. The research models the transaction between the collectors and consolidators of cores and then evaluates the other transaction between the consolidators and remanufacturers in a single period situation. Based on the single period models, an integrated model is developed for multiple period transaction situations. Numerical studies have been carried out for each model to show their applicability. The contribution of this thesis comes from the analysis of transactions in remanufacturing and the modeling of transaction in remanufacturing. In order to maximize the remanufacturing profit, more values are captured through joint optimization of pricing and quantity decisions in remanufacturing.

CHAPTER 3

Modeling Framework

The literature review showed the research gap for the development of models for transactions of cores and remanufactured products. Therefore, a framework and basic assumptions required for the development of the models are discussed here. Specific assumptions required for the development of different models will be discussed later in the subsequent sections.

3.1 Remanufacturing Frameworks and Activities

Fig 3.1 Modeling Framework

There are five main players that take part in the transactions of remanufacturing. They are the customers of cores, the collection centers of cores, consolidation centers for cores, the remanufacturing company and the customers of remanufactured products as shown in Figure 3.1. First, the customers own cores and return them to the collection centers. The customers of cores are assumed to be motivated by economic incentive to return the cores and the customers of remanufactured products are attracted by lower prices to purchase the remanufactured products.

Customers need to return cores to designated locations called collection centers. Retailers or distributors can also act as collection centers. Collection centers accept cores, inspect them, and provide incentives to the customers according to the quality of their cores. The incentive is decided by the collection centers based on what they are going to receive from the consolidation center. However, this incentive is not under the focus of this study.

As the collection centers are dispersed, it is necessary to have the consolidation centers as intermediaries, which consolidate all the cores from several collection centers nearby, segregate them into different quality levels and then send them to the remanufacturing company. Depending on the decision making process at core collection level, the consolidation centers may eventually assign quality levels for cores. The consolidation center is also entitled to the planning of quantity and prices for core acquisition, specifically the quantity and price for each quality level core.

Although the incentives offered by the collection centers may be different for different customers at different locations, consolidation center has to offer the collection centers a standard price list for different quality cores. Since the remanufacturing company would like to obtain the sorted cores from the consolidation centers, the consolidation centers have the economic motivation to consolidate the cores from different collection centers. They are willing to provide the information on requisite quantity and price of each quality level core to the collection centers in order to obtain the core supply from them. The profit of running the consolidation centers comes from the difference between the prices offered by the remanufacturing company and the prices paid to collection center. As the fulfillment of the demand of the remanufacturing company is the main objective of the consolidation centers, and since the consolidation centers are also the decision makers in terms of cores acquisition transactions, the only way they could maximize their profit is by monitoring the quantity and quality of returned cores at the collection centers. In this regard, there is an uninterrupted exchange of information on the quantity and quality of cores between the collection centers and the consolidation centers. Furthermore, surplus cores are recycled and shortage are fulfilled by purchasing new parts

The remanufacturing company is an important player as it initiates and sustains the remanufacturing process. The remanufacturing company eventually needs to tackle the issue concerning quality levels since these quality levels have impacts on remanufacturing costs and the process. Moreover, it needs to decide on the quantity of

cores to be obtained from the consolidation centers, as well as provide a price to the consolidation centers for each quality level core required for remanufacturing. The remanufacturing company is the decision maker when it announces the prices and quantities to the consolidation centers for different quality level cores. However, the consolidation centers cannot predict the exact quantities of incoming cores of different quality levels, which are supplied stochastically by the collection centers. At the other end of the remanufacturing company, the retailers' demand is also stochastic, causing the remanufacturing company to engage in the difficult decision-making task of balancing the supply and demand. This is a general assumption for all the models developed hereafter. All the cores obtained by the consolidation centers can be remanufactured: one core can be remanufactured into one remanufactured product. Therefore, the remanufacturing company would have to rely on a mixture of both new and old parts as supplied by the consolidation centers. Although remanufacturing can use only the old parts from cores, it will require the disposal of many usable parts due to parts mismatch.

The retailers (or distributors) play the role of transferring the demand for remanufactured products to the remanufacturing company. Although retailers, like collection centers, are not explicitly modeled in this thesis, the access to information on demand for remanufactured products through continuous link with customers is a prominent feature that would help the decision maker, the remanufacturing company, to model a demand function and to decide on the quantities and price of cores

required for remanufacturing and the price of the remanufactured products.

The assumptions in the framework mentioned above will be shown during the development of the models, which will be based on two transactions: (a) the transaction among the collection centers, consolidation center and the remanufacturing company; (b) the transaction among the consolidation centers, the remanufacturing company and the retailers (distributors). These two transactions by five players are first analyzed with two single period models. The integration of single period models into a multiple period model mimics the continuous transaction that represents a remanufacturing chain.

3.2 Economic Incentive

As mentioned above, economic incentive is assumed to be the sole reason for customers to return cores and to buy remanufactured products. There could be other reasons, such as legislation and environmental awareness as mentioned by Fleischmann (2001), Rogers and Tibben-Lembke (1999), and de Brito et al. (2003a), but they are not considered in this thesis. Specifically, the economic incentives among different actors are the motivators to promote delivery of materials (cores and new replacement materials or parts). Guide et al. (2003) derived a model of economic incentives for remanufacturing. Although some researchers look at the economic factors of remanufacturing, pricing policy for inbound transaction and outbound

transaction of remanufacturing process is still an undeveloped field. In this thesis, the significant assumption is that pricing policy and quantity decision can jointly optimize the total profit from acquisition transaction, redistribution transaction and holistic transactions (integrating the acquisition and redistribution). The acquisition pays attention to the stochastic supply, while redistribution focuses on the stochastic demand and holistic transactions consider both stochastic nature of the supply of cores and the demand for remanufactured products.

3.3 Quality Levels of Cores

Quality levels were implicitly considered for cores in the past. Guide et al (2003) have proposed segregation of cores into different quality classes. The remanufacturing costs of cores vary with quality of cores. Therefore, there is a need to have a systematic method to classify the cores according to their quality. Cores can have n quality levels, 1 for the best quality and n for the worst quality. Any core above quality level 1 can be reused directly without remanufacturing, and any core below quality level n cannot be remanufactured, and should be sent to landfill or recycling. In this thesis, cores with quality above quality level 1 and below quality level n will not flow into consolidation centers from collection centers since all of them are either sent for reuse or disposal. Therefore, distinction of quality level for cores provides the best way to design the price policy for cores, namely pricing core according to its quality level. The assumption of quality levels for core classification is important to

pricing and quantity control policy for transactions. In this thesis, quality level system has been considered and utilized for developing models in order to relate the quality levels of cores with remanufacturing costs. Furthermore, the quality levels are also considered when planning prices and quantities for cores and remanufactured products simultaneously in their transactions.

3.4 Summary

In this chapter, framework for development of models for remanufacturing is discussed. Several important assumptions are given. The focus in this thesis is to analyze and derive a quality based core acquisition and remanufactured products transaction models so that the decision makers are able to achieve an economically viable remanufacturing. The management of core acquisition and remanufactured products transactions considers the price and quantity control policy jointly. Development of individual models is discussed in the following chapters.

CHAPTER 4

Model for Single Period Core Transaction

In this chapter, the first model for single period cores acquisition transaction is defined for three players of transactions. In this case, the consolidation center is assumed to be the decision maker. The center acquires the cores from collection centers and then sells to the remanufacturing company based on the demand for cores. The corresponding model is developed and the numerical study for three scenarios of cores supply situation are made at the end of this chapter

4.1 Basis for Transaction of Cores

The framework for the development of an analytical and mathematical model is shown in Figure 4.1 and is extracted from Figure 3.1. There are three transactions among the collection centers, consolidation centers and the remanufacturing company. The first transaction is between the remanufacturing company and the consolidation center. This center receives demand and prices for cores of different quality levels from the remanufacturing company, which is just looking at the remanufacturable cores plus replacement parts from the consolidation center in order to initiate its process. The second transaction is between the consolidation center and the collection centers to provide cores at a price fixed by the consolidation center by jointly considering the

demand for core, price of core and historical data on core collection. The third transaction is between the customers and the collection centers. These centers provide an incentive to returned cores.

Fig 4.1 Framework of Core Transaction

The determination of control policies for pricing different quality level cores and their corresponding quantities between collection centers and the consolidation center is our focus in the development of the model in this chapter. After knowing the price and quantity requirements from the remanufacturing company, the consolidation center decide on price of cores with respect to quality levels of cores and historical collection of cores. These prices and requisite quantity are communicated to the collection centers.

This action becomes the key to the transaction management.

For simplicity, without losing the essence of modeling, it is assumed that several collection centers supply the cores to one consolidation center and the consolidation center offer the same price for each cores of a certain quality to these collection centers. This consolidation center supplies to the remanufacturing company based on a predefined price list for different quality level cores and needs to fulfill a determined quantity for total cores regardless of quality level.

4.2 Assumptions of the model

The list of symbols to be used for the development of the model is given in Table 4.1.

Further specific assumptions are discussed next.

Assumptions:

1. Core supply at quality level n , S_n , is stochastic, but the demand for total quantity of cores, d , is fixed.
2. Core supply quantity at quality level n follows a probability density function $f(S_n)$ with known mean μ_n and standard deviation σ_n .
3. There are no initial inventories.
4. Cores in each quality levels require a predefined set of parts for remanufacturing. Therefore, the type and cost of new replacement parts for a

- core in a quality level , b_n , is predefined.
5. Core acquisition price p_n satisfies $r_o < p_n < P_o - b_n$, in order to promote the core collection and to avoid purchase of too many cores.
 6. It is assumed that core transaction is dependent only on the economic incentives. Therefore, any other non-economic conditions are not considered in the model.
 7. The model is developed by assuming consolidation center as the decision maker and the focus of transactions are only between the collection centers and the consolidation center, which receives a demand and price schedule from the remanufacturing company.
 8. Product updates or obsolescence is not considered.

Table 4.1: Notation and indices used for the development of the model

Symbol	Description
n	Quality level of cores, defined by the remanufacturing company, $n = 1, 2, \dots, N$
P_n	Price of a core with quality level n , offered by the remanufacturing company to the consolidation center
p_n	Core acquisition price for quality level n to be offered by the consolidation center to the collection centers. The cost of inspection and logistics is also included in this price.
q_n	Core acquisition quantity for quality level n by the consolidation center
b_n	Total costs of predefined replacement new parts required by one unit of quality level n core to be supplied to the remanufacturing company by the consolidation center
r_o	Salvage (recycle) value of surplus cores with any quality level
P_o	Penalty value for shortages of cores at any quality level, which is the same as the price of new product
d	Deterministic demand for cores of the remanufacturing company
C	Total cost of the consolidation center

S_n	Expected core supply quantity at quality level n
$f(S_n)$	Probability density function of core supply at quality level n
$F(S_n)$	Cumulative probability density function of core supply at quality level n
$N(\mu_n, \sigma_n)$	Mean value and standard deviation with normal distribution.
σ_n	Standard deviation of core supply, from collection centers to consolidation center, at each quality level n
$\lambda, \alpha_n, \beta_n$	Lagrange multipliers

4.3 Model Formulation

The model for core transactions between the collection centers and the consolidation center is developed here. The cost function, C , for total acquisition by the consolidation center can be written as,

$$C(p_n, q_n) = \sum_{n=1}^K \left[S_n p_n + b_n q_n + P_0 \int_0^{q_n} (q_n - S_n) f(S_n) dS_n - r_0 \int_{q_n}^{\infty} (S_n - q_n) f(S_n) dS_n \right] \quad (4.1)$$

where the first element is the cost of core acquisition to be paid to the collection center, the second element is the cost of new parts that are necessary to complete remanufacturing of a core at a certain quality level, the third element refers to the penalty cost to be incurred by the consolidation center when there are less than demanded quantities are obtained from the collection center, and the fourth element refers to recycling revenues due to recycling of the surplus supply. The constraints to (4.1) are:

$$\sum_{n=1}^K q_n = d \quad (4.2)$$

$$p_n \geq r_o \quad n=1, 2, \dots, N \quad (4.3)$$

$$p_n \leq P_o - b_n \quad n=1, 2, \dots, N \quad (4.4)$$

If $p_n = P_o - b_n$ is offered by the consolidation center to the collection centers, it is possible that quantity of cores received would be large and it will lower the profit to the consolidation center. However, if $p_n = r_o$ is offered, the collection centers may not be attracted to send the collected cores instead of recycling them by themselves. Therefore, Equations (4.3) and (4.4) define the range for core prices.

Optimization of Equation (4.1) provides the optimal quantity q_n and price p_n of cores at each quality level by balancing the incoming cores with the required demand quantities. Here, core prices, p_n , are chosen as a tool to adjust quantity balance. Rewriting Equation (4.1) in Lagrange form,

$$L = \sum_{n=1}^K \left[S_n p_n + b_n q_n + P_o \int_{q_n}^{q_n} (q_n - S_n) f(S_n) dS_n - r_o \int_{q_n}^{q_n} (S_n - q_n) f(S_n) dS_n \right] - \lambda \left(\sum_{n=1}^K q_n - d \right) - \alpha_n (r_o - p_n) - \beta_n (p_n + b_n - P_o), \quad (4.5)$$

where λ , α_n and β_n are Lagrange multipliers; λ providing the constraint on the total quantity of core acquisition, and α_n and β_n providing the lower and upper bound constraints on p_n .

The Kuhn-Tucker (KT) conditions are the commonly used method to define the quantity and price simultaneously (Kim and Lee, 1998). The first order KT conditions for Equation (5) with respect to the price and quantity are:

$$\frac{\partial L}{\partial p_n} = S_n + \alpha_n - \beta_n = 0 \quad (4.6)$$

$$\frac{\partial L}{\partial q_n} = B_n + P_o F(q_n) + r_o(1 - F(q_n)) - \lambda = 0. \quad (4.7)$$

Further,

$$\sum_{n=1}^K q_n = d, \quad \lambda \geq 0, \quad \lambda(\sum_{n=1}^K q_n - d) = 0 \quad (4.8)$$

$$r_o - p_n \leq 0, \quad \alpha_n \geq 0, \quad \text{and} \quad \alpha_n(r_o - p_n) = 0 \quad (4.9)$$

$$p_n + b_n - P_o \leq 0, \quad \beta_n \geq 0, \quad \text{and} \quad \beta_n(p_n + b_n - P_o) = 0 \quad (4.10)$$

Remarks:

- If $p_n = r_o$, and $p_n < P_o - b_n$, then $\alpha_n \geq 0$ (by Equation (4.9)) and $\beta_n = 0$ (by Equation (4.10)) in order to facilitate the core transactions. Otherwise, it will give $S_n \leq 0$ or strictly, $S_n = 0$, from Equation (4.6), meaning that there would be no return of cores from the customers. This happens because, if the collection centers are not provided with sufficient margin for their profit, they will provide a smaller incentive to the customers for cores and such an incentive may not attract any core from the customer. Consequently, consolidation center would not obtain any supply from the collection centers.
- If, $p_n > r_o$ and $p_n = P_o - b_n$ then $\alpha_n = 0$ by Equation (4.9) and $\beta_n \geq 0$ by Equation (4.10). Then from Equation (4.6), $S_n = \beta_n$, the Equation (4.10)). Such high prices can attract the return of more cores.

Therefore, the acquisition quantity, q_n , is obtained by simultaneously satisfying Equations (4.11) and (4.12), which are obtained from the KT conditions,

$$\sum_{n=1}^K q_n = d \quad (4.11)$$

$$F(q_n) = \frac{\lambda - b_n - r_o}{P_o - r_o} \quad (4.12)$$

From Equation (4.12) if $\lambda > P_o + b_n$ then the probability $F(q_n) > 1$ and if $\lambda < b_n + r_o$ then the probability $F(q_n) < 0$. For both cases, there are no solutions for probabilities.

Therefore, λ would vary between the two threshold values as given below.

$$P_o + b_n > \lambda > b_n + r_o \quad (4.13)$$

Cost minimization is the main target for the consolidation center and that can be obtained by identifying optimal quantities of different quality level. The critical probabilities for such optimal quantities balance at a point where the expected profit is equal to the expected loss for all cores. The unit expected profit by selling one more core can be obtained as,

$$F(q_n)(P_n - p_n) \quad (4.14)$$

Similarly, the unit expected loss of one more unsold core is,

$$(1 - F(q_n))(p_n - r_o) \quad (4.15)$$

Therefore, for profit maximization,

$$F(q_n)(P_n - p_n) = (1 - F(q_n))(p_n - r_o) \quad (4.16)$$

$$\text{Or, } F(q_n) = \frac{p_n - r_o}{P_n - r_o} \quad (4.17)$$

Equations (4.12) and (4.17) provide the joint optimization for acquisition price and quantity of cores and the following equation, where both λ and p_n are unknown.

$$\lambda = \frac{(p_n - r_o)(P_o - r_o)}{(P_n - r_o)} + b_n + r_o \quad (4.18)$$

4.4 Solution Algorithm

Based on Equation (4.12), the values for λ and corresponding quantities can be derived from the following steps:

1. Obtain the values for d , P_n , P_n , b_n and r_o as prescribed
2. Calculate a set of λ values from Equation (4.13)
3. Calculate $F(q_n)$ from Equation (4.12) for all n .
4. Calculate q_n for all n by using known μ_n and σ_n .
5. Use the information on the return of cores (μ_n and σ_n) to calculate the acquisition quantities by using distribution formula (for normal distribution,

$$\phi\left(\frac{q_n - \mu_n}{\sigma_n}\right) = F(q_n) \quad \forall n. \quad (4.19)$$

6. Calculate $\sum_{n=1}^K q_n$ and compare $\left|\sum_{n=1}^K q_n - d\right| \leq \varepsilon$, where ε refers to a small number chosen by the consolidation center. In this case, as we are looking at integer values, a difference of less than 1 may be acceptable. If $\left|\sum_{n=1}^K q_n - d\right| > \varepsilon$, then increase λ to $\lambda + \varepsilon_1$, where ε_1 is a step value, again decided by the consolidation center. This could be anything between 0.1 to 0.001 depending on the precision required in calculation.

- a. If $\sum_{n=1}^K \mu_n = d$, then it is possible to obtain an optimal quantities for each

quality level that satisfies $\sum_{n=1}^K q_n = d$.

- b. If $\sum_{n=1}^K \mu_n > d$, then there is an expected high supply situation thus requiring a lower λ (a value that is closer to the right hand side value of

Equation (4.13), which will force down the acquisition price for all n in order to match the demand to the best extent possible. However, depending upon the distribution, the acquisition quantities may not exactly match the demand. This shows stochastic nature of return situation which will have an impact on the prices and therefore, subsequently in the total cost.

- c. If $\sum_{n=1}^K \mu_n < d$, then there is an expected low supply situation thus requiring λ to be adjusted upwards, closer to the left hand side constraint of Equation (4.13). Similar to the case above, acquisition quantities may not exactly match the demand and it will increase the total cost of the system compared to that for condition where mean of the return and demanded quantities are equal.

7. Obtain $F(q_n)$ as provided in step 6 and calculate the acquisition price for cores for quality levels using Equation (4.17).

As the focus in this thesis is to evaluate acquisition prices and quantities jointly, we do not proceed with total cost calculation, which can be done rather intuitively. The application of the algorithm and the model is shown by using an example that uses simulated data based on the experience of the authors' work in supply chain systems. The remanufacturing companies, however, do have this type of data and can be extracted by using data mining.

4.5 Numerical Study

We assume the core types with $n=6$. The remanufacturing company requires $d=2000$ and offers a fixed price P_n schedule to the consolidation center. The consolidation center has a fixed $b_n, r_o=\$10, P_o = \100 and historical (or forecast) return data that is used to obtain optimal acquisition quantities, q_n and acquisition prices, p_n . The probability distribution of returned (or forecast) core of each quality level is assumed to follow a normal distribution. The values for P_n as offered by the remanufacturing company and b_n as assessed by the consolidation center are given in Table 4.2. As the quality of cores degrades, it will require more new parts and subsequently increase the value of b_n . Similarly, with lower quality products, the remanufacturing cost would be higher, therefore, a low purchase price is offered by the remanufacturing company for lower quality cores.

In Table 4.2, the threshold values of λ are calculated with $P_o + b_n > \lambda > b_n + r_o$ as mentioned in Section 4.4. The result shows that λ varies between 45 and 110, and for these two extreme values there are no solutions for probabilities as mentioned earlier. The optimal value of λ would lie in between these two extreme values. In a sense, λ defines the opportunity cost that will minimize the difference between the demand and the supply and therefore its higher value means higher demand compared to the return situation and vice versa.

Table 4.2: Data used for numerical study

Quality level	P_n (\$)	b_n (\$)	λ range
1	40	10	(20,110)
2	35	15	(25,115)
3	30	20	(30,120)
4	25	25	(35,125)
5	20	30	(40,130)
6	15	35	(45,135)

4.5.1 Sensitivity Analysis

Scenario where $\sum_{n=1}^K \mu_n = d$

The algorithm (Section 4.4) provides a value of $\lambda = 76.15$ that satisfies $\sum_{n=1}^K q_n = d$, the acquisition quantities of cores. With the optimal value for λ , p_n values are obtained.

In Table 4.3, solution for the numerical example for the ‘base case’ ($d=2000, \sum_{n=1}^6 \mu_n = d$) is shown. The table shows that in the case when the historical mean is equal to demand, it will provide the solution (that the return will match demand) with optimal cost. For the given distribution of returns, the collection center can make a good profit. This information is useful to the consolidation center to make a decision on profit level by adjusting acquisition prices. With these values the consolidation center can make a profit of more than 22%. It is to be noted that as the prices are fixed and announced to the collection centers based on the past return pattern, the total cost depends on the collected returns. Therefore, if there are changes in the return quantities from the levels shown in Table 4.3, the cost will be affected accordingly.

Table 4.3: Prices and Quantities for the base case, for $\lambda=76.15$

Quality level	μ_n	σ_n	$F_n(q_n)$	q_n	$p_n, \$$	$P_n, \$$	Price difference
1	500	40	0.6239	513	28.7	40	-28%
2	300	20	0.5683	303	24.2	35	-31%
3	300	18	0.5128	301	20.3	30	-32%
4	400	24	0.4572	397	16.9	25	-32%
5	200	12	0.4017	197	14.0	20	-30%
6	300	28	0.3461	289	11.7	15	-22%
Total	2000			2000			

Scenario where $\sum_{n=1}^K \mu_n > d$

In a real situation, demand and the mean will seldom match. Therefore, it may not be possible to obtain the values as provided in Table 4.3. To highlight this case, a scenario with historical mean larger than demand is considered here ($\mu_n = 2200; d = 2000$).

As mentioned earlier, a higher mean value would lead to the conclusion that there would be an expected oversupply of cores and therefore, there is a need to reduce the acquisition price from the levels that were proposed in earlier section. This is to avoid uncontrollable quantity of returns when prices are offered as that given in Table 4.3. Various price and quantities can be analyzed by choosing different values of λ within the given range (45, 110). As the return is expected to be higher, the opportunity cost of meeting the demand would also be higher, therefore, a lower value of λ is chosen to start the analysis. Various scenarios can be developed to obtain a set of scenarios to choose from as shown in Table 4.4. The analysis shows that when λ takes the lowest value, the lowest acquisition price is equal to the recycling revenues and therefore,

collection centers might recycle the cores by themselves and may not supply any of them to the consolidation center. This will reduce the total collected cores below the demand level. Therefore as mentioned earlier this value of λ should be avoided at all cost. The consolidation center can consider this sensitivity and possibly offer a higher acquisition price. The analysis shows that when $\lambda=74.5$, the collected quantities equals the historical mean, however, consolidation center would have to avoid it as the quantities so obtained are lot higher than demand.

Table 4.4: Scenario for quantity and prices for different λ with $\mu_n = 2200; d = 2000$.

$\lambda \rightarrow$	45	50	55	60	65	74.5
	Acquisition quantities for various values of λ					
q_1	472	479	486	493	500	493
q_2	382	386	390	393	397	403
q_3	299	303	307	311	314	320
q_4	466	473	479	483	488	496
q_5	275	280	285	288	291	295
q_6	0	176	182	185	189	193
Total	1892	2098	2128	2154	2177	2200
	Acquisition price for various values of λ					
p_1	18.33	20.00	21.67	23.33	25.00	28.00
p_2	15.56	16.94	18.33	19.72	21.11	23.61
p_3	13.33	14.44	15.56	16.67	17.78	19.78
p_4	11.67	12.50	13.33	14.17	15.00	16.50
p_5	10.56	11.11	11.67	12.22	12.78	13.78
p_6	10.00	10.28	10.56	10.83	11.11	11.61

After examining the scenarios, the consolidation center may want to set an acquisition price, say for the lowest cores at \$10.5, then Equation (4.18) can be used to obtain λ directly and subsequent optimal acquisition quantities and prices can be found by using the solution method given in Section 4.4. This is to note that due to stochastic nature of return, the supply may not match the demand exactly. Therefore, there would be an added cost due to a shortage or surplus of cores.

Table 4.5 is obtained by assuming $p_6 = \$10.5$, which is slightly higher than the revenues collected from recycling. For this price, $\lambda = 54$ from Equation (4.18). It is to note that both the mean and standard deviation values for each quality level in this scenario are different from that presented in Table 4.3, although the demand quantity is still the same. The analysis shows that if the minimum price is fixed, due to the dependency of acquisition quantities, the consolidation center may receive more cores. Therefore, it adds to the cost to the consolidation center. Choosing a lower value of p_6 may reduce the difference between the supply and demand. The consolidation center cannot control the supply situation, therefore, it should accept all the cores delivered by the collection center in a given time period. This type of purchase guarantee is important to give continuity to the remanufacturing business and to the long term relation between the collection centers and the consolidation center. What is important here is the indication that there would be a need to adjust acquisition prices if the volume of return needs to be adjusted when faced with a stochastic supply situation. However, this should be done prior to announcing the price schedule to the collection

centers.

Table 4.5: Price and acquisition quantity for $p_6 = \$10.5, \lambda = 54$.

Quality level	μ_n	σ_n	$F(q_n)$	q_n	$p_n(\$)$
1	500	48	0.37778	485	21.33
2	400	24	0.32222	389	18.05
3	320	22	0.26667	306	15.33
4	500	28	0.21111	478	13.17
5	300	16	0.15556	284	11.55
6	200	15	0.1	181	10.50
Total	2220			2122	

4.6 Summary

A model for obtaining the acquisition prices to be paid to the collection centers by the consolidation center after obtaining the demand for cores and respective prices from the remanufacturing company is considered here. In general the remanufacturing company is concerned with the continuity of remanufacturing and will provide the demand ahead to the consolidation center. This is outsourcing of cores collection and it avoids the remanufacturing investment for core collection and transport. By using the consolidation center, collection centers know what to collect, how much the business to generate and where to supply. The consolidation center will be liable for meeting all demand for cores and, therefore, it needs to devise better incentives to the collection centers.

The numerical study here identify that the matching of core supply and demand for cores require careful planning. Due to the nature of cores, acquired cores come with

different quality and their quantity is also difficult to forecast. At one end, core supply is uncertain, at the other end, the remanufacturing company requires a stable core supply. Therefore, the decision maker, the consolidation center, has to balance both ends. The model and numerical study also verify that the pricing mechanism is critical to the transaction of cores and the economic results of the core acquisition. The higher the core's price, the more supply the collection centers tend to provide. However, expected to the supply is in surplus, the core acquisition price tends to decrease correspondingly. Therefore, the setting of core acquisition price is difficult but the model presented here gives direction as to the use of analysis for making decision on optimal acquisition price and quantities of cores of different quality levels. This model helps in the development of integrated model discussed later.

CHAPTER 5

Model for Single Period Remanufactured Product Transaction

In the last chapter, core acquisition was studied by assuming that the collection centers have stochastic supply, the consolidation center is the decision maker and there is a fixed demand for cores by the remanufacturing company. However the demand for cores fluctuates with the demand for the remanufactured products. Therefore, the transaction between the consolidation center and the remanufacturing company should be analyzed to consider demand fluctuation and it is the focus of this chapter.

The framework for the development of the model is given in Figure 5.1, where the remanufacturing company is assumed as the decision maker. The remanufacturing company not only has to accept the supplied cores but also has a commitment to sell the remanufactured products to the retailers as per stochastic demand and at a planned price. Therefore, there are two types of decisions that need to be made by the remanufacturing company: the quantity and price of remanufactured products for retailers and the quantity and price of different quality cores to be obtained from the consolidation center.

Fig 5.1 Framework of Remanufactured Product Transaction

It is assumed that the remanufacturing company is able to assess the demand function for remanufactured products and can make decisions on price and quantity of remanufactured products based on historical demand data and the price of new products. Due to the uncertainty in demand quantity of remanufactured products, the determination of requisite order quantities and price of remanufactured product becomes challenging and is the focus of the model in this chapter.

The price of new product is an important parameter as customers generally compare the prices of new and remanufactured products before making a purchasing decision.

Although the consumer utility is not modeled here, the underlying principle to develop the model is clear; that is, the customers would only be attracted and show a preference for remanufactured products if there is a justified price difference between the new and remanufactured products.

5.1 Assumptions for the Development of the Model

The following additional assumptions are made for the development of the model and they are discussed below. Additional symbols used for the development are of model given in Table 5.1.

Table 5.1 Notation and Indices Used in the Development of the Model

$\overline{PR}$	Price of remanufactured product charged to the retailers by the remanufacturing company
D	Demand for remanufactured products
$f'(D)$	Probability density function of remanufactured product demand
$F'(D)$	Cumulative probability density function of remanufactured product demand
$\mu(D)$	Mean of remanufactured product demand
$\sigma(D)$	Standard deviation of remanufactured product demand
P	Price of new product
C_{in}	Unit inspection cost of quality level n cores
C_{dn}	Unit disassembly cost of quality level n cores
C_r	Unit remanufacturing cost
L	A ratio between price of new product and that of remanufactured product

$g(P_n)$	Average unit cost of one core to the remanufacturing company
k	Coefficient between price of remanufactured products and average unit cost of one remanufactured product, $k \cdot g(P_n) = \overline{PR}$
K	Probability of sales of remanufactured products
a, b, e	Constant
$n(z)$	Probability density function of standard normal distribution
$N(z)$	Cumulative probability density function of standard normal distribution
A	Actual sales quantity

- 1) The quality of all remanufactured products is ‘as good as new’ and with consistent. In retrospect, all cores within a quality level have the same quality;
- 2) The surplus remanufactured products are salvaged at the recycle revenue r_0 ;
- 3) If there are shortages in supplying of remanufactured products to the retailers, then the remanufacturing company will have to provide the retailer with new products of same type or agreed type to meet the shortfall. Therefore, the price of new products is the main factor here and it is assumed as a penalty for shortages of remanufactured products. Similar assumptions are also made by Bayindir et al (2007). This assumption will assure the retailers of obtaining products; .
- 4) As batch production is being considered for remanufacturing, the lead time for supplied cores to the remanufacturing, the lead time for remanufacturing, and the lead time to supply remanufactured products to the retailer is not considered here;

- 5) There are no remanufacturing capacity constraints;
- 6) Product obsolescence is not considered here. It is also assumed that remanufactured products would always be able to compete with equivalent new products.

5.2 Model Formulation

The profit of the remanufacturing company depends on the price paid for core acquisition, cost to purchase new parts and the revenue obtained from remanufactured products. The profit function (Π) for joint optimization of price and quantities can be written as,

$$\Pi = \overline{PR} \cdot A + r_0(A - Q) + P(A - D) - C_r Q - \sum_{n=1}^N (C_{dn} + C_{in} + B_n + P_n)q_n \quad (5.1)$$

Subject to,

$$A = \min(Q, D) \quad (5.2)$$

$$Q = \sum_{n=1}^N q_n \quad (5.3)$$

$$P > \overline{PR} > P_n > r_0 \quad (5.4)$$

The first term on the right side of equation (5.1) represents the revenue from selling the remanufactured products; the second term accounts for the revenue of surplus remanufactured products, if any; the third term represents the penalty if any shortfall to meet the demand; the fourth term represents the remanufacturing cost and the last

term represents the costs of disassembly, inspection, replacing failed parts and acquisition price. Equation (5.2) shows the actual sales quantity A of the remanufactured products; equation (5.3) represents the supply balance equation and equation (5.4) represents the price constraints. The prices of remanufactured products are considered to be less than those of brand new products. Using the example of photocopiers, Maslennikova and Foley (2000) mentioned that the price of reconditioned photocopy machines was around 30% lower than that of brand new photocopy machines. As there are segmented markets for remanufactured products (Bayindir et al., 2007), the economic motivation to supply and purchase the remanufactured products should be the price difference between new and remanufactured products. The expected value for A can be written as shown in Equation (5.5) as it is influenced by the probability distribution of the stochastic demand.

$$E(A) = \int_0^p Df'(D)dD + \int_p^{\infty} Qf'(D)dD \quad (5.5)$$

5.2.1 Demand Analysis

The demand for remanufactured products is exogenous and is influenced by the relative price difference between remanufactured products and new products. It is assumed that higher relative price difference between new and remanufactured products would create a market for the sale of remanufactured products. An additive demand function is developed in Equation (5.6) based on historical information,

$$D = a - b\overline{PR} + e(L \cdot P - \overline{PR}) \quad (5.6)$$

where,

$$\mu_D = a - b\overline{PR} \quad (5.7)$$

In Equation (5.6), the values of a , b and e are derived by the observation of demand pattern and can be obtained from the regression of the historical data. It is assumed that the price of remanufactured products is preset by the remanufacturing company as a fraction L of new product price P , shown in Equation (5.6). Price P for the new product is exogenous to the model. If $\overline{PR} > L \cdot P$, then it leads to a negative contribution to demand, which means that higher price of remanufactured products can reduce the demand for them. If $\overline{PR} < L \cdot P$, then it leads to a positive contribution to the demand, which means adversely that lower price of remanufactured products attract people to buy them. When $\overline{PR} = L \cdot P$, demand is based on the prices of remanufactured product and new product. Due to the price change of remanufactured product and new product, the last term at the right side of Equation (5.6) can be either positive or negative. Thus, the last term is assumed as random with the standard deviation, σ_D , and this random term follows the normal distribution with mean value equal to zero. The first term and last term at the right side of Equation (5.6) form an additive demand. The additive demand follows the normal distribution as well with the mean value, $a - b\overline{PR}$; and with the standard deviation, σ_D . Further, the price of new products has a positive effect $\left[\frac{\partial D}{\partial P} = eL \right]$ and the price of remanufactured products has a negative effect $\left[\frac{\partial D}{\partial PR} = -(e + b) \right]$ on the demand for remanufactured products.

These two derivatives indicate that the demand would change based on the prices of

remanufactured product and new product.

5.3 Solution Algorithm

The expected value of the profit function (5.1) depends on the expected demand for the remanufactured product; therefore it can be rewritten as,

$$E(\Pi) = (\overline{PR} E(A) + C_h E(A) + P\{E(A) - E(D)\} - (C_h + C_r)Q - \sum_{n=1}^N (C_{dn} + C_{in} + P_n + B_n)q_n) \quad (5.8)$$

where,

$$\begin{aligned} \Pi &= \overline{PR} \cdot D - r_0(Q - D) - C_r Q - \sum_{n=1}^N (C_{dn} + C_{in} + B_n + P_n)q_n \quad \text{for} \quad Q > D; \\ &= \overline{PR} \cdot Q - P(D - Q) - C_r Q - \sum_{n=1}^N (C_{dn} + C_{in} + B_n + P_n)q_n \quad \text{for} \quad D > Q; \\ &= \overline{PR} \cdot Q - C_r Q - \sum_{n=1}^N (C_{dn} + C_{in} + B_n + P_n)q_n \quad \text{for} \quad D = Q. \end{aligned}$$

When $Q > D$, there is a surplus revenue for the surplus units and when $D > Q$, there is a penalty for shortages. The condition $D = Q$ is ideal for the design of pricing mechanism. On the demand side, the requisite order quantity is driven by the prices of remanufactured product and new product. On the supply side, differential prices are offered for designated quality levels of cores. Thus, $E(\Pi)$ should be maximized through three variables, Q , $\overline{PR}$, and P_n . For the given optimal values of $\overline{PR}^*$ and P_n^* , referring to Appendix III for the detail derivative,

$$Q^* = F^{-1}(K^*)$$

$$K^* = \frac{\overline{PR}^* - g(P_n^*) - C_r + P}{\overline{PR}^* - r_0 + P} \quad (5.9)$$

where $g(P_n)$ represents the average unit cost of one core and is written as,

$$g(P_n) = [\sum_{n=1}^N (C_{dn} + C_{in} + P_n + B_n)q_n] / Q \quad (5.10)$$

The two variables $g(P_n^*)$ and $\overline{PR}^*$ in Equation (5.9) form certain relationship in order to reflect the cost before remanufacturing and potential revenue after remanufacturing, thus to achieve the optimal acquisition quantity.

Setting $k \cdot g(P_n) = \overline{PR}$, with k as a decision making parameter by the remanufacturing company, acquisition quantities for various values of k can be obtained if k is assumed.

It is worth noting that a higher value of k suggests a lower acquisition price to be paid to the consolidation center. It is noted that when $k = 1$, the unit cost of one core would be equal to the price of remanufactured products, $g(P_n) = \overline{PR}$, and it would not be attractive for the remanufacturing company to purchase cores. Replacing $g(P_n^*)$ in

Equation (5.12), we have

$$K = \frac{\overline{PR}^* - (\overline{PR}^* / k) - C_r + P}{\overline{PR}^* - r_0 + P} \quad (5.11)$$

As $\overline{PR}^*$ and k are set by the remanufacturing company, the value of K , the probability of remanufactured product sales, can be obtained from Equation (5.9). The order quantity is decided directly by the value of K ($0 < K < 1$), the mean, and the standard deviation of normal distribution. This means that the order quantity would increase with increasing value of K . However, for given values of C_r , r_0 and P , the value of K is decided by $\overline{PR}^*$ and k , therefore, setting values for these two parameters become

critical in deciding the remanufactured acquisition price and obtaining profits.

To achieve acquisition prices for different quality level cores, given the deterministic costs of inspection, disassembly and replacement of new parts, the costs for different quality level cores must satisfy,

$$C_{d1} + C_{i1} + P_1 + B_1 = C_{d2} + C_{i2} + P_2 + B_2 = \dots = C_{dn} + C_{in} + P_n + B_n \quad (5.12)$$

By using Equation (5.12), we can obtain the prices and quantities that optimize acquisition costs for profit maximization. In order to relate the demand function with expected sales of remanufactured products, Equation (5.5) is rewritten as,

$$E(A) = \mu_D N(z) - \sigma_D n(z) + Q[1 - N(z)] \quad (5.13)$$

where $z = (Q - \mu_D) / \sigma_D$, $n(z)$ and $N(z)$ are standard (0,1) PDF and CDF respectively.

When $Q = Q^*$ and $z = z^*$, based on $z = (Q - \mu_D) / \sigma_D$, optimal values for order quantity and z can be related as

$$z^* \sigma_D + \mu_D = Q^* = F^{-1}(K) \quad (5.17)$$

Since $z^* = N^{-1}(K)$, we can rewrite Equation (5.16) as

$$E(A) = \mu_D K - \sigma_D n(z^*) + Q[1 - K] \quad (5.18)$$

Therefore, expected sales of remanufactured product, $E(A)$, is based on the mean and standard deviation of normal distribution of historical data, and probability of sales of remanufactured products, K . The expected revenues for the remanufacturing company

would also change with a change in the sales of remanufactured products.

5.4 Numerical Study

A numerical study is conducted to replicate the cores and remanufactured products transaction situation in a remanufacturing context. The remanufacturing company as the decision maker needs to decide the prices of different quality level cores and the remanufactured products. Based on market demand, the other assumptions for the numerical study are as follows:

- $L = 0.7$ is set by assuming that the price difference will attract customers to buy the remanufactured products;
- The price of new product is assumed as $P = \$100/unit$;
- $C_r = \$10/unit$, $r_0 = \$5/unit$ and the penalty for potential shortages is $P = \$100/unit$;
- $\sigma_D = 200$ units and $\mu_D = 3600$ units, $a = 5000$, $b = 20$ and $e = 10$ based on historical data, (see Appendix II for details); and
- Consistent with earlier chapter, six quality levels are assumed for disaggregating cores.

Various costs for different quality levels are given in Table 5.2. While disassembly cost for cores is assumed as constant, the cost of inspection is variable subject to the quality levels of cores. The poor quality cores require less inspection for their

disassembled parts, versus good quality cores. Depending on the quality of cores, costs of replacing failed parts would also change. In general, it is better for the remanufacturing company to have a bulk of good quality cores than the bad ones.

Table 5.2 Costs (\$/unit) for Cores at Different Quality Levels

Quality level	Disassembly cost, C_{dn}	Inspection cost, C_{in}	New parts cost, b_n	Total
1	3	8	3	14
2	3	7	5	16
3	3	6	8	17
4	3	5	10	18
5	3	4	13	20
6	3	3	15	21

As mentioned earlier, $P_n > r_o$. Therefore, the minimum average cost $g(P_n) > 26$. However, as $\overline{PR} < P$, we can write that $26 < g(P_n) < 100$ or $1 < k < 3.8$. The analysis at $\overline{PR} = 70$, given in Table 5.3, shows that when the value of k is low (i.e., $k \leq 1$), the transaction would cause a loss to the remanufacturing company. With increased value of k , remanufacturing option becomes more attractive. The value of $k = 3.8$ yields the maximum profit for the remanufacturing company. Therefore, this finding verifies that the remanufacturing business can be profitable if cores can be obtained at low prices. An option is to promote collections through different channels in order to increase the financial viability of remanufacturing.

Table 5.3 Profit Values when $\overline{PR}=70$, $C_h = 5$, $P = 100$

k	$\overline{PR}$	K	z	Q^*	$Profit$
1	70	0.545455	0.114185	3623	-49078
1.5	70	0.686869	0.486994	3697	36307
2	70	0.757576	0.698526	3740	79685
2.5	70	0.800000	0.841621	3768	105961
3	70	0.828283	0.947401	3789	123595
3.5	70	0.848485	1.029957	3806	136254
3.8	70	0.858054	1.071618	3814	142270

The effect of fixing the value of $k = 2.5$ but changing the value of $\overline{PR}$ is shown in Table 5.4. When k value is fixed, the analysis of profit level of the remanufacturing company discloses the sensitiveness of the price change, which influences the profit level. It shows that the remanufacturing company is able to modify the price of remanufactured products when cores supply is stable in terms of cost in order to compete with new products in the market. Thus, the results obtained from the analysis with the model show that when $g(P_n)$ is fixed, the demand quantity would decrease with increasing price of remanufactured products and it will lead to a decrease in the profit level. Due to the decreasing demand quantity and increasing price of remanufactured products, requisite core quantity also decreases. This can be clearly identified through Equation (5.14).

Table 5.4 Profit Values when $k=2.5$, $C_h = 5$, $P = 100$

k	$\overline{PR}$	K	z	Q^*	$Profit$
2.5	60	0.81290	0.888646	3978	112595
2.5	65	0.80625	0.864160	3873	111828
2.5	70	0.80000	0.841621	3768	110467
2.5	75	0.79411	0.820792	3664	108512
2.5	80	0.78857	0.801474	3560	105961
2.5	85	0.78333	0.783500	3457	102815
2.5	90	0.77837	0.766728	3353	99073

Results shown in Tables 5.3 and 5.4 prove the fact that profit will increase if the remanufacturing company spends less on core acquisition. Similarly, if a remanufacturing company is able to reduce the price of remanufactured products compared with the price of new products, it will lead to an increase in the demand of remanufactured products. However, all the above is subject to the assumptions that the price of new products is fixed and the demand for remanufactured products follows the demand function.

The relationship between the price of remanufactured products $\overline{PR}$ and the prices offered to the consolidation centers, P_n , for $k = 2.5$ is given in Figure 5.2. The figure

shows that when $\overline{PR} = \$65$, P_n for worst quality core is equal to r_o . If the price of remanufactured product is too low, this will also have an impact on the price of core acquisition. Also, P_n decreases with the decreasing price for all choices of $\overline{PR}$. Therefore, the remanufacturing companies are always searching the cheapest cores in the market in order to amplify the margin. That is the remanufacturing company is able to decide the cores acquisition quantity and remanufacturing quantity through planning the variables, k and $\overline{PR}$.

Fig 5.2 Relationship between PR and P_n ($k=2.5$)

5.5 Summary

The transaction between the consolidation center and the remanufacturing company, in order to decide on core prices to be paid to the consolidation center when faced

with stochastic demand and supply was the focus in this chapter. The setting of price of remanufactured products drives the demand for remanufactured products and the quantity of cores to be obtained from the consolidation center. Although lower price of remanufactured products can increase the demand, it is to note that there is a limit to adjust the price of remanufactured products as it also should reflect the collection cost and the incentive that are subsequently paid to the individual customers. Lower price of remanufactured products will result in lower acquisition price and it will subsequently lead to lower incentive to the customer making the return of cores economically unattractive as shown in Chapter 4. Therefore, decision makers should look into the pricing and quantity decision holistically and for more than one transaction period. Next chapter focuses on such a longer term transaction.

CHAPTER 6

Multi Period Integrated Model for Transactions

Analytical models for core flow from sparse collection centers to the consolidation center and from the consolidation center to the remanufacturing company were discussed in the earlier chapters. In a remanufacturing situation, both supply and demand of cores cannot be controlled and they are stochastic in terms of quantity and quality of incoming cores. Therefore, it is necessary to integrate the whole process of acquisition and redistribution if the remanufacturing company has to handle a complete reverse logistics operation: acquisition, remanufacturing and redistribution. Moreover, as remanufacturing is not a one-time operation, the remanufacturing company might have to assure the core supply beyond a single transaction. This will help to sustain a continuous collection at the collection center (or consolidation center) and the delivery at the time of need by the remanufacturing company. This will optimize the profit for the whole reverse logistics chain in which the remanufacturing company acts as the centralized decision maker. Therefore, the need for an integrated model is not overemphasized.

6.1 Multiple Period Integrated Model for Transactions

Remanufacturing is used to restore used products into 'as good as new' conditions.

However, there is a limited life cycle for each generation of products due to obsolescence and due to product worn-out. The remanufacturing company has to consider this limited life cycle since the remanufacturing for each generation products also could be limited due to their limited life cycle and recoverable values at different stages. Therefore, a finite planning horizon has to be assumed for an integrated model in order to cater to a particular type of product.

Similarly there could be large difference between supply of cores and demand for remanufactured products. For example, during the introduction stage of a new product, there are few cores available. Remanufactured products can be quite expensive because new products are very expensive at that stage. However, beyond a stipulated planning horizon for remanufacturing, there is no economy of scale to remanufacture this generation of products as the market becomes flooded with the next generation of products and remanufacturing of new generation of products may become economically feasible. Therefore, ideally remanufacturing is a good option for products with relatively longer lifecycle. Therefore, products such as mobile phone, which has a relatively short life cycle due to obsolescence in a market, are also being remanufactured for another market. As the volumes of such products grow, it can drive demand upwards in the secondary market thereby creating a new demand for remanufactured products.

In order to facilitate core transactions, the finite planning horizon is divided into

different periods. The transaction control parameters are valid for one period as it is assumed that the market situations will not change too much within a single period. In the integrated model, it is important that decisions for prices and quantities are periodical. That is, the acquisition quantities, core prices and the price of remanufactured products are reviewed at the beginning of each period based on the feedback obtained in the last period (if any). It is assumed that a simultaneous decision is made regarding the order quantities for different quality level cores, the corresponding prices for each quality level core, and a suitable price set for remanufactured products at the beginning of each period. Acquisition quantities and prices for different quality level cores are decided according to historical information on supply and demand of different quality level cores. Meanwhile, remanufactured products are sold as alternatives to new products and the demand for remanufactured products depends on the prevailing prices of remanufactured products and new products.

Figure 6.1 describes the framework for this integrated model. There are two inventory bins, one is serviceable inventory and the other is non-serviceable inventory. Serviceable inventory, inventory of remanufactured products, is used to fulfill the demand for remanufactured products. Cores are non-serviceable inventory. and cores are stored at non-serviceable inventory. Further decisions will need to be made for new products addition to serviceable inventory or disposal of surplus cores from non-serviceable inventory.

Fig 6.1 Framework for an Integrated Model

The following are the additional assumptions made for the development of the integrated model. Similarly, additional symbols used for the integrated model are given in Table 6.1.

Table 6.1 Additional Notation and Indices Used for the Development of the Model

Q_t	Expected value of demand for remanufactured products, D_t , in period t , $E(D_t) = Q_t$
$\overline{PR}_t$	Price of remanufactured products in period t
D_t	Demand for remanufactured products in period t
u_t^D	Random term of demand for remanufactured products in period t
$\psi(\cdot)$	Probability density function of random term u_t^D
$\phi(\cdot)$	Cumulative probability density function of random term u_t^D
$P_{\min}$	Lowest possible unit price of remanufactured products
$P_{\max}$	Highest possible unit price of remanufactured products

x_t	Quantity of remanufactured products on hand at the remanufacturing company at the beginning of period t
z_t	Expected quantity of remanufactured products on hand at the remanufacturing company at the end of period t
y_t	Remanufactured quantity of cores by the remanufacturing company at the end of period t
$I_{s,t}$	Serviceable inventory (remanufactured products) position at the end of period t
$I_{non,t}$	Non-serviceable inventory (cores) position at the end of period t
c_t	Average unit core and remanufacturing cost in period t
θ	Discount factor, is equal to 0.9
C_h	Holding cost per unit
$R(Q_t)$	Expected revenue from serviceable inventory
δ_t	Constant in period t , it can be different in different period
$\Pi(\cdot)$	Expected total profit over periods
γ_t	Constant in period t , it can be different in different period
$q_{new,t}$	New product supply quantity in period t
$q_{d,t}$	Quantity of disposed cores in period t
$S_{n,t}$	Quantity of different quality level, $n=1 \dots N$, core supplies in period t
H	Non serviceable inventory capacity

This model represents multiple period transactions of the remanufacturing company.

It presents the way that the remanufacturing company manages the serviceable and non- serviceable inventory.

In addition to assumptions mentioned earlier, the following assumptions are needed for the development of integrated multi period model,

- Demand is stochastic, so is the supply;
- There are constraints in terms of supply and demand;
- Core return is independent of demand;
- Revenues and costs in future periods are discounted with a discount factor $\theta \leq 1$.

The demand for remanufactured products and supply of different quality level cores in consecutive periods are assumed independent and nonnegative. It is assumed that demand for remanufactured product in period t is decided by the price of remanufactured products and a random term.

$$D_t = r(\overline{PR}_t) + u_t^D \quad (6.1)$$

where u_t^D is a random term with known distribution in period t . It is assumed that $(u_1^D, u_2^D, \dots)$ is a sequence of independent identically distributed (i.i.d.) variables with zero mean, which have a continuous density function $\psi(\cdot)$ and a cumulative distribution function $\phi(\cdot)$:

$$\phi(u) = \int_{-\infty}^u \psi(u_t^D) d(u_t^D) \quad (6.2)$$

The expected value of demand is,

$$Q_t = r(\overline{PR}_t) = E(D_t) \quad (6.3)$$

where $\overline{PR}_t$, the price of remanufactured products in period t and set by the remanufacturing company, and is confined to a finite interval $[P_{\min}, P_{\max}]$,

$$P_{\min} \leq \overline{PR}_t \leq P_{\max} \quad (6.4)$$

$P_{\min}$ is the lowest possible unit price to be charged and $P_{\max}$ is the highest possible unit price to be charged. In the case of $P_{\min}$, it should be equal to total costs of obtaining a core and converting it into a remanufactured product. It is reasonable to announce that $P_{\max}$ is equal to the price of a new/equivalent product. The remanufacturing company would not offer the remanufactured product with a price lower than cost incurred on it.

The quantity of remanufactured products at hand in the beginning of period t , x_t , is used to fulfill the stochastic demand during period t . While, remanufactured quantity of cores at the end of period $t-1$, y_{t-1} , is accumulated throughout the period. It is assumed that the remanufacturing company acquires the cores and accumulates the quantity throughout one period and releases the quantity y_{t-1} at the end of period $t-1$ and remanufactures them instantly, to fulfill the demand in the next period t . Moreover, the model also include these two inventory positions, namely non-serviceable cores and serviceable remanufactured products, $I_{non,t}$ and $I_{s,t}$ respectively. Thus, we can obtain,

$$x_{t+1} = x_t - (Q_t + u_t^D) + y_t + q_{new,t} = I_{s,t} + y_t + q_{new,t} \quad (6.5)$$

$$I_{non,t} = I_{non,t-1} + \sum_{n=1}^N S_{n,t} - y_t - q_{d,t} \quad (6.6)$$

In Equation (6.5), the quantity of remanufactured products at hand in the beginning of period $t+1$ is equal to the summation of inventory position at the end of period t , remanufactured quantity of cores at the end of period t and new product supply quantity in period t , if any. This quantity at hand, x_{t+1} , is available for sales in period

$t+1$. Since $u_1^D, u_2^D, \dots$ is a sequence of independent identically distributed random (i.i.d.) variables, $x_1, x_2, x_3, \dots$ is also a sequence of independent identically distributed (i.i.d.) random variables. When $I_{s,t} + q_{new,t} \geq 0$, there will be no shortage at the end of period t because new products can be taken in to fulfill the demand during period t . The remanufacturing quantity of remanufactured products, y_t , is only available for use in the next period and released from non-serviceable inventory at the end of this period t . Therefore, in Equation (6.6), inventory position of non-serviceable inventory at the end of period t , $I_{non,t}$, is equal to non-serviceable inventory position at the end of period $t-1$, $I_{non,t-1}$, plus total core supplied during period t , $\sum_{n=1}^N S_{n,t}$, and minus the remanufacturing quantity of remanufactured products at the end of period t , y_t , and disposal quantity, $q_{d,t}$, if any, within this period t .

The revenue from serviceable inventory in period t is defined as $R(Q_t)$ and the price of the remanufactured product drives the expected value of demand for the remanufactured, thus obtain,

$$Q = r(\overline{PR}_t) \text{ can be rewritten in the form of } \overline{PR}_t = r^{-1}(Q);$$

$$\text{Then, revenue, } R(Q_t) = Q_t \cdot r^{-1}(Q_t)$$

Here, it is assumed that the expected revenue $R(\cdot)$ is twice differentiable and strictly concave. Concave here means that there is an optimal value Q_t for the maximization of revenue.

6.2 Solution Algorithm

Now the demand side is analyzed and a discount dynamic programming function is proposed. The discounted profit is,

$$\begin{aligned} \Pi(x) = \max_{Q,y} \{ & R(Q_t) - C_h[x_t - (Q_t + u_t^D)]^+ - P[x_t - (Q_t + u_t^D)]^- \\ & - c_t \cdot y_t + \theta[\Pi[x_t - (Q_t + u_t^D) + y_t + q_{new,t}]] \} \end{aligned} \quad (6.7)$$

In Equation (6.7), the last element on the right hand side is the next period profit, which is entitled to a discount factor θ , and all the other elements before it indicate costs and revenue at the end of the current period t . Equation (6.7) is the objective function of this model.

Defining a new variable $z_t = x_t - Q_t + y_t$, which is the expected quantity of remanufactured products at hand at the end of period t , then replacing z_t in Equation (6.7), we then obtain Equation (6.8),

$$\begin{aligned} \Pi(x) = \max_{Q,z} \{ & R(Q_t) - C_h[x_t - (Q_t + u_t^D)]^+ - P[x_t - (Q_t + u_t^D)]^- - c_t Q_t \} \\ & + c_t x_t + \{ \theta[\Pi[x_t - (Q_t + u_t^D) + y_t + q_{new,t}]] - c_t \cdot z_t \} \end{aligned} \quad (6.8)$$

where the maximization is now over Q and z . The problem hereafter becomes the maximization over Q and z in the current period t . Here, optimal z_t is the unique solution of the derivative of $\Pi(x_t)$ with respect to z ,

$$\theta \cdot E[\Pi'(z_t - u_t^D + q_{new,t})] = c_t \quad (6.9)$$

The maximization over Q_t can be derived through two separate functions. They are sales-response function and supplies-response function. Denoting the sales-response function $g_{sales}(Q_t/x_t)$, it is the first part of Equation (6.8),

$$\begin{aligned} g_{sales}(Q_t/x_t) = & R(Q_t) - C_h \int_{-\infty}^{x_t - Q_t} (x_t - Q_t - u_t^D) \psi(u_t^D) d(u_t^D) \\ & - P \int_{x_t - Q_t}^{\infty} (Q_t + u_t^D - x_t) \psi(u_t^D) d(u_t^D) - c_t \cdot Q_t \end{aligned} \quad (6.10)$$

Equation (6.10) shows the demand fulfillment response of the remanufacturing company when it has a quantity of remanufactured products at hand, x_t .

Differentiating $g_{sales}(Q_t/x_t)$ with respect to Q_t ,

$$g_{sales}'(Q_t/x_t) = R'(Q_t) + C_h \int_{-\infty}^{x_t - Q_t} \psi(u_t^D) d(u_t^D) - P \int_{x_t - Q_t}^{\infty} \psi(u_t^D) d(u_t^D) - c_t \quad (6.11)$$

It can be shown that $g_{sales}(\cdot/x_t)$ is concave in Q_t . The derivative $g_{sales}'(Q_t/x_t)$ is equal to the net marginal benefit from selling the Q th unit. The sale brings expected cash inflow of $R'(Q_t)$ by paying a unit cost of c_t . At the optimum, the net marginal benefit from increasing sales should be zero. The first-order condition of Equation (6.11) is,

$$R'(Q_t) = (c_t + P) - (C_h + P) \cdot \phi(x_t - Q_t) \quad (6.12)$$

On the supply side, the supplier response function can be written as

$$c_t \cdot y_t = \sum_{n=1}^N [S_{n,t} p_{n,t} + (B_n + C_{dn} + C_{in}) q_{n,t}] + c_{h,t} I_{non,t} + C_r y_t - R_0 q_{d,t} \quad (6.13)$$

In Equation (6.13), it is assumed that in each period, the cost of supplied remanufactured quantity of cores is limited within a budget of $c_t y_t$. The first element at the right hand side is the acquisition cost of different quality level cores and the associated new parts, inspection, and disassembly cost; the second element is cost, in this period, of keeping the non-serviceable inventory. The third element is the remanufacturing cost and the last element is the disposal revenue through selling cores to recyclers. Through remanufacturing, the required remanufactured products can be supplied, $\sum_{n=1}^N q_{n,t} = y_t$. Disposal of cores becomes necessary when

non-serviceable inventory is higher than the capacity of the warehouse, H .

When $I_{non,t} > H$, the portion of inventory more than full capacity, H , will be disposed.

Otherwise, cores are kept as non-serviceable inventory for future remanufacturing.

6.3 Numerical Study

This numerical study is used to validate the model proposed above for multi period transactions. The following assumptions are applicable for this numerical study.

- First of all, a demand function is assumed, $D_t = (\gamma_t - \delta_t \overline{PR}_t) + u_t^D$, where δ_t and γ_t are constants. It means that the expected value of demand in period t , $Q_t = \gamma_t - \delta_t \overline{PR}_t$, is a decreasing function of increasing price of remanufactured products. Thus, $\overline{PR}_t = (\gamma_t - Q_t) / \delta_t$ can be derived. Moreover, δ_t and γ_t can vary in different periods and are as assumed in Table 6.2;
- u_t^D is i.i.d. and assumed in Table 6.2, so is x_t (not all data are listed and only 6 periods are shown as an example). It is assumed that u_t^D follows a normal distribution, when mean and standard deviation of this normal distribution is 0 and 10 respectively, which are verified by historical data;
- The price of new product is assumed as $P = \$100/unit$, there is no shortage allowed due to instantaneous supply of new products;
- $C_r = \$10/unit$, $r_0 = \$5/unit$, $C_h = \$5/unit$, Some other costs are as listed in Table 5.2 in the last chapter;

- Consistent with the earlier chapters, six quality levels are assumed for disaggregating cores.

Table 6.2 Periods Parameters Assumption, $t=1,2, 3,\dots 6$

Period	x_t	u_t^D	γ_t	δ_t	$\overline{PR}_t$
1	30	18	100	1	80
2	39	10	100	1	75
3	38	9	100	1	70
4	50	-6	100	1	65
5	60	-9	100	1	60
6	62	-12	100	1	55

In last column of Table 6.2, six periods of analysis is assumed for a planning horizon. It is reasonable to assume a higher price of remanufactured products at the early stage, and a lower price at the later stage of product life cycle, since prices of new products also follow this trend and it is one of product life cycle features. Thus, prices of remanufactured products are in a decreasing manner from period to period. Moreover, the demand function is assumed the same for the 6 periods but actual demand varies in 6 periods. Therefore, it is assumed the same demand function but different demand in each period. Demand itself is an increasing function of decreasing price of remanufactured products.

Based on Equation (6.12), we can derive the relationship between the price of remanufactured products and the average unit core and remanufacturing cost, which can be used to develop the cores prices hereafter.

Table 6.3 Price of Remanufactured Products Setting, $t = 1, 2, 3, \dots, 6$

Period	$\overline{PR}_t$	Q_t	x_t	c_t	y_t
1	80	20	30	48.34	40
2	75	25	39	46.52	36
3	70	30	38	22.76	42
4	65	35	50	27.99	35
5	60	40	60	22.61	30
6	55	45	62	10.32	33

In Table 6.3, according to different prices for remanufactured products, the corresponding average unit core and remanufacturing cost are shown. Moreover, the remanufacturing quantity and expected value of demand are also obtained. The procedure to obtain the above results is as follows:

- Use the demand function to replace the $\overline{PR}_t$ in the revenue function $R(Q_t)$;
- Use this $R(Q_t)$ in Equation (6.12) and input x_t and Q_t ;
- Obtain the value of c_t , average unit core and remanufacturing cost;

With the opening quantities of u_1^D , $u_2^D, \dots$, and x_1 , $x_2, x_3, \dots$, the price of remanufactured products and the demand function as defined in Table 6.2 and all the parameters for profit calculation are listed in Table 6.4, the profits for 6 periods are shown in Table 6.5.

Table 6.4 Parameters for Profits Calculation, $t = 1, 2, 3, \dots, 6$

Period	x_t	u_t^D	$\overline{PR}_t$	c_t	y_t
1	30	18	80	48.34	40
2	39	10	75	46.52	36
3	38	9	70	22.76	42
4	50	-6	65	27.99	35
5	60	-9	60	22.61	30
6	62	-12	55	10.32	33

Based on the parameters given in Table 6.4, the profits for 6 periods are calculated in the Table 6.5.

Table 6.5 Profits for 6 Periods, $t = 1, 2, 3, \dots, 6$

Period	Revenue	Holding cost	Penalty	Core and remanufacturing cost	Profit
1	3040	0	800	1933.6	306.4
2	2625	20	0	1674.72	930.28
3	2730	0	100	955.92	1674.08
4	1885	105	0	979.65	800.35
5	1860	145	0	678.3	1036.7
6	1815	145	0	340.56	1329.44

As shown in Table 6.5, the most profitable period among 6 periods is the period 3. In that period, the price of remanufactured product is \$70 and the profit is \$1674.08. As shown in Table 6.4, it is assumed that the price of remanufactured product follows a descending trend, which is logical for the product life cycle. Also, the random term of demand for the remanufactured product follows the similar descending trend. The insights from this numerical example show that the demand function influences the profits very much. Based on the demand function, the corresponding core and remanufacturing cost, and the remanufactured quantity of cores are derived in Table

6.4. By using the results from Table 6.4, in Table 6.5, the revenue, holding cost, penalty, and profit of different periods are calculated. A better planning is achievable by reducing the holding cost and penalty in different period. Although demand function is somehow uncontrollable, the remanufacturing company is able to manage the quantity of acquisition and remanufacturing.

The relationship between profit and price of remanufactured products are plotted in Figure 6.2. The profit tends to be higher when the price of remanufactured products decreases, which leads to a higher demand for remanufactured products. However, the price with high profit is not the lowest price. Therefore, it is critical to select the price for remanufactured products as the price influences not only demand but also the margin of each remanufactured product.

Fig 6.2 Profit and Price of Remanufactured Products (\$)

Table 6.6 Demand Changes for Parameters Variation at $\overline{PR} = 65$

Parameters	Relative Variation				
γ_t	100	100	100	90	110
δ_t	0.9	1	1.1	1	1
c_t	30.29	35	42.3	45	24.98
Q_t	42	35	29	25	45
Profit	1201	825	462	325	1526

In Table 6.6, it is assumed that $\overline{PR}_t$ is equal to 65, the relative variations of the average core and remanufacturing cost and corresponding profits are shown. When the demand parameters change, as shown in above table the coefficient in the demand function fluctuates, the demand fluctuates as well. When demand increases, the average core and remanufacturing cost decrease. Thus the conclusion can be made. The average core and remanufacturing cost is very sensitive to the demand. When demand goes up, the cost tends to decrease and the optimal marginal benefit tends to increase. Such a conclusion gives a hint that the marketing of remanufactured products becomes even more important since the cost is driven by the demand change.

At the end of planning horizon, due to the products becoming obsolete, the remaining remanufactured products would have to be salvaged. Due to the price and quantity planning for joint optimization of remanufacturing, the unnecessary remanufacturing is prevented. The non-serviceable inventory still can fetch income through recycling although it may mean a loss to the remanufacturing company.

In the development and application of multiple period model, the dynamics of the demand function, pricing of cores and remanufactured products and their quantities requests that the optimization is necessary in each period. The parameters should be reviewed in each period in order to conform to the joint optimization of the price and quantity in the remanufacturing process. Moreover, due to stochastic random term in demand function, it leads to the stochastic remanufactured products with different costs at hand in each period. Therefore, a dynamic model becomes necessary to obtain price and quantity decision for a certain period.

6.4 Summary

In this chapter, an integrated model for transactions of cores and remanufactured products is developed. A dynamic discount programming model is proposed to consider multiple periods. Therefore, optimality is determined for each period within a planning horizon, making the model more realistic to be adopted in a remanufacturing context.

The lower the price of remanufactured products, the higher the demand for remanufactured products is. However, if the price of remanufactured products is close to core's price, then it squeezes the profit margin of each core. Thus, sensitivity analysis would be necessary to help decision makers to make informed decision on price and quantity.

CHAPTER 7

Conclusions

Remanufacturing is an important option for product recovery in reverse logistics. Therefore, there is an increasing need to manage and control remanufacturing activities in an effective and efficient manner. This research provides analytical and modeling approaches.

Remanufacturing requires investment in networks in order to facilitate collection, logistics and processing of the cores. The development of good acquisition price for cores by considering the quality is the main motivation of this thesis. There are transactions of cores at various levels in reverse logistics supply chain. These transactions are concerned with not only the economic aspect of product exchange, but they also include the routines and terms to make the exchange happen. There are three sets of models expected to help the decision makers to carry out such transactions. The first model is proposed to evaluate the cores transaction in the single period situation. Corresponding optimal transaction control parameters, that is, acquisition quantities and prices of the cores according to their supply information, are obtained. The second model considers the transaction by considering a stochastic demand and the need to develop core acquisition quantity and price to be provided to a consolidation center so that further process of collection of cores can be initiated

early. The decision can hinge on the demand function for remanufactured products and the ratio of price of remanufactured products and price of new products. The third model integrates end points of demand and supply of a reverse logistics supply chain in a fixed planning horizon. Obsolescence of products is generally forecasted and therefore multiple transactions of cores and remanufactured products must be considered within such a planning horizon. The integrated model considers the inventory of cores and remanufactured products in order to evaluate prices and quantity jointly. The model mimics real situation of high volume short life cycle products remanufacturing, which is an increasing trend in the market. Sensitivity analysis using simulated data show that these models can be considered for decision making by understanding the optimality of the solutions of a given demand, price and supply scenarios.

7.1 Contributions

The analytical modeling of core acquisition and redistribution of remanufactured products is the main contribution of this thesis. Although there are papers which have assumed some pricing and supply situations for cores and remanufactured products, they are not modeled analytically to develop the insight for the linkages of price and quantity. The models examine the transaction situations in two parts: core acquisition in a single period and the redistribution of remanufactured products in a single period. This is the first contribution made in this area.

- Acquisition of cores and redistribution of remanufactured products need to be integrated. Integration helps to coordinate the supply quantities with the expected demand. Integration would also help in dealing with inventory of surplus cores and remanufactured products. Integration would help to examine the real situation of price and quantity fluctuations during the transactions and to design core acquisition policy accordingly. Lastly, integration would help to maximize of the profits of core acquisition and redistribution of remanufactured products. Therefore, the development of an integrated model to handle multiple period transactions is the second contributions made in this thesis.

7.2 Limitations and Future Works

7.2.1 Limitations

As development of price and quantity decision models for remanufacturing is still at early stage, the limitations exist in the models. First, the models are generic models and involve only generic actors. If models are applied to implementation, specific considerations for actors and parameters should be taken. Secondly, for model implementation, the supply and demand information and data are rarely available. For example, the information and data of demand for remanufactured products and cores supply are seldom available in most cases. The model assumes that demand could be

studied through pricing which may not be true in the real situation. The assumption of stochastic nature of supply of cores may not materialize or overwhelm the whole logistics chain and make remanufacturing infeasible. The assumptions that cores are returned purely based on incentive may not be true as other factors, such as concerns willingness, collection period, ease of return and the location of collection cater for cores and the market for remanufactured products can matter a lot in real situation.

7.2.2 Future Works

As the remanufacturing is going to be one of the main activities in the business stream, more research works need to be carried out in this area. The following are the possible directions in future research: operational considerations and marketing considerations.

Planning for remanufacturing capacity to match the supply and demand is one potential topic for remanufacturing planning. Hybrid remanufacturing/manufacturing system needs to consider both capacities and to coordinate them in a cost efficient method. One clue for this can be obtained from flexible remanufacturing. But, once the investments are tied up for remanufacturing, it might be difficult to use them for manufacturing process. Further research can be and need to be done in modeling this type of situation.

Marketing is an indispensable part of remanufacturing. Remanufacturing requires a

continuous supply of cores and needs a continuous demand for remanufactured products. Planning horizon in this thesis is limited. Since new generation products will replace the old ones, supply and demand for remanufactured products would have to be carefully planned. Models have to be able to tackle the continuous modifications in prices in order to liquidate inventory after a certain period. Incorporating this discount factor would be a challenge for multiple period transactions. Generation of market through price differentiation assumed over here is a strict assumption and was needed to contain the focus of the research. Methods to assess consumers utility for assessing demand for remanufactured products can be a strong area of research that can consolidate the models presented in this thesis.

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APPENDIX I

List of Publication

Pokharel, S., Liang, Y., and Lim, G.H., (2004). "Managing Reverse Logistics through Value Analysis", *In Proceedings of the 2nd International Conference on Project Management ProMAC 2004*, 12-14 October, Tokyo, Japan.

Liang, Y., Shaligram, P., and Lim, G.H., (2006). "Analysis of Core Price in Remanufacturing", *In Proceedings of the 11th International Conference on Industrial Engineering Theory, Applications and Practice*, Nagoya, Japan, 7-13.

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APPENDIX II

Demand Data for 20 Periods

Period	$\overline{PR}$	$L \cdot P$	Actual Demand
0	50	70	4290
1	52	70	4160
2	54	70	4102
3	56	70	4035
4	58	70	3972
5	60	70	3915
6	62	70	3868
7	64	70	3794
8	66	70	3734
9	68	70	3670
10	70	70	3610
11	72	70	3520
12	74	70	3473
13	76	70	3378
14	78	70	3337
15	80	70	3267
16	82	70	3245
17	84	70	3161
18	86	70	3112
19	88	70	3008
20	90	70	2950

*Through regressions, $D = 5000 - 20\overline{PR} + 10(LP - \overline{PR})$.

APPENDIX III

$$\Pi = \overline{PR} \cdot A + C_h(A - Q) + P(A - D) - C_r Q - \sum_{n=1}^N (C_{dn} + C_{in} + B_n + P_n)q_n$$

$$E(\Pi) = (\overline{PR} E(A) + C_h E(A) + P\{E(A) - E(D)\} - (C_h + C_r)Q - \sum_{n=1}^N (C_{dn} + C_{in} + P_n + B_n)q_n$$

$$\text{Since } E(A) = \int_0^Q Df'(D)dD + \int_Q^\infty Qf'(D)dD; g(P_n) = [\sum_{n=1}^N (C_{dn} + C_{in} + P_n + B_n)q_n] / Q$$

We obtain,

$$\begin{aligned} E(\Pi) &= \overline{PR} \left(\int_0^Q Df'(D)dD + \int_Q^\infty Qf'(D)dD \right) + C_h \left(\int_0^Q Df'(D)dD + \int_Q^\infty Qf'(D)dD \right) \\ &+ P \left\{ \int_0^Q Df'(D)dD + \int_Q^\infty Qf'(D)dD - \int_0^\infty f'(D)dD \right\} - (C_h + C_r)Q - g(P_n) \cdot Q \end{aligned}$$

Get the derivative with respect to Q

$$(E(\Pi))' = \overline{PR} \cdot \int_Q^\infty f'(D)dD + C_h \cdot \int_Q^\infty f'(D)dD + P \cdot \int_Q^\infty f'(D)dD - (C_h + C_r) - g(P_n)$$

For the first order condition,

$$\overline{PR} \cdot \int_Q^\infty f'(D)dD + C_h \cdot \int_Q^\infty f'(D)dD + P \cdot \int_Q^\infty f'(D)dD - (C_h + C_r) - g(P_n) = 0$$

From the above equation, obtain,

$$\overline{PR}^* \cdot (1 - F'(Q^*)) + C_h \cdot (1 - F'(Q^*)) + P \cdot (1 - F'(Q^*)) - (C_h + C_r) - g(P_n^*) = 0$$

$$F'(Q^*) = \frac{\overline{PR}^* - g(P_n^*) - C_r + P}{\overline{PR}^* - C_h + P}$$

As $Q^* = F'^{-1}(K)$, then

$$K = \frac{\overline{PR}^* - g(P_n^*) - C_r + P}{\overline{PR}^* - C_h + P}$$