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Investigating Product Acquisition Strategies

in

Closed-Loop Supply Chains

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Abstract

Remanufacturing is one of the main recovery operations in Closed-Loop Supply Chains (CLSCs) that not only can contribute to a more sustainable environment, but also has significant economic and social benefits. A key factor for having an efficient remanufacturing operation is to control the heterogeneous characteristics of product returns in terms of quantity, quality and timing. Product Acquisition Management is an essential process in CLSCs, which aims to deal with these characteristics of product returns. The present study extends knowledge in Product Acquisition Management, by developing quantitative models that generate meaningful insights into the economics of proactive product acquisitioning. In addition, case studies inform the present study with the current status of product acquisition management in practice and the relevant challenges. The economic-oriented decision about operating a proactive or passive strategy is explored under quantity and quality-based incentive approaches. Closed-form solutions and quality thresholds are derived for the optimal return rate and optimal quality rate that minimises the total cost of the proactive strategy. The analysis of the infinite planning horizon models show that, the optimal acquisition strategy depends on a trade-off between the relevant remanufacturing cost advantage and the acquisition cost structure. A diseconomy of scale in the acquisition of returns leads to a decrease of the remanufacturing amount. Sensitivity analysis further highlights the differences between the quantity and the quality-based incentive approaches. This study extends its investigation on the economic viability of the proactive acquisition strategy under the finite planning horizon. Using the product life cycle as a basis for matching demand and supply, the analysis shows that delays in the processing of returns will reduce the cost advantages of a proactive acquisition strategy and that applying a dynamic acquisition policy will increase the cost improvement of the proactive strategy. Finally, the study investigates a dynamic manufacturing-remanufacturing system with a responsive buy-back policy by considering multiple quality levels and decay rates. The model is formulated using optimal control theory, and shows that the optimal acquisition strategy depends on the manufacturing-remanufacturing cost difference and price sensitivity of the return response function for high and low quality used products. The sensitivity analysis indicates that in general it is beneficial to obtain a higher rate of high quality returns in the beginning of the planning horizon, and a higher rate of low quality returns towards the end. The fluctuation in demand is mainly absorbed by manufacturing new products and much less by remanufacturing returns. Within the optimal buy-back policy, the result has indicated that it is the acquisition of high quality of returns that mirror the fluctuation in the demand, while the acquisition of low quality of returns show a relatively stable trend.

Conferences

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Contents

List of Figures:

List of Tables

List of Acronyms

BT	British Telecommunication
CLSC	Closed-Loop Supply Chain
CRC	Component Rebuild Centre
EEE	Electric and Electrical Equipment
ELT	End-of-life Tyres
ELV	End-of-life Vehicle
EOL	End-of-Life
EOU	End-of-Use
EVA	Economic Value Added
ICT	Information and Communication Technology
IT	Information Technology
MFP	Multi-Function Printers
MILP	Mixed Integer Linear Programming
MVT	Marginal Value of Time
NLP	Non-Linear Programming
OEM	Original Equipment Manufacturer
OM	Operations Management
OR	Operational/Operations Research
PA	Product Acquisition
PAM	Product Acquisition Management
PLC	Product Life Cycle
RL	Reverse Logistics
RoHS	Restriction of the Use of Certain Hazardous Substances
EEE	Electric and Electrical Equipment
WEEE	Waste Electric and Electrical Equipment

Chapter 1

Introduction

1.1 Background

As the world economy grows, competition for resources increases with associated environmental and economic implications. Intensive industrial activities with little concern about the negative impact on the environment causes resource crises and environmental issues such as diminishing raw material resources, overflowing waste sites and increasing levels of pollution (Srivastava, 2007).

Population growth only serves to exacerbate the above processes and, taken together, these issues suggest that the traditional linear economy model, in which products are designed, made, used and discarded, should change (Dawkins et al., 2010). These concerns have led countries, businesses and individuals to move towards a circular economy. The core concept of the circular economy is closing the material loop to maximise the utilisation ratio of resources and minimise environmental damage (Towards The Circular Economy, 2013). RL is a key process for the implementation of the circular economy. RL includes all the necessary steps for processing backward flows of materials, from a manufacturing, distribution or use point, to a point of recovery or point of proper disposal (Rogers and Tibben-Lembke, 1999).

In line with the concept of the circular economy, different types of environmental legislations (e.g. WEEE, ELV) have been developed in order to reduce the negative impact of excessive consumption. OEMs are increasingly facing responsibility for their products throughout their life cycles, and must provide for collection, product recovery or proper disposal. In addition to such environmental legislation, consumer pressures have also forced businesses to become more environmentally friendly by engaging in product recovery activities.

Remanufacturing is one form of product recovery that includes disassembling, cleaning, inspecting, repairing, replacing and reassembling the components of a part or product in order to return it to an “like-new” condition (Nasr and Thurston, 2006). Other terms such as rebuilding, refurbishing, reconditioning, overhauling are also frequently used with very similar meaning in various industry sectors. Remanufacturing, however, is becoming the standard term for the process of restoring used products to a “like new“ condition (Steinhilper, 1998).

According to Lund and Hauser (2010), the remanufacturing industry in some developed countries has proved that this form of product recovery can contribute to businesses, environment and society (Figure 1—1). For instance, the U.S., as one of the largest remanufacturers, increased the economic value of remanufacturing by 15% between 2009 and 2011, to reach at least $43 billion (£26 billion). This supported 180,000 fulltime U.S. jobs in over 70,000 remanufacturing firms (U.S. International Trade Commission 2012). Estimates suggest that remanufacturing in the United Kingdom (UK) in just three sub-sectors of electrical, electronic and optical products, machinery and equipment, and transport equipment can create

£5.6 to £8 billion of value for manufacturers, and support over 310,000 new jobs (Lavery et al., 2013).

Besides the economic opportunities, remanufacturing retains more of the energy associated with the original conversion of raw materials to a finished product (Nasr and Thurston, 2006). The energy spent in remanufacturing is estimated to be around 85% less than manufacturing (All-Party Parliamentary Sustainable Resource Group, 2014). This energy reduction has environmental benefits, particularly in a reduction in carbon emissions. In the UK, the carbon emission saving from remanufacturing is estimated to be over 10 million tonnes CO_2 per annum (Chapman et al., 2010). All these figures suggest that remanufacturing has the potential to make a greater contribution to businesses, environment and sustainable development.

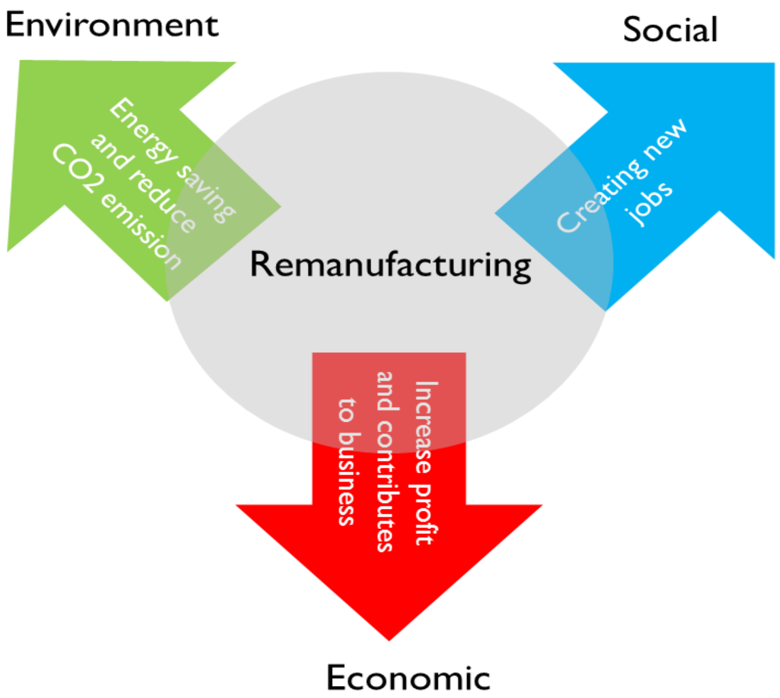

Figure 1—1: Benefits of remanufacturing (adapted from Lavery et al. 2013).

Nonetheless, remanufacturing operations are complex to plan, manage and control in terms of material planning, capacity planning, and scheduling and inventory management (Guide and Jayaraman 2000). The main reason for this complexity is the high degree of uncertainty in the quantity, quality and timing of the returned products that are source of input in the remanufacturing process. Thus, a unique planning and control decision-making tool is required in order to manage this uncertainty.

There are two major systems for obtaining used products from the end-user: The waste stream and the market-driven strategy. In the waste stream approach, the firm passively accepts returns (Guide and Van Wassenhove, 2001). This approach is often imposed to OEMs by environmental legislation (e.g. WEEE and ELV) by making them responsible for the collection, reuse and/or recycling of their products. The main objective of this regulation is to divert discarded products from landfills. In the waste stream, firms face an uncontrolled returns volume with a low recovery potential. In contrast to the waste stream, in the market-driven strategy, firms incentivise end-users to encourage them to return their products. This way the acceptance of returns is conditioned by the firm’s standards, so the level of quality, quantity, and timing of returns can be controlled appropriately (Guide and Van Wassenhove, 2001).

The concept of product acquisition management (PAM) has been proposed by Guide and Van Wassenhove (2001) as part of a market-driven strategy in which financial incentives (e.g. deposit systems, trade-in rebates or buy-back) are offered for acquisition of returns that are compliant to the firm’s standards. The primary objective of PAM is to reduce uncertainty in the quality, quantity and timing of product returns. PAM is a key component of remanufacturing operations because it is focused on managing the supply of used products to support remanufacturing activities throughout the product life cycle. Successful PAM not only has an effect on the profitability of the remanufacturing operation, but also affects various operational issues, such as facility design, production planning and inventory policies (Guide and Van Wassenhove 2006).

Uncertainty in returns quantity/timing

The uncertainty in timing (when products are available) and returns volume (how many used products are available) is one of the major challenges in the remanufacturing environment. The period of time that a product stays with customers varies dramatically. This variation can be caused by many factors, such as product life cycle stage, rate of technological changes, supply chain relationship and the firm’s return policies. A survey study conducted by Guide and Jayaraman (2000) indicates that the majority of firms have no control over the timing and quantity of returns, although some strategies, such as leasing or deposit systems, are suggested to manage this uncertainty. In cases where these strategies are not an option, other methods such as financial incentives can help managers reduce this uncertainty.

Uncertainty in returns quality

The quality of returns is one of the important factors in remanufacturing operations. Used products with a higher quality are clearly more economically attractive for remanufacturing. Yet, the quality of returns varies significantly based on the time and intensities of their previous usage, and the environmental conditions in which they were used. Determining the precise condition of used products can be done only after they are disassembled, cleaned and tested. This condition then defines the amount of parts, material and labour that are required for remanufacturing. The variability in quality, therefore, results in a high variation in material recovery rates and processing times, which in turn leads to variability in remanufacturing cost.

Apart from the above mentioned uncertainties, the balance between product returns and demand for remanufactured products is an important factor for a successful remanufacturing system (Östlin et al. 2008). The cost saving from remanufacturing operations depends on the product life cycle characteristics and the return behaviour of the customers. Factors such as technological innovation influence the return rate and shorten the life cycle for many products. This can mean that, even when the remanufacturing cost is lower than the cost of manufacturing a new product, it makes no sense to remanufacture a used product after the life cycle. Considering the product life cycle and the value of time are, therefore, important issues that need to be considered when making product acquisition decisions (Guide et al. 2005). Based on the problem described above, the research objectives of this thesis are formulated in the next section.

1.2 Research objective and scope

The aim of this research is to investigate the economic advantage of proactive acquisition strategies (i.e. the market-driven approach) for OEMs who face uncertainty in the quality and quantity of returns, and associated constraints on the availability of returns as well as on the demand for remanufactured products. The research is predominantly undertaken through quantitative (analytical) modelling. To complement the quantitative models, empirical case studies are conducted in order to gain a broader understanding of the current product acquisition (PA) strategies in practice and their industry-relevant challenges. The objective of the case studies is to investigate:

(1) *The PA strategies that are currently used in practice, and the industry-related issues in managing product returns*

The research primarily seeks to develop models to provide a general understanding of the important trade-offs involved in product acquisition decisions. The research does not seek to produce complex situation specific models with a lack of generalizability. The OR models in the CLSC literature have been criticized for having little or no connection to industrial practice, mainly due to their complexity and their focus on an isolated part of the problem rather than keeping the business model perspective (Flapper et al., 2006; Guide and Van Wassenhove, 2009). Although some of the assumptions in this study do lead to the work being somewhat divorced from reality, and may mean that the work is unable to produce readily applicable tools for specific practical instances, the insights offered by the models provide valuable guidance for improving the quality of decisions and are easier to communicate (Rogers et al., 2012). With this aim in mind, the quantitative model seeks to address the following objectives:

(2) *Investigating the economics of market-driven strategies under quantity-based incentive and quality based incentive approaches*

(3) *Investigating the optimal product acquisition decisions during the product life cycle*

(4) *Understanding the impact of costs (testing, remanufacturing and scrapping), financial incentives and life cycle characteristics on the PA strategy*

(5) *Investigating dynamic remanufacturing systems and buy-back policies in the context of multiple quality levels and quality decay.*

1.3 Outline of the thesis

This thesis is structured into eight chapters. Each of these are briefly described, as follows:

Chapter 1 Introduction

This chapter discusses the background, objectives and scope of this research, and outlines the structure of the thesis.

Chapter 2 Literature review

This chapter reviews the literature on various aspects of RL and CLSCs. The chapter starts with a general review of the literature on RL and different aspect of CLSCs, such as network design, strategic issues in CLSCs, competition between OEMs and independent remanufacturers, and marketing issues for the remanufactured product. The review then focuses specifically on those studies related to product acquisition management and remanufacturing operations, which are the issues explicitly investigated in this research. The chapter concludes with the identification of a number of research gaps in the literature and a discussion on how this research addresses some of the identified gaps.

Chapter 3 Research methodology

This chapter will describe the concepts and methods that are used in this research. The chapter first provides an overview of the methodological approaches employed in this research and discusses the strengths and weaknesses of the approaches. This is followed by an overview and a detailed explanation of the stages in this research.

Chapter 4 Empirical case studies

This chapter presents the findings from the empirical study of three remanufacturing firms in the UK. Findings from each case are discussed separately and the analysis and the key findings are presented at the end.

Chapter 5 The economics of the market-driven strategy under the infinite planning horizon

In this chapter economic models are developed to investigate the optimal product acquisition strategy for firms in a CLSC, and the economic attractiveness of the market-driven strategy over the passive strategy. Within the market-driven strategy, quantity-based and quality-based incentives are examined. The aim of the work presented in this chapter is to provide insights into the different product acquisition strategies and the impact of some important cost components on the economic attractiveness of these strategies.

Chapter 6 The impact of the returns quality and lead time on the firm's product acquisition decisions

In chapter 5, market-driven models were developed under the finite planning horizon. In chapter 6 the product life cycle is considered as a basis for balancing supply and demand and the impact of used product quality as well as returns lead time on the firm's product acquisition decisions are examined. In addition, under the quality-based incentive approach, both static and dynamic acquisition strategies are examined.

Chapter 7 Investigating the dynamic product acquisition strategy with consideration of quality decay

In chapter 7, the dynamic manufacturing-remanufacturing system is modelled based on the optimal control theory. In contrast to chapter 6, where quality was modelled as yield rate, in chapter 7 quality is considered as predefined quality classes with different remanufacturing and acquisition costs. Furthermore, the model includes the concept of quality decay, by which the quality level will be degraded over time.

Chapter 8 Conclusions and further research directions

In the final chapter of the thesis, the main contributions and the outcomes of the research are summarised, and some areas for further study area are proposed.

Chapter 2

Literature Review

2.1 Introduction

This chapter reviews the literature on various aspects of RL and CLSCs. The review particularly focuses on product acquisition management and remanufacturing operations, which are the topics explicitly investigated in this research.

The chapter is organized as follows. The concepts of reverse logistics and product recovery management are reviewed in Section 2.2. This covers the motivations for firms to be engaged in product recovery activities, different types of product returns and appropriate recovery decisions, along with reverse logistics activities and their network structures. In section 2.3, the focus is on the closed-loop supply chain and discusses the studies that investigate different aspects of CLSC management such as network design, strategic issues in closed loop supply chains, competition between OEMs and independent remanufacturers, and finally marketing issues for remanufactured products. Section 2.4 provides an overview of the remanufacturing environment and discusses the complex characteristics of remanufacturing operations, the impact of the product life cycle, the importance of product acquisition management and different mechanisms for obtaining products from the market. In section 2.5, the focus is specifically on studies that investigate product acquisition decisions. Section 2.6 summarises the main highlights from the literature review and identifies some gaps. Finally, Section 2.7 briefly discusses the ways in which the objectives of this research can address some of the gaps and contribute to overall knowledge.

2.2 Reverse logistics and reverse supply chains

2.2.1 Definition and concept of reverse logistics

The concept of reverse logistics appeared in the literature as early as the seventies, emphasizing reverse channels for recycling (Guiltinan and Nwokoye, 1974). The Council of Logistics Management provided the first formal definition of Reverse Logistics (RL) by emphasising the element of waste reduction and defined it as *"…The term often used to refer to the role of logistics in recycling, waste disposal, and management of hazardous material; a broader perspective includes all relating logistics activities carried out in source reduction, recycling, substitution, reuse of material and disposal"*(Stock, 1992).

Carter and Ellram (1998) put more emphasis on the environmental aspect of RL and describe it as a *"process whereby companies can become more environmentally efficient through recycling, reusing, and reducing the amount of materials used"* (Carter and Ellram 1998, p. 85).

The European Working Group on Reverse Logistics (REVLOG) suggests a general definition for RL by emphasizing the return flow of material. In this way, RL can capture those returns that were not consumed first (e.g. stock adjustments or spare parts which were not used) and also returns that might go to a different point of recovery. They define RL as *"the process of planning, implementing and* *controlling backward flows of raw materials, in process inventory, packaging and finished goods, from a manufacturing, distribution or use point, to a point of recovery or point of proper disposal"*(REVLOG, 1998).

Alternatively, Rogers and Tibben-Lembke (1999) accentuate the economic aspects of RL and define it as *"the process of planning, implementing and controlling the efficient, cost effective flow of raw materials, in process inventory, finished goods, and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal"* (Rogers and Tibben-Lembke 1999, p.2).

Although different definitions have been suggested for RL, they all overlap substantially. In particular, all the definitions include the idea of flows of used products that start from returning parties (end users), and receiver parties (e.g. OEMs) that accept and collected returns for value recovery purposes.

It has to be mentioned that different scholars have used the term "reverse logistics" and "reverse supply chain" interchangeably. Guide and Van Wassenhove (2002) define Reverse Supply Chains (RSCs) as the series of activities required to retrieve a product from a customer in order to either dispose of it or recover value. Prahinski and Kocabasoglu (2006), however, delineate between these two terms, suggesting that the scope of RSCs is to some extend broader than that of RL. According to them, the latter concept is more focused on the transportation, warehousing and inventory management activities, while the former one covers the coordination and collaboration with channel partners.

It is important to note that the term RL should not be confused with waste management, as the latter mainly refers to the management of activities involved from waste collection to final disposal of waste, while RL emphasises the recovery of value from returned products (de Brito and Dekker, 2004). The cornerstone of RL, therefore, is the value recovery operation and it is this that can make the difference between the success and failure of RL operations.

The following sections discuss the forces that drive companies and institutions to become active in RL, and the types of product returns and product recovery decisions that RL entails.

2.2.2 Drivers for product recovery

de Brito and Dekker (2004) categorized the driving forces for firms to become active in RL under three headings: direct and indirect economic benefits, environmental legislation and corporate citizenship.

2.2.2.1 Economic benefit

The first motivation for firms to be involved in RL is the direct economic benefit that can be achieved by recovering used products, and transforming these into a functional product for a new use. Successful examples are refilling toner cartridges, remanufacturing single use cameras, tire re-treading, refurbishing electrical motors, remanufacturing IT-equipment, plastics recycling, etc. Also, superfluous or discarded materials can provide a cost saving when used in the production of new products, for instance use of scrap metal which can be recycled and mixed with virgin material (de Brito and Dekker, 2004).

Besides these direct economic benefits, companies can get involved with RL because of competition and/or strategic objectives. In some industries (e.g. aerospace) asset protection is the main motive for companies to take back their product after use. In this way, companies seek to prevent sensitive components from leaking to secondary markets or competitors. Moreover, potential competition between original products and recovered products will be avoided (Fleischmann et al., 2001).

2.2.2.2 Legislation

Apart from the economic benefits, in some countries, manufacturers are obliged by environmental legislation to take back and recover their products after use in order to reduce waste disposal volumes (Fleischmann et al. 2001). European Union regulations regarding electrical and electronic equipment such as WEEE and RoHS are some examples of legislation that dictate the prevention of waste and promote the recovery of waste.

In some cases, recycling of used products is well established, due to the inherent profitability of recovering materials from those used products. For instance, in the pulp and paper industry and the metal industry, scraps are regularly used as raw materials for new products (Schultmann et al., 2006). As Guide and Van Wassenhove (2001) pointed out, however, it may not be reasonable for every OEM to engage in such product recovery activities, and in these circumstances economic analysis is needed to identify the best recovery option (e.g. remanufacturing, recycling, etc.).

2.2.2.3 Corporate citizenship

Corporate citizenship refers to a set of values or principles that oblige an organisation to become responsibly engaged with RL. The implication of RL helps companies to establish their image as an environmentally responsible organisation.

According to Thierry et al. (1995), many manufacturers have historically not felt responsible for their product after use. Most products were designed in such a way that repair, reuse and disposal requirements were not taken into account.

Consequently, many used products were disposed of or incinerated, with considerable damage to the environment. As people have become more environmentally consciousness, organisations have come under pressure to become environmentally responsibility by engaging in RL. Companies are expected to act responsibly regarding the environment in every aspect of their operations, therefore establishing a "green" image to meet this consumer expectation has become an important element in companies' marketing strategies (de Brito and Dekker, 2003).

2.2.3 **Product returns and product recovery decisions**

Product returns can happen for a variety of reasons over the product life cycle. When this occurs, the value of the returned products can be recovered in various ways depending on the product's condition (Atasu et al., 2008). de Brito and Dekker (2003) considered the whole supply chain when examining the reasons for product returns and classified returns into three main categories: (1) *Manufacturing returns* happen when components or products have to be recovered in the production phase (e.g. raw material surplus, quality-control returns and/or production leftovers). (2) *Distribution returns* happen after the product has been distributed in the supply chain. Product recalls, commercial returns, stock adjustments and functional returns fall into this category. (3) *Customer returns* refer to those returns that are collected from the ultimate consumer. These returns include reimbursement guarantees, warranty returns, service returns for damaged goods.

Similar to Krikke et al. (2004) and Guide and Van Wassenhove (2009), in this study returns are classified according to their life cycle stage. *End-of-Life Returns (EOL)* refer to the return of those products that are predominantly technologically obsolete or worn out, where recycling is the only practical recovery option, e.g. recycling procedures for batteries, packaging, tires and vehicles. *End-of-Use*

Returns (EOU) is when products or parts have been used extensively over a period of time. Although end-of-use products are not really new, they are often in a reasonable or good condition, but may require refurbishing or remanufacturing depending on their quality. *Commercial Returns* are all those returns where the buyer has a contractual option to return products to the seller within a specified period (e.g. 30, 60, or 90 days) after purchase (Rogers et al., 2002). The volume of this type of returns are estimated at 15% of sales for mass merchandisers (Jayaraman and Luo, 2007). In the United States the number of commercial returns is estimated to be up to 35% (Russo and Cardinali, 2012). Ketzenberg and Zuidwijk (2009) argue that part of the growth in commercial returns arises from a liberalisation of policies that allow this type of return. The authors state that expansion of e-businesses contributes to the growth of commercial returns by enabling consumers to return goods under more liberal terms since they have been purchased remotely from the customer’s location and therefore allowances have to be made for the product being fit for use and the customers’ ability to evaluate products online. The authors further discuss that the liberalisation of return policies that has been observed over the past decade arises because consumers value the opportunity of returning products after purchase and because of the need for firms to provide a competitive offering to the marketplace. A lenient return policy reduces the cost of reversing a bad decision and enables consumers to make decisions while maintaining flexibility. Products in this stream have been barely used and usually have sufficient value remaining to make their reintroduction to the market feasible (Tibben-Lembke, 2004).

All of the abovementioned returns can be recovered with a different recovery option. In order to achieve the best possible result from the recovery process, however, a suitable strategy has to be followed (Guide et al., 2003b, Guide and Van Wassenhove, 2009). Thierry et al. (1995) proposed five different product recovery options with respect to the degree of required disassembly (1) repair, (2) refurbishing, (3) remanufacturing, (4) cannibalization, and (5) recycling.

Repair: this recovery option requires limited product disassembly in order to fix and/or replace broken parts. The purpose of repair is to bring the used product up to a “working level”. Repair operations can be performed at the customer’s location or at a repair centre.

Refurbishing: the aim of this recovery operation is to increase the quality of used products and extend their life cycle. The quality of the refurbished products, however, is still lower than the quality of new products. For instance, commercial and military aircraft are usually refurbished during their life cycle in order to prolong their functionality. This recovery process requires disassembly of used products into modules, allowing all the critical modules to be inspected and then fixed or replaced. Most of the time, refurbishing is combined with technological upgrading.

Remanufacturing: the main objective of remanufacturing is to bring used products up to the quality of new products. One of the benefits of this recovery option is that remanufactured products are indistinguishable from new products and can serve the primary market (at a lower price) along with new products (Ferrer and Swaminathan, 2006). In the remanufacturing process, the products are completely disassembled and all parts and components are comprehensively inspected. Those parts that meet the quality specification are sub-assembled into modules and subsequently into remanufactured products. Remanufacturing is the focus of this research and will be further discussed in section 2.4.

Cannibalization: in this recovery option only some components and parts are recovered, to be reused in the repair, refurbishing and/or remanufacturing process. Cannibalization therefore requires selective disassembly of used products depending on the process in which they will be reused.

Recycling: in previous recovery options, the identity and functionality of used products are retained as much as possible. In recycling only the material is recovered from used products. Based on the quality of materials, they can be reused in original parts or in the production of other parts. Recycling requires the used part to be dismantled into smaller parts and these parts are then separated into material categories.

It is worth mentioning that the higher value recovery options (e.g. remanufacturing, refurbishing) are not necessarily the most ecological options. The environmental aspects of RL are discussed in (Pappis et al., 2004). In that paper the authors introduced Life-Cycle Analysis (LCA) as a quantitative approach for measuring the environmental impact of logistics activities. Bloemhof-Ruwaard et al., (2004) develop an Eco(nomy)-eco(logy) MILP model for a closed-loop supply chain design which takes into account the forward and reverse supply chain as well as multiple objective optimisations of supply chain costs and environmental impacts (measured by energy in use and waste volume). Their findings suggest that reuse at a component/module level is the most beneficial recovery option. However, when the recovery feasibility decreases, then material recycling and thermal disposal are the second-best option. Recently, Quariguasi-Frota-Neto and Bloemhof (2012) studied the remanufacturing operation from an environmental perspective and showed that remanufacturing is not always the environmentally preferred option, despite savings in material and energy during production. For instance, old refrigerators should not be remanufactured but recycled, because the bulk of their environmental impact (in excess of 80%) is in the use stage of the life cycle, and thus, newer and more energy efficient refrigerators are preferred (Souza, 2013). Figure 2—1 illustrates different types of returns and the corresponding recovery options.

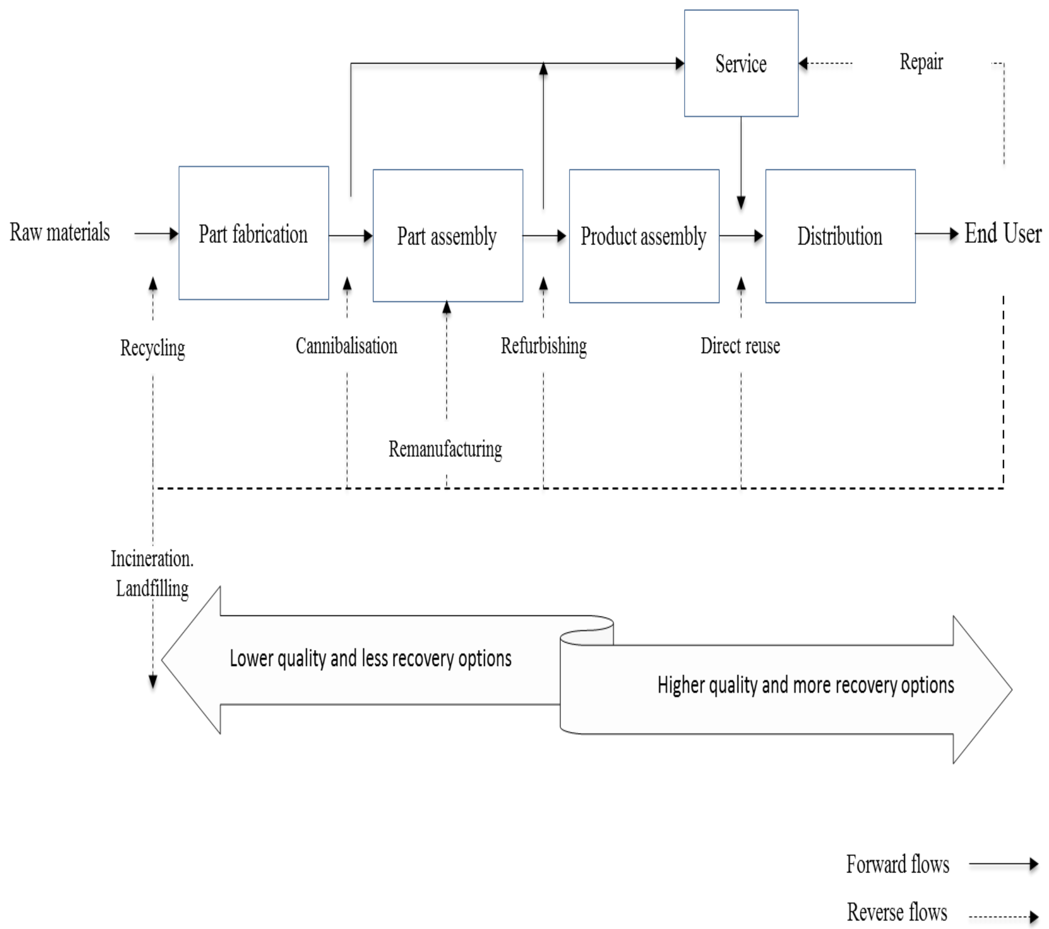

Figure 2—1: Integrated supply chain for each type of return (adapted from Thierry et al., 1995).

2.2.4 **Product recovery activities and network structure**

In recent years, extended producer responsibility, among other reasons, has encouraged Original Equipment Manufacturers (OEMs) to integrate a reverse supply chain with their forward supply chain (Dowlatshahi, 2000). If the forward and reverse supply chains are considered simultaneously a CLSC network is created. According to Fleischmann et al., (2000), in a closed-loop system, the source of supply and demand coincides so that flows “cycle” in the network. An alternative product recovery network is an open-loop system that has a “one-way” structure in the sense that flows enter at one point and leave at another. The main difference between these two networks is in the relationship between the incoming and outgoing of materials flow (Fleischmann et al., 2000). Remanufacturing and reuse often lead to closed-loop systems since the product returns to the OEM, while recycling is often considered as an open-loop system because the possibilities for integration of forward and reverse distribution are scant (the products may not return to the OEMs but will be used in other industries) (Fleischmann et al. 1997).

Guide and Jayaraman (2000) study the closed-loop supply chains structure of a diverse range of products such as refillable containers, photocopier remanufacturing and the re-use of consumer electronics. They conclude that each type of return needs a CLSC appropriate to the characteristics of the returned products. Activities that are common to all CLSCs, however, are product acquisition, reverse distribution, inspection and disposition, reconditioning and remarketing (Guide and Van Wassenhove, 2002). *Product acquisition (PA)* is the first activity in RL and CLSC. PA involves obtaining the used products from the end-users. This is the key to a profitable system since the quality, quantity and timing of returns should be carefully managed, otherwise the firm may end up with a huge amount of inventory of highly variable quality, making efficient remanufacturing impossible. The importance of product acquisition will be discussed further in section 2.4.4. *Reverse distribution* is the next step, where acquired products have to be transported to return facilities for testing, sorting and disposition. *Inspection and disassembly* has to be done in order to determine the product's condition and the most economically attractive recovery option. Disassembly can be a time consuming and labour-intensive task involving scheduling issues (Kim et al., 2007). Inspection is carried out to identify the component quality and, usually, includes cleaning operations such as removal of dirt, degreasing, de-rusting and removing components from paint (Steinhilper, 1998). If a firm subjects the returns to quality standards at the earliest stage in the process, however, many logistic costs can be eliminated and remanufactured products can be reintroduced into the market faster. *Reconditioning* serves to capture value from returned products by reconditioning components/parts for reuse, or by completely remanufacturing the product for resale. The reconditioning and remanufacturing process tends to be more complex than traditional manufacturing, due to the greater uncertainty in respect to the quality, quantity and timing of returns. *Remarketing and redistribution* is the final step in closing the loop. The firm has to determine whether there is demand for the reconditioned product or whether a new market has to be created (Guide and Van Wassenhove, 2002).

2.3 Closed-loop supply chain

CLSC research has evolved from examining individual activities to considering the entire reverse supply chain process as a potentially profitable business proposition (Guide and Van Wassenhove, 2009). Atasu et al. (2008) provide an overview of analytical research on the business economics of the product recovery in CLSC, while Guide and Van Wassenhove (2009) provide an interesting analysis of the evolution of CLSC. Also, Bulmuş et al. (2014), Govindan et al. (2015), Junior and Filho (2012), Souza 2013 and Tang and Zhou (2012) each provide a comprehensive review of more recent studies on RL and CLSCs. The following sections briefly discuss some of the key studies that have contributed to the advancement of research in CLSC.

2.3.1 Theoretical background of CLSC research

Thierry et al. (1995) investigated the product recovery system of a green copier line at Xerox, and a number of proactive manufacturers such as BMW and IBM, from a general management perspective, and discussed how product recovery, as a value-added activity, influences the firm's operations. One of the key findings of their study was that the firm's operations, production and logistics management will be significantly improved if PAM is integrated into their systems. Studying the developments at Xerox and other companies also encouraged researchers to focus on value creation in the remanufacturing process, rather than just minimizing the cost of compliance.

Fleischmann et al. (1997) provide a comprehensive review of the main Operational Research models for RL that address issues such as distribution planning, inventory management and production planning. Fleischmann et al. (2000) contributed to this field by characterising product recovery networks. They provide a process-oriented classification: bulk-recycling network, remanufacturing network and reusable item networks.

The REVLOG working group establish a theoretical basis for reverse logistics and structured the field around six clusters: production planning and inventory control, distribution, business economics, information, computational aspects and environmental impact, and this classification has made a remarkable contribution to the definition and solution of new OR problems (Dekker et al., 2004).

Guide and Van Wassenhove (2001) proposed the concept of the PAM as part of a market-driven strategy, and as a key input in the evaluation of the potential economic attractiveness of reuse activities. If companies are unable to identify the potential financial benefits of engaging in CLSC they are unlikely to become active in the value recovery operation (Guide and Van Wassenhove, 2002; Guide et al., 2003a; Guide and Van Wassenhove, 2006). They argue that, most of the time, it is not the remanufacturing operation that matters, but rather the lack of a market for remanufactured products or the lack of used products of sufficient quality and quantity. Based on the above perspective, Guide and Van Wassenhove (2006) define CLSC management as *"the design, control, and operation of a system to maximize value creation over the entire life cycle of a product with the dynamic recovery of value from different types and volume of returns over time".* This definition emphasises the explicit business view instead of legal, social responsibility, or even operational and technical details. From this business management perspective, three groups of activities are highlighted; (1) product returns management, (2) remanufacturing operational issues, and (3) market development for remanufactured products. All these three parts need to be managed carefully to unlock the potential economic value of CLSCs (Figure 2—2).

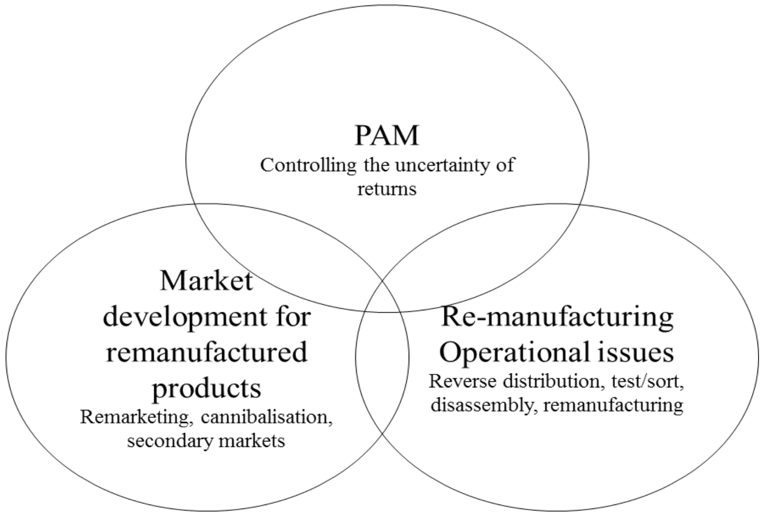

Figure 2—2: Business management view (adapted from Guide and Van Wassenhove, 2009).

Many scholars have addressed the strategic implications of product recovery using this business management perspective. The main objective of studies in this stream is to address problems such as, network design, collection channels for used products, competition between OEMs and independent remanufacturers and marketing issues for remanufactured products.

2.3.2 Network design

Fleischmann et al. (2001) provide a comprehensive review of CLSC network design models, and more recent reviews are provided by Akçali et al. (2009) and Aras et al. (2010). Fleischmann et al. (2001) propose a generic MILP-based model for the optimal design of a recovery network in CLSC. The proposed MILP formulation constitutes an extension of the traditional warehouse location problem where two such models are integrated: one for the forward chain connecting factories to customers through warehouses, and the other for the reverse chain connecting customers to factories through disassembly centres. The two chains are integrated by means of a balance constraint that assures, for each factory, that its total return is not greater than its total production. One of the advantages of the model presented by Fleischmann et al. (2001) is that it can capture different scenarios (e.g. if a firm decides to have two separate networks for forward and reverse chains). Based on this model, Salema et al. (2007) investigate the design of a capacitated multi-product reverse logistics network with uncertainty by including production/storage capacity limits, multi-product production and uncertainty in demand/return flows.

Guide et al. (2005) investigated Hewlett-Packard's refurbishing operation for products with a short life cycle to be sold in the secondary market. They consider a recovery network with either in-house refurbishing (when the product requires minimal refurbishing) or outsourced repair. Demand and return are assumed to be deterministic and the quality of returns is modelled as a fixed rate of product returns. They develop a linear programming model and show the importance of the returns' lead times on the cost savings from the recovery operation. Based on this idea, Guide et al. (2006) used queuing networks to demonstrate the value of speedy recovery on profitability for time-sensitive consumer returns such as consumer electronics. Their work is based on data from two firms, Hewlett-Packard and Bosch. Their findings suggest that product returns (especially commercial returns) do not themselves levy a cost to the system, but if the recovery process is too slow then the hidden value is soon gone and the firm may end up incurring extra costs. Thus, time value is critical, especially when product life cycles are short. Failure to consider time in the design of the closed-loop supply chain will therefore be costly (Blackburn et al., 2004; Guide et al., 2006). In order to design a profitable CLSC network, firms need to consider the volume of returns, the marginal value of time and the quality of the returned products. Moreover, products with short life cycles (time-sensitive products) need a responsive decentralized CLSC, while a centralized CLSC can better serve less time-sensitive products (Guide and Van Wassenhove, 2009).

2.3.3 Strategic issues in CLSC

Savaskan et al. (2004) investigated the problem of choosing the appropriate reverse channel structure for the collection of used products. They investigated three strategies: (1) direct collection by OEMs, (2) incentivising retailers who already have a distribution channel, (3) subcontracting the collection activity to a third party. In their model, new and remanufactured products are perfect substitutes and demand is a linear function of price. Their results suggest that, when considering decentralised systems, the perfect collection agent is the retailer followed by the manufacturer and then a third party. It should be noted, however, that the cost of collection will increase respectively for retailer, manufacturer and third-party (profit margin decrease). Savaskan and Van Wassenhove (2006) extend (Savaskan et al., 2004) by considering two retailers in a competitive retailing environment. They find that retailer collection is still preferred for products where retailers compete on prices; manufacturer collection is preferred, however, for products where retailers have less impact on prices (e.g., toner cartridges).

Debo et al. (2005) investigate the joint pricing and production technology selection problem faced by an OEM operating in a market where customers differentiate between the new and the remanufactured products. Using an infinite period dynamic programming model, they found that an increase in the new product price will increase the profit potential from remanufacturing. Higher prices may reduce new product sales, which consequently will reduce the number of products available for return, thereby resulting in a lower profit potential from remanufacturing. Debo et al. (2006) extend their earlier study by introducing a life cycle perspective into the problem. In their model, sales of the new product follow a Bass-type diffusion model, with remanufacturing being constrained by the amount of new products sold. They find that remanufacturing is more attractive for new products with a slower diffusion rate, due to the greater overlap between the new and remanufactured product life cycles, and thus the greater opportunity to sell remanufactured products. Akan et al. (2013) also contributed to this area of research by investigating dynamic pricing strategies for new and remanufactured products under the assumption of imperfect substitution (remanufactured products are sold cheaper than new counterparts). In their model, returns are managed by the manufacturer's inventory i.e., the manufacturer makes storage and disposal decisions. They derived a solution analytically using optimal control theory and provide distinct sequences of the manufacturing-remanufacturing activities.

2.3.4 Competition between OEM and independent remanufacturer

One of the first studies that explicitly considered remanufacturing competition was that of Majumder and Groenevelt (2001), which considered the case of an OEM, who is also a remanufacturer, competing with a local remanufacturer. Using game theory, the authors modelled a scenario in which new product sales occur in the first period and determine the amount of product available for remanufacturing. In period two there is a competition between the OEM's remanufactured products and the local remanufacturer. They show that reducing remanufacturing costs for the OEM will decrease the average price of their product and increase sales. A higher level of sales, however, led to more returns, and benefited the local remanufacturer. A similar study carried out by Ferrer and Swaminathan (2006) extends Majumder and Groenevelt's model to a multi-period setting. They show that, if remanufacturing is very profitable, the OEM may accept some of the first-period margin by dropping the price and selling additional units to increase the rate of returned products for remanufacturing in future periods. Furthermore, as the threat of competition between OEM and independent remanufacturer increases, the OEM is more likely to exploit all available used products fully, offering the remanufactured products at a lower price. Ferguson and Toktay (2006) also explored the strategic role of OEMs that engage in remanufacturing operations as an entry barrier for local remanufacturers. The authors assumed that the OEM monopolist may not offer remanufactured products because the sales of new products might be cannibalized by the remanufactured products. The OEM monopolist, therefore, has no incentive to obtain the returns because it is too expensive. This, however, is an opportunity for the local remanufacturer to collect used products and introduce a remanufactured version of the monopolist's product. They have shown that remanufacturing by OEMs may be a feasible option to prevent the entry of local remanufacturers into the market, even if remanufacturing itself is not an attractive option for a monopolist OEM. More recently, Bulmus et al. (2014) investigated the competition between an OEM and an independent remanufacturer, not only for selling their products but also for collecting returned products (cores) through their acquisition prices. One interesting insight of their study is that the acquisition price of the OEM only depends on its own cost structure, and not on the acquisition price of the independent remanufacturer.

2.3.5 **Marketing issue for remanufactured products**

A recent stream of research in the area of CLSC has empirically addressed the market for remanufactured products. Studies in this stream mainly focus on the consumer perception of remanufactured products and the cannibalization of new product sales by remanufactured products (Subramanian and Subramanyam, 2012; Subramanian and Subramanyam, 2008; Guide and Li, 2010). Guide and Li (2010) empirically investigate the potential for cannibalization of new product sales by remanufactured products. They hypothesised that the fear of cannibalization is a barrier to OEMs introducing remanufactured products. Using online auctions data for power tools and Internet routers they found that cannibalization may negatively influence Business-to-Business (B2B) products but for Business-to-Consumer (B2C) the impact is far less. They also recognized that consumers value new products more highly than their remanufactured equivalents. Subramanian and Subramanyam (2012) examine drivers of price differentials between new and remanufactured products for video games consoles and some consumer electronics. Using online prices on eBay, they show that seller reputation significantly explains the price differentials between new and remanufactured products. They also find that products that are remanufactured by OEM or their authorized factories are purchased at relatively higher prices than products remanufactured by third parties.

More recently, Neto et al. (2015) investigate how consumers perceive remanufactured products relative to used and new products. They construct a database containing 1716 eBay listings, and use that to investigate the factors that influence the differences in prices between used, remanufactured and new iPods. They conclude that consumer perception of remanufactured products relative to their used and new counterparts, and hence their willingness to pay, depends in subtle and not yet well-understood ways on the nature of the product.

Ovchinnikov (2011) investigate the cannibalisation issue for new and remanufactured laptops. The cannibalization effect is measured by the fraction of customers who switch from buying new to buying an equivalent remanufactured product for a given percentage discount in the price of the remanufactured product relative to the new product’s price. Through a lab experiment, they find that consumers may infer that the remanufactured product is of low quality if it is priced too low. Thus, higher price discounts may decrease cannibalisation, particularly for high-end segments. Similarly, Agrawal et al. (2015) investigates whether or not the presence of remanufactured products, and the identity of the remanufacturer, influence the consumer perception of new products. Using lab experiments, they show that the perceived value of new products is reduced when products are remanufactured and sold by the OEM. Their results suggest that it is possible that the competition between OEMs and third-parties may actually be beneficial for an OEM. Their result is in contrast with previous research where it is suggested that the remanufactured product has no impact on the willingness to pay for the new product (Souza, 2013).

Lab experiments, however, may not capture the exact market conditions and actual purchasing behaviour. It has been suggested that studies that use actual sales data provide a better insight into the market conditions and purchasing behaviour (Guide and Li, 2010; Subramanian and Subramanyam, 2012; Neto et al., 2015). In addition, the result of studies that focus on a particular product category (such as iPods, laptop) cannot be extended to other products, such as medical equipment and automotive parts (Souza, 2013).

2.4 Remanufacturing

Remanufacturing has existed for centuries, typically for high-value and low-volume items such as locomotive engines and aircraft (Lund, 1996). These products are composed of tens of thousands of parts, therefore disassembly, remanufacturing and reassembly present technical challenges with respect to shop flow control, testing of critical parts and coordination of parts at the reassembly point (Guide and Van Wassenhove, 2009). These complexities have led some researchers to work on improving remanufacturing shop control and coordination (Guide, 1997; Guide and Srivastava, 1998). These early studies, which were often sponsored by the U.S military, were carried out to make remanufacturing operations more efficient. In Europe, however, companies were affected by EU legislation, such as the paper recycling directives, ELV and WEEE (Guide and Van Wassenhove 2009). Under these circumstances, companies were forced to seek ways to minimize the cost of compliance. Researchers consequently focused on issues such as design for disassembly, or design of minimum-cost-recycling networks and on reducing the environmental impact (de Ron and Penev, 1995; Fleischmann et al., 2001). The focus of many studies, therefore, was on individual activities in the reverse supply chain such as disassembly, shop floor control, or distribution networks. Several scholars have employed an optimisation approach to identify and explain a plethora of issues in the context of remanufacturing, ranging from inventory control systems (DeCroix et al., 2005; DeCroix and Zipkin, 2005; DeCroix, 2006; Ferrer and Whybark, 2001; Inderfurth, 1997; Laan et al., 1999; Toktay et al., 2000), reverse distribution (Fleischmann et al., 2001; Fleischmann et al., 2003), hybrid manufacturing and remanufacturing (Aras et al., 2006), value of information (Ferrer and Ketzenberg, 2004; Ketzenberg et al., 2006), lot sizing for remanufacturing (Atasu and Çetinkaya, 2006; Beltrán and Krass, 2002; Golany et al., 2001; Tang and Teunter, 2006), to remanufacturing shop design (Kekre et al., 2003; Ketzenberg et al., 2003; Souza et al., 2002).

2.4.1 Characteristics of remanufacturing

Remanufacturing focuses on valued-added recovery, rather than material recovery (i.e. recycling systems). Value-added recovery is based on the premise that used products have value-added still embedded in the product (Guide, 2000).

Guide and Jayaraman (2000) identified five characteristics of remanufacturing operations. These characteristics are briefly discussed as follows:

Uncertain timing and volume of returns: uncertainties in the quantity and timing of returns are a result of a number of factors, such as technological innovation (Östlin et al., 2009) or liberal return policies (Guide et al., 2005). At the early stage of the product life cycle there are not enough returns for remanufacturing, while at the end of the life cycle there is no demand for remanufactured products. Therefore, considering that the product life cycle and the value of time have become important issues that have to be considered when making product acquisition decisions, the remanufacturer can apply different mechanisms (e.g. leasing, buy-back, etc.) to control these uncertainties to some extent. These mechanisms will be further discussed in section 2.4.5.

Matching returns with demand: The problem of matching returns with demand is an important issue in the product acquisition management. An imperfect balance between demand and returns may lead to excess inventory of used products with a risk of obsolescence, or shortages of units needed to satisfy demand and, therefore, lost sales. Balancing demand with returns, is also a function of a product's expected life and the rate of technical innovation (Guide and Jayaraman, 2000). This issue can be controlled to some extent by applying an appropriate product acquisition strategy such as deposit-based, credit base, ownership based, etc. (see Östlin et al., 2009 for the different product acquisition mechanism)

Disassembly of the returned products: disassembly has to be done in order to determine the product's condition and the most economically attractive recovery option. Disassembly can be a complicated, time consuming and labour-intensive task involving scheduling issues (Kim et al., 2007) and it will impact on the other operations such as production planning and inventory control (Wiendahl et al., 1999).

Uncertainty in material recovered from returned products: Until the returned product has been fully disassembled, and all the parts cleaned and inspected, it is not known which of the parts are usable, or can be salvaged and rebuilt. This complexity is caused by the uncertainty regarding the quality of returns. Inspection and sorting are the common methods to control the quality of returns (Galbreth and Blackburn, 2006). The uncertainty in quality can be managed by different strategies such as offering quality-based incentives or leasing contracts (Guide et al., 2003b; Ferguson et al., 2009).

Requirement for a reverse distribution network: Reverse logistics activities are concerned with how the used products are returned from the user to the remanufacturing facility. A reverse distribution network entails decision regarding transportation method, number of collection sites and whether to handle reverse distribution in-house or through third-party providers. Fleischmann et al. (1997) provide an extensive review of quantitative models developed for reverse distribution. More recent reviews of research in reverse network design are provided by (Akçali et al., 2009; Aras et al., 2010) focusing on systems design and the number of decisions needed to provide a returned product.

Complications of material match restrictions: This characteristic is specific to cases where product recovery is serial-number-specific. In some industries, it is required that a product/component is remanufactured using the original “serial-number-specific” parts. For instance in aircraft engine recovery certain engine parts need to be recovered as a set (Inderfurth and Teunter, 2001).

Stochastic routing and highly variable processing times: The variable processing times and stochastic routings for materials are due to uncertainty in the quality of returned products. Highly variable quality will be translated into variable processing times that make resource planning, shop floor control, etc. more complex (Guide, 2000).

2.4.2 **Types of remanufacturers**

Remanufacturing operations are performed by OEMs or independent remanufacturers. OEM remanufacturers collect their products from their customers through sales channels (agents) and service contracts and distribute the remanufactured products through their own logistics channels (Seitz, 2007). For instance Caterpillar remanufactures its own products and offers them as a substitute for their new products at a lower price.

The independent remanufacturers (or local remanufacturers) are not related to OEMs in any way, but remanufacture OEM’s products. Independent remanufacturers tend to be small and work in a competitive environment. Also, independent remanufacturers have a limited access to customers and product knowledge.

One of the concerns associated with independent remanufacturers is that they might not be able to remanufacture a used product to be “as good as new”. This is an important factor because the low quality of remanufactured products undoubtedly damages consumer perceptions regarding remanufactured products and the remanufacturing industry in general. For instance, in the case of toner cartridges some independent remanufacturers simply refill the cartridges using nozzles. This leads to poor print quality and ink spillage (Centre for Remanufacturing and Reuse, 2010).

In some industries, such as heavy-duty vehicles, automobile and diesel engines, independent remanufacturers are subcontracted by the original manufacturer to perform remanufacturing for the OEM's products (Lund 1996). As pointed out by Lund and Skeels (1983) and Lund et al. (1984) there are several unique advantages for OEMs to engage in remanufacturing operations: feedback on product reliability and durability, competition in the market, a manufacturer's reputation for quality, and gaining an advantage over independent remanufacturers in data, tooling and access to suppliers. On the other hand, remanufacturing may reduce the sale of new products (the cannibalisation issue).

2.4.3 **Product life cycle**

The introduction of the idea of product life cycle goes back to 1950s (Dean, 1950; Dean, 1951). The product life cycle represents the evolution of a product, measured by the unit sales curve, extending from the time it is first placed on the market until it is removed (Rink and Swan, 1979).[1] The phases that a product goes through during it life cycle are the introduction, growth, maturity and decline stages (Cox, 1967).

Without doubt, the product life cycle is an important factor in manufacturing-remanufacturing decisions, and has an impact on both long-term strategies and

[1] In some studies PLC is referred to as the progress of a product from raw material, through production and use, to its final disposal (Östlin et al., 2009).

operational activities. According to Reiner et al. (2008), there is substantial risk of obsolescence cost if the product life cycle is not considered in the demand model.

Geyer et al. (2007) show that the possible remanufacturing volumes for a product are dependent on the relationship between the supply and demand curves. Balancing the returns with demand is a key factor in evaluating the profitability of remanufacturing operations (Östlin et al., 2009). At the beginning of the life cycle until the growth phase, the supply of used products for remanufacturing is limited. After a while, when supply increases and the demand starts to decrease, more returns are available than needed. Finally, in the decline phase, the demand for remanufactured products disappears. The product life cycle should, therefore, be considered in the firm's product acquisition decisions to ensure the right quantity of returns at the right time.

Geyer et al. (2007) advocated the idea of considering product life cycle in a remanufacturing context. They investigate a CLSC system that depends upon the interrelationships between collection rate, durability and life cycle. They assume that the remanufactured product is a perfect substitute for a new product, demand is price-independent and the collection rate is constant over time and cannot be influenced by financial incentives. They modelled the product life cycle as an isosceles trapezoid and derived the closed-form solution for the return rate and sales rate. Their study revealed that, when the life cycle and collection rate are both low, the product cannot be reused since it becomes obsolete and there is no longer a market for it. On the other hand, expensively designed products may not be returned and therefore cannot be reused. In general, CLSC design should have a dynamic focus on profitability over the entire life cycle and should take all types of returns into account. For instance, commercial returns that happen early in the life cycle may be best used to fill warranty demands, while products at the end of the life cycle may be best served to meet future demand for repair parts after production has terminated. Thus, it is important to note that there are different types of returns during the life cycle, products have different time sensitivities and it is necessary to maximize the value over the entire product life cycle.

Several studies investigate the impact of the product life cycle on inventory control problems. Dobos (2003) studied the optimal inventory policies in a hybrid manufacturing-remanufacturing system when demand is a known continuous function in a given planning horizon and the return rate of used items is a given function of demand that occurs with a constant delay from the beginning of the life cycle. They present their model as an optimal control problem to show that the remanufacturing activity is a residual activity to the behaviour of manufacturing and disposal.

Ahiska and King (2010) investigate the effects of changes in the demand and return rates on the optimal inventory policies. Using a discrete-time Markov decision process, they find the optimal manufacturing-remanufacturing strategy in each life cycle stage. Chung and Wee (2011) examined the integrated production inventory model in a green supply chain by considering a short life cycle product with a stationary demand. Hsueh (2011) investigated inventory control policies in a manufacturing/remanufacturing system during the product life cycle stage. They analytically show that different inventory control policies should be adopted at different stages of the product life cycle. The impact of the product life cycle has been also a major focus in studies that address marketing issues for remanufactured products (e.g. Debo et al. (2006); Geyer et al. (2007); Akan et al. (2013) or inventory control (e.g. Ahiska and King (2010); Chung and Wee (2011); Hsueh (2011)) rather than those who investigated product acquisition management.

2.4.4 Product returns: from waste stream to market-driven strategy

In dynamic markets, uncertainty in supply flows for remanufacturing operations and rapid changes in demand for remanufactured products can lead to uncontrolled accumulation of inventory or insufficient remanufactured products to meet demand (Cardoso et al., 2013; Guide and Van Wassenhove, 2001; Guide and Van Wassenhove, 2003). Heterogeneous characteristics of product returns (as the main source of input for remanufacturing operations) in terms of quantity, quality and timing make the remanufacturing operations complex to plan, manage and control (Guide and Van Wassenhove, 2001; Guide, 2000; Guide and Jayaraman, 2000). Thus, a unique planning and control decision-making tool is required in order to manage and control the uncertainty in returns (Guide and Jayaraman, 2000). PAM is an essential process in CLSCs, which aims to deal with these characteristics of product returns (Guide and Jayaraman, 2000 and Guide and Van Wassenhove, 2001).

The concept of PAM was first formally put forward by Guide and Jayaraman (2000). The authors argue that product returns which have been previously regarded as exogenous process can be effectively planned, controlled and managed by a formal set of activities termed PAM (Figure 2—3).

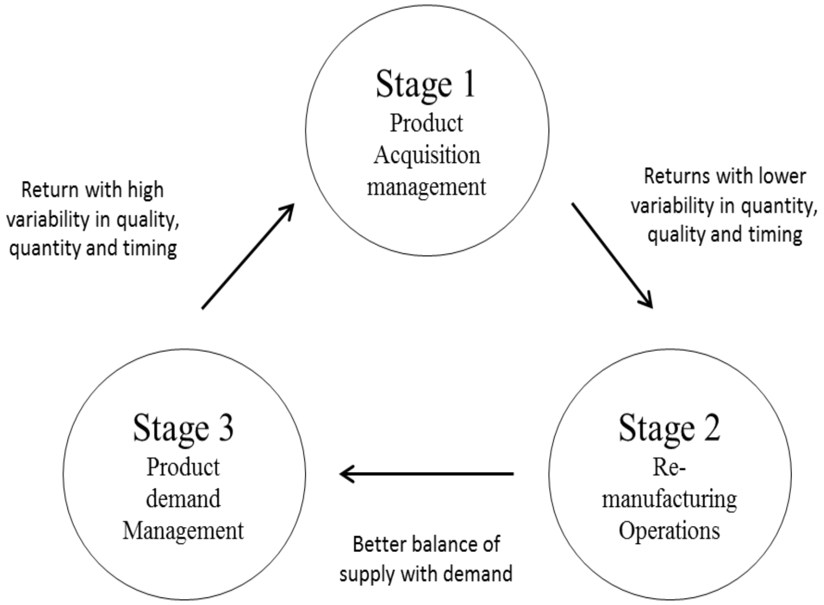

Figure 2—3: PAM in a CLSCs (adapted from Guide and Van Wassenhove 2001).

Guide and Jayaraman (2000) argue that PAM will reduce uncertainty in timing and quantity of returns thus leading to a decrease in inventories and resource costs, in turn reducing lead times and overall costs (Figure 2—4). In order to achieve this, however, functional areas such as operations, purchasing and marketing need to work in a coordinated fashion. Successful PAM not only affects the profitability of the remanufacturing operation, but also affects various operational issues such as facility design, production planning and inventory policies (Guide and Van Wassenhove 2006).

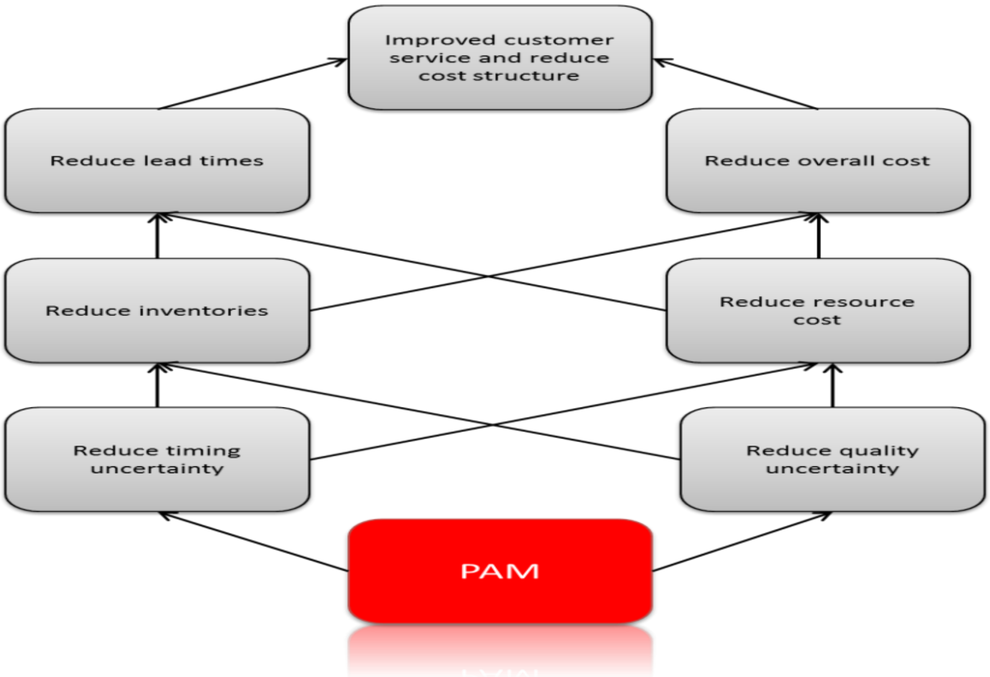

Figure 2—4: PAM and profitability (Guide and Jayaraman, 2000).

Guide and Van Wassenhove (2001) further explain this concept by discussing two major systems for obtaining used products from the end-user: The waste stream (passive strategy) and the market-driven strategy (proactive strategy). The waste stream aims to reduce discarded products from landfill and incineration by making the producer responsible for the collection and reuse of their products. A market-driven system, on the other hand, relies on financial incentives to encourage end-users to return their products for recovery.

In the waste stream system, firms passively accept all returned products since environmental legislation mandates them to engage in product recovery. Product returns in this system tend to be old with a low quality and consequently the recovery options are limited. The result of the product returns in this system is a large uncontrolled volume of used products flowing back to the OEM. This will add extra complexity to the firm's operations in terms of sorting and inventory control. Thus, firms will continuously seek a way to minimize the cost of operations (Thierry et al., 1995).

On the other hand, in the market-driven system, environmental legislation encourages firms (e.g., via tax credits) to engage in reuse activity (Guide and Van Wassenhove, 2001). Firms are able to control the level of quality of the returned product by giving incentives (e.g. a deposit system or cash for a specific level of quality) to end-users, accepting the returned products that meet the specific standards. When firms view reuse activity as a profitable proposition then the aim is to maximize the profitability of the process (Guide and Van Wassenhove, 2001; Jayaraman, 2006; Atasu et al., 2008).

These two approaches regarding product returns have a different impact on the operational characteristics of firms. In the waste stream system (Figure 2—5), since used products are passively accepted by the firm there is no control over the quality of those products. This means that additional facility space is required to store, sort and grade returned products (Guide and Van Wassenhove, 2001). The variance in quality leads to a parallel variability in the required processing time, long queues at work centres and unpredictable lead times. In this situation, planning, managing and controlling the remanufacturing facilities is both complex and challenging (Guide et al., 1997; Guide and Srivastava, 1998; Guide, 2000).

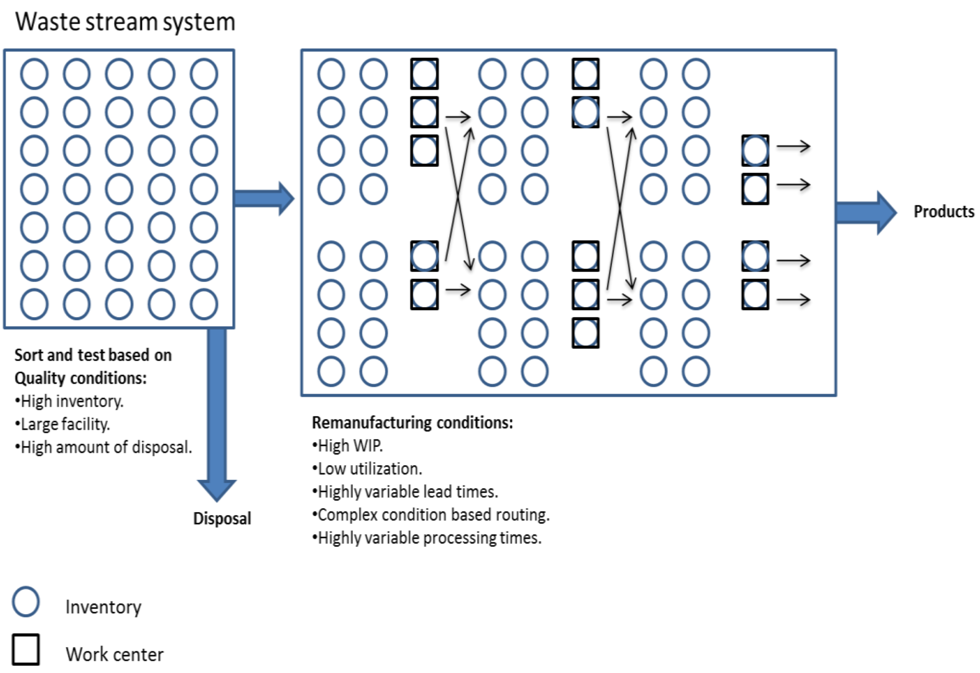

Figure 2—5: Waste stream system (Guide and Van Wassenhove, 2001).

Guide and Van Wassenhove (2001) argue that a market-driven system has several significant operational benefits for firms. Since products will be sorted and graded prior to entering the remanufacturing facility, the size of the facility will be smaller than under the waste stream system. In addition, a lesser amount of used product inventory is required. The variability of required processing times will be reduced due to the higher input quality, and this will improve flow time and the utilization of machines and labour, leading to a more productive and cost effective system (Figure 2—6).

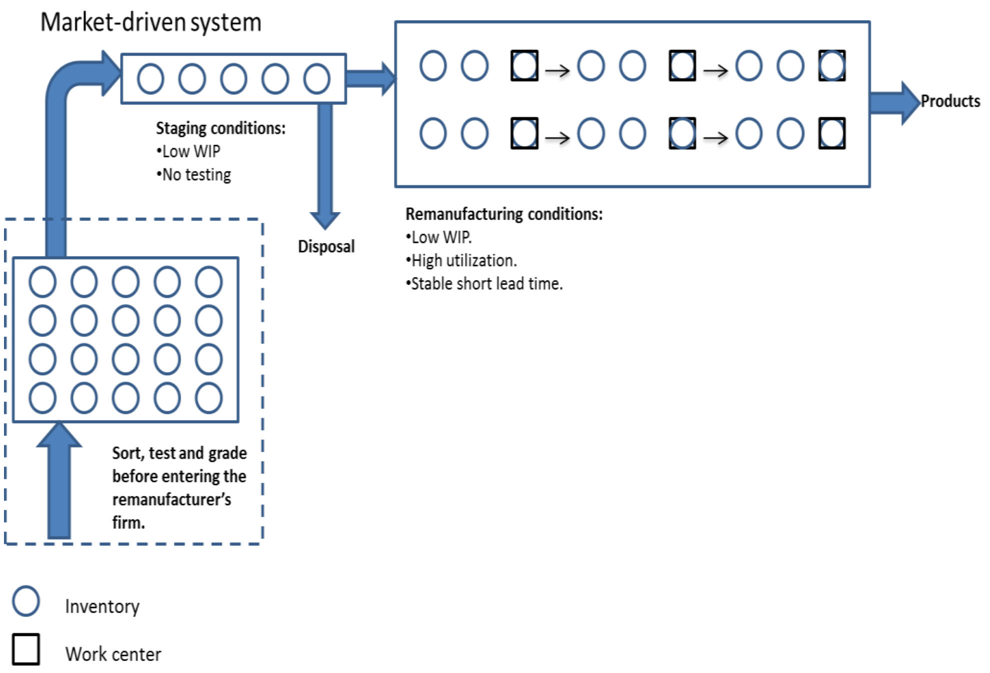

Figure 2—6: Market-driven system (Guide and Van Wassenhove, 2001).

PAM aims to proactively source adequate quantities of used products of the right quality and price at the right time in order to support remanufacturing activities throughout the product life cycle. In fact, PAM acts as an interface between reverse logistics, production planning and control activities for firms engaged in value-added recovery (Aras et al., 2004; Galbreth and Blackburn, 2006; Guide and Van Wassenhove, 2003; Guide and Van Wassenhove, 2001; Guide and Van Wassenhove, 2009). Although PAM is conceptually attractive, a careful cost analysis is required in order to evaluate the amount/type of incentives to offer such that the proactive acquisitioning becomes economically viable.

2.4.5 **Mechanisms for product acquisition**

Remanufacturers can choose different strategies to acquire used products from customers. Östlin et al. (2008) identified several relationships between remanufacturers and customers (suppliers of used product) through case studies. These relationships are introduced briefly below.

Buy-back: in this strategy the remanufacturer buys the used products from the end user or a dealer. Buy-back of used products mainly results in customers getting money. Other systems such as “rebate” also exist, where the remanufacturer gives a discount on a product if the customer agrees to return the product after use (Toffel, 2004). This strategy is reported to be efficient in prohibiting customers from returning or selling products to other companies. One of the major decisions in this strategy is to adjust the acquisition price in order to obtain sufficient returns for remanufacturing. The buy-back strategy is the main focus of this study and will therefore be discussed in more detail in section 2.5.

Ownership-based: In this type of strategy the product is owned by the OEM and the customer acts as the operator. Rental, lease or product-service offers are examples of this type of relationship. One of the main advantages of the ownership-based strategy is that returns are more predictable due to the additional information that is available for the remanufacturer (Thierry et al., 1995). Agrawal et al. (2012) compared leasing and selling strategies for durable products. Under a leasing strategy an OEM offers one-period operating leases in which the firm maintains ownership of the off-lease units and has the option of remarketing them and the obligation to dispose of end-of-life products. Under a selling strategy, the OEM only sells new products; used products are traded between consumers on the secondary market and it is the consumers who dispose of end-of-life products. Agrawal et al. (2012) find that the profitability and environmental impact of leasing compared to selling depends on the product durability and the product’s environmental impact during its life cycle. Robotis et al. (2012) investigate the optimal leasing duration and price when the production and servicing capacity are constrained, and where remanufactured and new products are perfect substitutes.

They formulate the problem as an optimal control problem (in a Bass-type diffusion model) and show that if remanufacturing provides a high saving, then the firm should offer long leasing contracts.

Service-contract: in this type of relationship the OEM is responsible for providing a remanufacturing service for customers. This type of relationship is very similar to the ownership-based strategy. In service-based contracts, however, the ownership goes to the customer. Also, usually the service-contract includes other activities such as repair and maintenance after a set period of time (Östlin et al., 2008)

Deposit-based: in a deposit-based relationship the customer is obliged to return the used product when purchasing a new/remanufactured product. This relationship can happen directly between a customer and an OEM, or through a retailer (middle-man). For instance, in the automotive industry, the retailer pays a price and a deposit to the OEM for a remanufactured product. Later, when the retailer sells the product, they collect the used core from customer and return it to the OEM to refund their deposit (Östlin et al., 2008). The amount of deposit that is refunded depends on the quality of the cores. Wei et al. (2014) study the refund policy for cores with variable qualities and compare this strategy with credit policies where no deposit is charged. They found that the deposit strategy is better if demand sensitivity is not too high. Section 4.2 in this thesis presents a case study based on a deposit-based strategy so as to gain more insight into the advantages and disadvantages of this policy.

Credit-based: this type of relationship is very similar to the deposit-based relationship, except that, instead of a deposit fee, the customer receives credits for what they supply to the company. Obviously, the amount of credit depends on the quality of the used products. This credit is then used as a discount when the customer buys a new remanufactured product.

Direct-order: In a direct order scenario the customer returns the used product to the remanufacturer, and the same product will be returned to the customer after being remanufactured (if performing a remanufacturing operation is possible). Direct-order relationships are usually for those products that have to be remanufactured using the original serial-number-specific parts. As discussed in section 2.4.1, the problem of material matching is the major complexity in this type of relationship (Guide and Jayaraman, 2000).

Voluntary-based: this system is based on the concept that the customers will voluntarily give back their used items. This system is common in the recycling of materials, although it also exists in CLSC with remanufacturing (e.g. refillable containers).

As pointed out by Östlin et al. (2008), the above relationships may be used in tandem to complement each other. For instance, BT industries uses both ownership-based and buy-back strategies, while Volvo Parts have deposit-based and buy-back strategies. Chapter 4 of this thesis provides several empirical case studies to investigate different product acquisition mechanisms currently used by remanufacturing firms in the UK.

2.5 Product acquisition decisions

As discussed previously, one of the key considerations in a remanufacturing environment is the management of used-product acquisition. The main objective of PAM is to control the quality, quantity and timing of returns. This section examines the studies that specifically address product acquisition decisions in CLSC. The main objective of these studies is to determine the optimal acquisition quantity and quality for remanufacturing and optimal acquisition price.

As mentioned in section 2.4.4, used products can be obtained through waste stream or market-driven strategies. If the remanufacturer passively accepts used items then the role of acquisition management is minimal. The majority of the acquisition models, therefore, assume some degree of control over quantity, and the research in the area can be divided into two broad streams based on the degree of control over the quality of acquired items. One stream of research assumes that quality can be influenced by the remanufacturer via pricing decisions. In these cases, the remanufacturer pays a higher price for better-quality units, effectively transferring the process of grading used items to the supplier of the items (e.g., the collector or the consumer). In the CLSC, this implies that grading occurs prior to acquisition by the remanufacturer, a fact that reduces uncertainties and streamlines remanufacturing operations. The second stream of research addresses the case where used item quality cannot be influenced by the remanufacturer. In this scenario, firms can influence the quantity of returns to increase the selectivity for remanufacturing operations. In this stream, items are acquired in unsorted lots, and the testing/grading process does not occur until after the remanufacturer has received the items.

2.5.1 Quality of returned products

The quality of returned products can vary significantly based on their previous usage pattern, which means that the acquisition of the right quality of used products is an important factor with a direct impact on the firm’s manufacturing-remanufacturing decisions. There are two main approaches to model the quality of returned products; (1) *Quality as yield rate*; in these studies quality is defined as the percentage of returns that pass a quality test and are thus suitable for remanufacturing. (2) *Predefined quality level;* in this type of model the quality of returns is classified in different quality classes (usually in two types; good quality and bad quality). Section 2.5.2 considers studies that look at a pure remanufacturing environment, where demand can only be satisfied by acquisition of returns and remanufacturing operations; section 2.5.3, meanwhile, looks at hybrid systems where remanufacturing is done by an OEM. In this case, market demand can be satisfied by both manufacturing new products and remanufacturing returns.

2.5.2 **Pure remanufacturing environment**

Guide and Van Wassenhove (2001) were among the first in the reverse logistics literature to advocate the concept of Product Acquisition Management (PAM) as a key input to the assessment of the potential attractiveness of recovery activities. They proposed the method of Economic Value Added (EVA) as the main framework to determine the potential profitability of reuse opportunities, and show that firms are able to control the level of quality of returned products using a market-driven approach. Based on this idea Guide et al. (2003b) developed an economic model to find the optimal acquisition prices, acquisition quantities and selling price for remanufactured products. Their research is motivated by work with Recellular, an independent mobile phone remanufacturer that needs to buy the optimal combination of products that can be remanufactured with different quality classes from several sources (e.g. airtime providers and third-party collectors). These intermediaries sort and maintain the used products in different quality classes. Recellular then buys the graded handset from these intermediaries by offering different price incentives (according to the quality level of the handsets). The return rate for each quality class is a function of acquisition price (poorer quality products have a lower acquisition cost but a higher remanufacturing cost). At some point, if the acquisition price falls below some threshold, intermediaries would not collect the used products, therefore the supply would disappear. They assume that demand is a function of selling price (i.e. demand rate is independent from return rate and decreases linearly with selling price). Assuming that supply is an increasing, twice differentiable function of price, the authors formulate a profit maximisation problem to determine the optimal combination of acquisition price and selling price for remanufactured items. Under the perfect remanufacturing assumption, they found an optimal combination between the acquisition and selling price. This research provides some important insights regarding PAM: it shows that product acquisition is a primary driver in determining whether reuse activities will be profitable or not; in addition, firms can optimize the overall profitability by controlling the quality of the acquired products; finally, it suggests that effective product recovery management should consider market demand, remanufacturing costs and product acquisition simultaneously. Karakayali et al. (2007) also assume that returns can be categorised into a number of quality classes, and model the supply of each quality category as a linear function of price. They determine the optimal acquisition price of end-of-life durable products, as well as the selling price of the remanufactured parts for centralized and decentralized reverse channels structures.

Bakal and Akcali (2006) investigated the effect of random recovery yield on the acquisition and selling price decisions. Their study focuses on end-of-life-vehicles (ELV) products wherein a specific part that conforms to a certain quality level can be remanufactured with the rest being recycled for material recovery.

They consider a single acquisition price and a single unit remanufacturing cost, and quality is defined as a simple threshold (all returns above the threshold are remanufactured, and those below the threshold are scrapped). They developed three single-period models to determine the optimal acquisition price for ELV products and the selling price for remanufactured parts. In their base model, they assume that yield is deterministic, i.e. the remanufacturer knows the amount of the ELV with remanufactured parts in advance. In the second model, they assume that the yield is random, but that the remanufacturer has the opportunity to set the price of the remanufactured parts after realization of the random yield. In the last model, the acquisition price, and the price of the remanufactured part, will be determined prior to the realization of the random yield. Thus, in the third case, if the yield is not enough to satisfy demand, then the remanufacturer should be bound by their price decision (which they made prior to the realization) and may have to incur a penalty cost for unsatisfied demand. Bakal and Akcali (2006) assumed that the quantity of end-of-life products and the demand for the remanufactured parts are linearly dependent on the acquisition and selling prices respectively. The result of their analysis suggested that there is a benefit in delaying pricing decisions until after the yield is realized, and until the value of the perfect yield rate is understood. Due to the random yield, however, the firm cannot set prices to match the demand exactly, as in (Guide et al., 2003b).

Ray et al. (2005) focus on optimal pricing and trade-in rebate decisions for a profit-maximizing firm selling a durable, remanufacturable product. The authors assume that the potential market consist of first time buyers and replacement customers who are only considering trading in their existing products. They investigate the optimal prices/trade-in rebates under three pricing schemes 1) a uniform price for customer segments 2) age-independent price differentiation i.e. one price for the new customers and a fixed, age-independent trade-in rebate (price) for the replacement, 3) Age-dependent price differentiation: One price for the new customer segment and a continuous set of age-dependent trade-in rebates (prices) for the replacement customers. The authors identify the most favourable pricing and trade-in strategy for the firm and define the market characteristics for which each strategy is optimal. Their model advocates that during the incubation phase customer segmentation and price differentiation are not critical (i.e. charging uniform price for all customers is reasonable). The adoption of a price-discrimination mechanism and offering differentiated prices (age-independent) trade-in rebates for replacement customers is more favourable during the growth phase. Finally, when the product completely diffuses into the marketplace and reaches maturity, it is appropriate to further differentiate replacement customers by offering age-dependent rebates.

Another stream of research addresses the scenario where the remanufacturer acquires unsorted returns of used products with no influence over the quality. Here, the acquisition decision is mainly on the quantity of returns and, therefore, in this stream of research the focus is mainly on the sorting operation. The importance of sorting is that the remanufacturer can decide which returns are good for remanufacturing and which have to be scrapped to reduce the cost of disassembly.

Galbreth and Blackburn (2006) investigate the optimal acquisition and sorting policies in a single-period model. The authors assume that for any batch of acquired used products, the quality distribution can be approximated by a known probability distribution. The remanufacturer assigns returns into two categories: remanufacture or scrap. Under this assumption, higher acquisition amounts enable firm to be more selective in meeting a given demand. This implies a trade-off between scrapping and acquisition cost, on the one hand, and remanufacturing cost on the other hand. The higher the total amount of returns collected, the higher the acquisition cost, but the total remanufacturing cost is lower because there are more returns with better quality. In this situation, the firm has to make two related decisions: first how many used products to acquire, and second, how selective to be during the sorting process. The main objective of Galbreth and Blackburn's model is to optimise this trade-off. They found that increased selectivity in sorting will lead to a lower yield (accepting products that have better quality) but that the remanufacturing cost will decrease. Galbreth and Blackburn (2006) assumed that the probability distribution of the returns quality is known, and constant with respect to the quantity of returns. This assumption however holds if the acquisition quantities are high enough such that the probability distribution associated with the sample closely matches the overall population of returns (Souza, 2013). Galbreth and Blackburn (2010) extend this work by assuming that there is uncertainty in the condition of returned products i.e. the quality distribution of the acquired products is unknown. They analyse several models with different quality levels and cost functions, confirming the results of their earlier work. In both Galbreth and Blackburn (2006) and (2010) the focus was on the grading but not on acquisition decisions and price.

Zikopoulos and Tagaras (2007) also investigate the impact of the variable quality of returns on the profitability of the reuse activities. They examine a reverse supply chain with two collection sites and a refurbishing centre which faces a stochastic demand. Their objective was to determine the optimal remanufacturing quantity to meet demand from each collection site. They assume that returns originate from two collection sites, but that the firm cannot influence the return rate.

They optimise acquisition quantities from each collection site and the total production quantity for a firm facing an uncertain demand. Their model confirms that the quality of product returns has a substantial impact on the system profitability. Zikopoulos and Tagaras (2008) study a special case of their previous model in which there are misclassification errors in the sorting operation (used products with a good quality are classified as bad or vice versa). They compared two systems in terms of profitability; remanufacturing with and without grading/sorting before disassembly operations. The result of this comparison reveals the condition in which it is optimal to set up a sorting operation before disassembly operations. Ferguson et al. (2009) examined the potential benefits of quality grading of returns, however, in their model the acquisition price plays no role since leasing acts as a product acquisition management technique. The paper investigates the value of a nominal quality grading system, without classification error, and the advantages of keeping separate inventories for each quality class. They derive an optimal production plan and, through a numerical investigation, show that the presence of a grading system will increase profit.

Nikolaidis (2009) proposed a mixed integer programming model to determine the optimal quantities to be procured and remanufactured. The result of this study implies that when a product acquisition system is encouraged the profitability of reuse activity can be substantial. Nenes and Nikolaidis (2012) extend the study of Nikolaidis (2009) to a multi-period model, and investigate optimal procurement, remanufacturing, stocking and salvaging decisions. Similar to Nikolaidis (2009), they formulated a MILP with deterministic demand and return. They also assumed that third party collection sites have several batches of returned products available which the recovery facility may choose to acquire or ignore, while it also has the option of using a certain part of acquired batches. In their model, the quantity of products which belong to a certain quality level for each particular batch is known. The result of their study suggests that the acquired used products need different remanufacturing efforts due to the heterogeneous quality of the items.

More recently, Pokharel and Liang (2012) assumed a linear relationship between the acquisition price and return rate and proposed an analytical model to evaluate optimal quantity and acquisition price. In their model, they consider multiple collection centres and one consolidation centre. The consolidation centre is the decision-maker, which obtains demand and price information from the remanufacturer and develops acquisition quantities and the price to be offered to the collection centres.

In contrast to Galbreth and Blackburn (2006, 2010), Teunter and Flapper (2011) consider multiple quality classes and multinomial quality distribution for an acquired lot and derive optimal acquisition and remanufacturing policy for both uncertain and deterministic demand. In contrast to Guide et al. (2003), they assume that the acquisition cost is quality-independent and does not affect the supply of used products (i.e. acquisition price does not influence the quality distribution of supplied cores). In this situation, if the number of returns is less than the demand then the firm has to remanufacture all the returns, otherwise, the firm exactly remanufacturers to satisfy demand. Under these assumptions, the authors show that an increase in demand variation leads to an increase in the optimal number of acquired cores and the optimal remanufacturing-up-to levels but it still yields a higher lost sale. This means that an increase in the optimal safety stock only partially offsets the increase in demand uncertainty. Similarly, Xiong et al. (2014) proposed dynamic pricing for obtaining returns in a stochastic and continuous time environment using Markov decision processes. The authors assume that the firm can only control the quantity of returns by offering a dynamic price incentive (i.e. price does not depend on the quality of products). Different to Galbreth and Blackburn (2006), where the condition is defined as the cost of remanufacturing, they assume that the cost of remanufacturing is exogenous but that the time required for remanufacturing varies depending on the condition of the used product.

All these studies investigate product acquisition decisions in a pure remanufacturing environment. The following section looks at the studies that assume hybrid systems to investigate PAM.

2.5.3 Hybrid manufacturing-remanufacturing systems

Aras et al. (2004) was one of the first to analyse the cost effectiveness of quality-based categorization in a hybrid manufacturing/remanufacturing system. Through a continuous-time Markov chain model and numerical studies, the authors show that incorporating returned product quality in the remanufacturing and disposal decisions can lead to significant cost savings for firms. The authors assume that the newly manufactured and remanufactured items are perfect substitutes and there is no capacity restriction for remanufacturing. Mondal and Mukherjee (2006) also developed an analytical model to determine the optimal time to buy-back used products to maximize the economic benefit from remanufacturing, by investigating the economic parameters that influence product acquisition decisions.

Minner and Kiesmüller (2012) investigate the dynamic buy-back policy in a hybrid manufacturing and remanufacturing environment. In their model, it is assumed that all the returns are of the same quality, and that firms can influence the rate of returns by offering dynamic buy-back prices. Furthermore, they assume a linear relationship between the return rate and the incentive price. The authors present a deterministic, dynamic optimisation model based on the Pontryagin's Maximum Principle and provide an insight into dynamic buy-back and manufacturing-remanufacturing decisions. They find an optimal policy that includes the time intervals at which returns are acquired so as to synchronise demand and remanufacturing, where returns are acquired and stored for future remanufacturing, and intervals when demand is satisfied by a mix of manufactured and remanufactured products. In their model, the acquisition decision is based on the relationships between demand and returns and not on the quality of returns. Although their study provides an interesting insight into the dynamic environment of a hybrid system, the impact of the quality of returns has not been addressed, either by quality-dependent price incentives, or by testing and grading operations.

Kleber et al. (2012) considered a scenario in which OEMs buy-back broken products in order to improve control of both demand for spare parts and supply of recoverable parts. This contribution seeks to assess the potential benefit of buy-back strategies in contrast to both traditional sourcing and trade-in policies. For each situation, a MILP formulation is presented and, in a numerical study, they analyse the circumstances under which the buy-back of broken products is especially beneficial for the OEM.

Kaya (2010) also considers a hybrid manufacturing-remanufacturing system where demand can be satisfied by manufacturing new products using virgin materials and remanufacturing products using customer returns. The author assumes that the manufacturer offers an incentive to customers to influence the quantity of returns and that remanufactured products are a perfect substitute for new products. Kaya determines the optimal manufacturing-remanufacturing quantities, as well as the optimal incentive price in a stochastic demand setting, and investigates this problem using newsboy models, considering both centralized and decentralized settings.

Cai et al. (2014) investigated the optimal acquisition pricing and production planning problems when returned products are in two quality conditions: high- and low-quality. The authors assume that there is no acquisition lead time and that both low and high quality returns are able to be remanufactured, i.e. no scrapping or disposal is required.

2.6 Identification of research gaps

Studies in the area of CLSC initially focused on individual activities in the reverse supply chain such as design for disassembly, shop floor control or distribution networks. Several scholars have employed an optimisation approach to identify and explain a plethora of issues in the context of remanufacturing, ranging from inventory control, reverse distribution, value of information, to remanufacturing shop design. These studies typically assume that product returns are exogenous and uncontrollable.

Guide and Van Wassenhove (2001) was one of the first papers to delineate the concept of product acquisition management as part of a market-driven strategy. In the market-driven strategy, remanufacturing firms seek to control the timing, quantity, and quality of product returns through appropriate economic incentives. PAM is identified as a key input into the evaluation of the potential economic attractiveness of reuse activities. If companies are unable to identify the potential financial benefits of engaging in CLSC, they are unlikely to become active in the value recovery operation (Guide and Van Wassenhove, 2002; Guide et al., 2003a;

Guide and Van Wassenhove, 2006) Most of the time, however, it is not the remanufacturing operation that matters, but rather the lack of a market for remanufactured products or the lack of used products of sufficient quality and quantity.

Through the literature review, it can be observed that the number of papers on product acquisition management is relatively small. This is remarkable given that product acquisition is one of the key processes in CLSC (Ferguson and Souza, 2010). Recently, however, it does appear that this field of research is attracting more research interest. In the studies that investigate product acquisition decisions, it is the cost structure (in particular, the acquisition cost) that is the main element. The majority of the models simply assume a linear acquisition cost structure (i.e. a linear relationship between return rate and acquisition price), but this assumption may not adequately reflect reality and more general acquisition cost functions can be used to allow for a broader application (Mahapatra et al., 2012; Rubio and Corominas, 2008). Factors such as location, advertising, transportation, etc., have an influence on acquisition costs i.e. it becomes more expensive for companies to increase the number of returns. Consequently, the cost advantage of the remanufacturing operation might be offset by the high acquisition cost. Thus, it is imperative that research incorporates a more realistic cost structure to represent the return response function (Souza, 2013). In addition, the impact of quality-based incentives has received little attention. The majority of studies assume that the firm influences the quantity of returns by offering incentives and that the quality will be handled by the sorting operation.

Another important factor that has received little attention is the impact of the product life cycle. The dynamic imbalance between return and demand is caused by the product life cycle and the time lag of returned products. At the beginning of the product life cycle the demand for products is relatively high and returns are insufficient since the products are with customers. Later in the life cycle, however, this relationship changes, as the demand reaches a stable or decline phase and the returned volume increases. The product life cycle, therefore, certainly affects the product availability for remanufacturing operations and has to be considered in product acquisition management studies.

Furthermore, the review of the literature has revealed the importance of the product life cycle in the remanufacturing environment. The impact of the product life cycle has been investigated in inventory control problems and the marketing issues in CLSC. It should also be considered, however, in the firm's product acquisition decisions so as to ensure the right quantity of returns at the right time. Surprisingly, despite the importance of the product life cycle, there are very few studies that take it into account when investigating product acquisition decisions.

Finally, the majority of studies investigate product acquisition management in a pure remanufacturing environment, but the relationship between manufacturing and remanufacturing cost, quality and quantity of returns is an important factor for OEMs who are engaged in remanufacturing operations. There is a need, therefore, for more investigation into product acquisition management in hybrid systems.

Table 2—1 summarises the studies relevant to product acquisition management. The key features of these studies are shown in the table to give a clear picture of the variety of research carried out in this area.

The two main streams for modelling the quality are distinguished as "recovery yield" and "quality level". "Hybrid manufacturing-remanufacturing" and "pure remanufacturing" indicate the assumptions regarding the remanufacturing environment. The studies that addressed product acquisition decisions are shown in the "PAM" column. The "Acquisition cost structure" column shows the properties of the acquisition cost function that have been used in the previous studies. Furthermore, consideration of life cycle characteristics, inventory, network design, secondary market and lead time are shown in the corresponding columns. "Period" indicates if the study investigates product acquisition under the "S" (for single) or "M" (for multiple) period setting. The dynamic ("D") and static ("St") models are distinguished in the "Modelling environment" column. The column related to demand includes "deterministic" and "uncertain" to show the characteristics of the modelled demand. Finally, a brief description of the mathematical method is presented in the "Method" column.

Table 2—1: Summary of the papers related to this work

Paper	**Quality**		**Model features**											**Demand**		Types of recovery routes	**Method**
	Recovery yield	Quality level	Hybrid manufacturing-remanufacturing	Pure remanufacturing	PAM	Acquisition cost structure	Product Life cycle	Inventories	Network design	Secondary market	Lead time	Period	Modelling environment	Uncertain	Deterministic		
This study (Chapter 5 and 6)	X	_	X	_	X	L& NL	X	_	_	_	X	S	St	_	X	1	Analytical optimisation
This study (Chapter 7)	_	X	X	_	X	L	X	_	_	_	_	M[1]	D	_	X	1	Optimal control
Teunter and Vlachos (2002)	_	_	X	_	_	_	_	X	_	_	X	S	St	X	_	1	Simulation
Guide et al. (2003)	_	X	_	X	X	NL	_	_	_	_	_	S	St	_	X	1	Analytical optimisation
Aras et al. (2004)	_	X	X	_	_	_	_	X	_	_	X	M	D	X	_	1	Markov Chains
Guide et al. (2005)	X	_	_	_	_	_	_	X	_	X	X	M	St	_	X	2	LP
Galbreth and Blackburn (2006)	X	_	_	X	X	L[2]	_	_	_	_	_	S	St	X		1	Analytical optimisation
Guide et al. (2006)	_	_	_	X	_	_	X	_	X	X	X	S	St	_	_	1	Analytical + Simulation
Geyer et al (2007)	_	_	X	_	_	_	X	_	_	_	X	S	St	_	X	1	Analytical optimisation
Zikopoulos and Tegaras (2008)	X	_	_	X	_	_	_	X	_	_	_	S+M	St	X	_	1	Analytical optimisation
Rubio and Corominas (2008)	X	_	X	_	X	NL	_	_	_	_	_	S	St	_	_	1	Analytical optimisation
Ferguson et al. (2009)	_	X	_	X	X[3]	_	_	X	_	_	_	M	D	X	_	1	DP
Galbreth and Blackburn (2010)	X[4]	_	_	X	X	L	_	_	_	_	_	S	St	_	X	1	Analytical optimisation
Kaya (2010)	_	_	X	_	X	L	_	_	X	_	_	S	St	X	_	1	Analytical optimisation

1. Continuous time; 2. Non-linear acquisition cost briefly examined; 3. Leasing is considered as the product acquisition strategy: 4. The uncertainty in quality condition is investigated.

Paper	Quality		Model features											Demand		Types of recovery routes	Method
	Recovery yield	Quality level	Hybrid manufacturing-remanufacturing	Pure remanufacturing	PAM	Acquisition cost structure	Product Life cycle	Inventories	Network design	Secondary market	Lead time	Period	Modelling environment	Uncertain	Deterministic		
Teunter and Flapper (2011)	_	X	_	X	X	L	_	_	_	_	_	S	St	X	X	1	Analytical optimisation
Che-Fu Hsueh (2011)	_	_	X	_	_	_	X	X	_	_	X	S	St	_	X	1	Analytical optimisation
Pokharel and Liang (2012)	_	X	_	X	X	L	_	_	_	_	_	S	St	_	X	1	Analytical optimisation
Minner and Kiesmuller (2012)	_	_	X	_	X	L	_	X	_	_	_	M	D	_	X	1	Optimal Control
Xiong et al. (2014)	_	X	_	X	X	L	_	X	_	_	_	M	D	X	_	1	MDPs
Cai et al. (2014)	_	X	X	_	X	L	_	X	_	_	_	M	D	X	_	1	MDPs
Bulmuş et al. (2014),	_	X	X	_	X	L	_	_	_	_	_	S	St	_	_	1	Analytical optimisation

D: Dynamic; DP: Dynamic Programming L: Linear acquisition cost function; LP: Linear Programming; M: Multiple; MDPs: Markov Decision Processes; NL: non-linear acquisition cost function; S: Single.

The research questions presented in Section 1.2 (Chapter 1), are developed to address some of the gaps highlighted in the previous section. The main contribution of the present study is that it extends the knowledge on product acquisition management in CLSCs by incorporating some important features that have not been studied previously.

A more general acquisition cost function (in the form of a rational function) will be introduced when investigating the economic viability of proactive product acquisition strategies (market-driven) over a passive strategy (waste-stream). Utilising this acquisition cost function enables us to capture a more realistic relationship between acquisition effort and returns quantities/qualities. Both quantity-based and quality-based incentives approaches will be considered in the present study and their sensitivity to the different cost parameters will be explored. In that manner the research works towards Souza (2013) call for further research to incorporate realistic cost structures in designing product acquisition management models for CLSCs.

As can be seen in the Table 2—1, product life cycle is another important factor that has received very little attention in the area of product acquisition management. The call for the incorporation of product life cycle considerations in product acquisition management is not new. Guide and Jayaraman (2000) called for this kind of research more than a decade ago and yet as Fleischmann et al. (2010) note little has been done to address the differentiation of product availability of different quality levels at different prices.

This study extends its investigation on the economic viability of the market driven strategy by using product life cycle as a basis for matching demand and supply. Incorporating the product life cycle allows us to investigate the impact of important elements such as returns lead time and synchronisation of supply and demand on the product acquisition decision. Finally, a dynamic model will be developed to explore dynamic manufacturing-remanufacturing and buy-back strategies for used products in multiple quality-level. The dynamic model can account for time dependent changes in the state of the system such as quality decay and seasonal effects.

The present study addresses the above gaps by developing generic quantitative models for broader understanding of the problem in product acquisition management. The results of the models will generate interesting managerial insights regarding the model cost behaviour in relation to the optimal acquisition strategy and buy-back level.

2.7 Conclusion

This chapter has reviewed the literature in the area of RL and CLSC. As discussed earlier, CLSC starts with the acquisition of used products to serve as a supply for remanufacturing operations. Given that used products inherit a high degree of uncertainty in terms of quantity, quality and timing, product acquisition management is the key to a successful remanufacturing operation and is critical to the management of the CLSCs.

Product acquisition management is the main focus of this study. Therefore, the emphasis has predominantly been on the characteristics and challenges of the remanufacturing environment and the economic role of product acquisition management in CLSCs. The key theory terms in the area of RL that are relevant to this study are presented in this chapter. These are *closed-loop supply chain*, *remanufacturing process*, *characteristics of remanufacturing* and *product acquisition management.* Subsequently, various mechanisms that remanufacturers can choose in order to acquire used products were discussed.

This review has highlighted gaps in the literature that were summarised in the previous section. Notably, the number of papers on product acquisition is fairly small. Furthermore, less attention has been paid to the structure of the acquisition cost function, which is one of the main elements in the studies that investigate product acquisition decisions. Another key factor that needs to be incorporated in the product acquisition decision is consideration of the product life cycle.

This thesis aims to address the gaps identified in previous studies on product acquisition management. Economic models will be developed to investigate the optimal product acquisition strategy in a CLSC and the economic attractiveness of the proactive acquisition strategy over the passive strategy. For the proactive strategy, a general acquisition cost function (in the form of a rational function) will be proposed, allowing both linear and non-linear relationships between the return rate/returns quality and acquisition cost to be captured. Furthermore, the product life cycle is incorporated into this model, allowing investigation of the impact on the product acquisition decision of important elements such as returns lead time and synchronisation of supply and demand. This investigation includes both static and dynamic acquisition policies in the finite planning horizon. The next chapter describes and justifies the research methodology used to achieve the research aims.

Chapter 3

Research Methodology

3.1 Introduction

This chapter will delineate a description of the concepts and methods that are used in this thesis. In general terms, this research applies an Operations Management research method to address its aim and objectives. Primarily, the research is based on quantitative modelling that falls under the Operational Research (OR) discipline. Besides developing and analysing the quantitative models, empirical case studies are conducted in order to better understand the motives and barriers of remanufacturing and product acquisition in practice. This chapter is arranged as follows. First, the philosophical position of this study is briefly discussed in section 3.2. Section 3.3 discusses the overall methodology of this research, highlighting the advantage and disadvantages of each approach. Finally, section 3.4 discusses the research process and provides details of each research step undertaken to complete this study.

3.2 Philosophical worldview

As pointed out by Mingers (2000), many issues are under debate when it comes to the philosophical worldview of OR studies. Is OR science or technology? Is it a natural or social science? Can it be realist as well as being interpretivist?

Pragmatism is one of the views that is very compatible with the practical, ends-oriented nature of OR and has been implicitly suggested by Raitt (1979) and Dando et al. (1977) (as cited in Mingers, 2000). There are several forms of this philosophy, but for many, pragmatism as a worldview arises out of actions, situations and consequences (Creswell and Clark, 2007). At a general level, pragmatism views science as an essentially practical activity aimed at producing useful knowledge rather than an understanding of the true nature of the world (Mingers, 2000).

A pragmatic worldview is concerned with applications (what works) and solutions to problems. It is one of the philosophical foundations for mixed method studies since the research focus is problem-based and then pluralistic approaches are used to derive knowledge about the problem (Creswell (2013) and Morgan (2007)). Creswell (2009) has classified the major assumptions for this worldview as below: (summarised from Creswell, 2009, pp.10-11):

- Pragmatism is not committed to any one system of philosophy and reality. This applies to mixed methods research in which explorations draw liberally from both qualitative and quantitative assumptions.
- Pragmatic researchers are free to choose the methods, techniques and procedures of research that best meet their needs.
- Pragmatists do not see the world as an absolute unity. Pragmatic researchers look to many approaches for collecting and analysing data rather than subscribing to only one way (e.g., quantitative or qualitative).
- Pragmatic researchers believe in an external world independent of the mind as well as a world lodged in the mind.

- Truth is what works at the time. It is not based in a duality between reality independent of the mind or within the mind. Thus, in mixed methods research, investigators use both quantitative and qualitative data because they work to provide the best understanding of a research problem.
- The pragmatist researchers look to the ‘*what*’ and ‘*how’* to research, based on the intended consequences—where they want to go with it. Mixed methods researchers need to establish a purpose for their mixing, a rationale for the reasons why quantitative and qualitative data need to be mixed in the first place.
- Pragmatism opens the door to multiple methods, different worldviews, and different assumptions, as well as different forms of data collection and analysis.

The pragmatic approach offers a flexible and effective alternative by working back and forth between the two extremes through its emphasis on the abductive–intersubjective–transferable aspects of research (Morgan, 2007). This study adopts both quantitative and qualitative approaches to address its research questions. Along with developing quantitative models, qualitative information has been gathered through empirical case studies to provide a better understanding of the research problem. The research process and the rationale for using case study along with the quantitative models are explained in further detail in the following sections.

3.3 Overview of research methodology

This study predominantly employs quantitative modelling to address the research objectives. In general, model-based research is classified as a rational knowledge generation approach (Meredith, 1998). In this type of research, objective models are developed based on researcher led assumptions in an attempt to explain (part of) the behaviour of real-life operational processes or to capture (part of) the decision-making problems that are faced by managers in real-life operational processes (Bertrand and Fransoo, 2002). In quantitative modelling, the relationship between variables is described as causal, meaning that it is explicitly recognized that a specified change of value in one variable will lead to a change in another variable. The fact that relationships are causal allows the model to predict the future state of the modelled process (Bertrand and Fransoo, 2002).

Model-based research can be classified into two distinct classes: axiomatic or empirical, with each of these classes also being either normative or descriptive. This study employs axiomatic quantitative modelling to investigate the optimal PA strategies in reverse and Closed–loop Supply Chains, as well as to explore the impact of different costs on these strategies. Meredith et al. (1989) frame axiomatic research as a rational-artificial approach. ‘Rational’ relates to the epistemological structure of the research process; rationalism uses a formal structure and pure logic as the ultimate measure of truth. Research falling into the rationalist approach is based on the belief that the phenomenon being studied exists independently of the research context or the beliefs and assumptions of the researcher (Guba, 1990; Klein and Lyytinen, 1985). ‘Artificial’ concerns the source and kind of information used in the research. An artificial approach is based on abstracted and simplified models and is characterized by a significant separation of the phenomenon from the researcher (Table 3—1).

Table 3—1: A framework for research methods (Meredith et al., 1989, P. 309).

Natural ⟷ Artificial

		Direct observation of object reality	People's perceptions of object reality	Artificial reconstruction of object reality
Rational	Axiomatic			Reason/logic/theorems **Normative modelling** **Descriptive modelling**
↕	Logical positivist/empiricist	Field studies Field experiment	Structured interviewing Survey research	Prototyping Physical modelling Laboratory experimentation Simulation
	Interpretive	Action research Case studies	Historical analysis Delphi Intensive interviewing Expert panels Futures/scenarios	Conceptual modelling Hermeneutics
Existential	Critical theory		Introspective reflection	

According to Bertrand and Fransoo (2002), the main objective in axiomatic research is obtaining a solution within the defined model and making sure that these solutions provide insights into the structure of the problem as defined within the model (Table 3—2).

It is difficult to label the quantitative model-based research in this study as either purely normative or descriptive. The optimisation methods that are used in this thesis can be classified as normative, while analytical models may classified as descriptive.

Table 3—2: Quantitative model based OM research (Bertrand and Fransoo, 2002).

	Normative research	Descriptive research
Axiomatic research	Normative research is interested to “develop policies, strategies and plans, to improve over the result available in the existing literature, to find an optimal solution for a newly defined problem, or to compare various strategies for addressing a specific problem”	Descriptive research is primarily interested in analysing a model, which leads to an understanding and explanation of the characteristics of the model.

The research conducted in the field of Operations Management is dominated by rationalist research methods consisting primarily of statistical survey analyses and mathematical modelling (Voss et al., 2002). The key strengths and weaknesses of the quantitative model-based research method can be summarised as below.

3.3.1 Advantages and disadvantages of quantitative model-based research

Operational processes can be very complex systems since the performance of an operational process can be affected by many different elements in the process. The quantitative model-based approach and OR techniques developed through the scientific management have been making a serious impact on the design and control of operational processes in order to deal with these complexities. This especially pertains to highly automated operational processes and decision problems where the impact of the human factor is negligible (Bertrand and Fransoo, 2002; Hillier and Lieberman, 1990).

One of the major advantages of quantitative model–based approaches is that they can generate valuable knowledge about certain aspects of operational processes and provide us with valuable insights in basic trade-offs, at a managerial level (Bertrand and Fransoo, 2002). Note that a model is always an abstraction from reality in the sense that they only reflect those aspects of problems that operations managers may encounter (Rogers et al., 2012; Altiok and Melamed, 2010).

In addition, precision can be achieved in well-defined variables, and these variables can in turn be precisely tested or checked by other researchers. These models can provide a wide coverage of different scenarios. They are familiar and widely accepted by researchers, and can provide good credibility. Finally, quantitative modelling is reliable, fast and economical and tends to yield conclusions with high reliability and internal consistency (Meredith et al., 1989)

One of the major critiques of the model-based research is that the results are only as valid as the assumptions upon which the model is based. There is clearly a risk that these assumptions could be based on convenience, and hence be unrealistic (Flynn et. al., 1990). In this case the insights of the models become irrelevant and not useful to operations managers and practitioners because they fail to recognize the applied nature of production/operations management (Flynn et. al., 1990). As McCutcheon and Meredith (1993) discuss, the need for empirical methods in the field of Operations Management is crucial since some widely held assumptions in OM are not necessarily accurate. The gap between what academics assume and the real conditions of operations have led to growing disparities between OM research advice and workable answers for managers (McKay et al., 1988). There is, therefore, a need to gather better information about real-life OM phenomena. Flynn et al. (1990) suggested that empirical data can be used in conjunction with a mathematical modelling approach to overcome this issue of unrealistic assumptions.

A further way of addressing this concern is to undertake empirical case studies, in parallel with the development of analytical models, in order to gain more insight into current PA strategies and practices. As mentioned earlier, although the focus of this research is to develop and analyse normative models, empirical case studies are also conducted to complement the quantitative modelling so that this research does not become detached from reality.

3.3.2 Case study research

Case study methodology is one of the many empirical approaches that aim to develop our understanding of "real-world" events and helps academics understand why or how events occur (McCutcheon and Meredith, 1993; Meredith et al., 1989). The case study can use multiple methods and tools for data collection in a single natural setting that considers temporal and contextual aspects of the phenomenon under study (Benbasat et al., 1987; Yin, 2013).

According to Meredith et al. (1989) case study research is classified as an interpretive and natural method. The interpretive perspective includes the context of the phenomenon as part of the object of study. Interpretive researchers study people rather than objects, with a focus on meanings and interpretations rather than behaviour. In contrast to the implicit absolutism of positivism, interpretivism is relativistic because facts are not considered independent of the theory or the observer. Interpretive explanations place behaviours in a broader context which illuminate their nuances.

Since the explanation of quantitative findings and the construction of theory based on those findings will ultimately have to be based on a qualitative understanding (Meredith, 1998), case research is very important for the field of OM.

Empirical case studies can lead to new and creative insights and the development of new theory, and have high validity with practitioners and the ultimate users of research (Eisenhardt, 1989; Voss et al., 2002). The key strengths and weaknesses of the case study research method a can be summarised as below.

3.3.2.1 **Advantages and disadvantages of case study research**

Three main strengths of case study approaches are identified by Benbasat et al. (1987) and Meredith (1998). First, the case study research allows the phenomenon to be studied in its natural setting, and meaningful relevant theory to be generated from understandings arrived at through observing actual practice. Secondly, the case study method allows the much more meaningful questions of *why*, rather than just *what* and *how*, to be answered, giving a relatively full understanding of the nature and complexity of the complete phenomenon. Lastly, the case study approach can provide early exploratory investigations where the variables are still unidentified and the phenomenon not understood. In addition to this, the case study approach has the potential to test hypotheses in well-described situations and deliver rich explanations of the investigated phenomena (Yin, 1994; McCutcheon and Meredith, 1993).

Flynn et al. (1990) and Meredith (1998), however, identify some major drawbacks with case study research. First, this type of research is time consuming and costly, since such studies often require significant financial and time resources for site visits and data gathering. Besides, doing case research requires direct observation in the actual contemporary situation, for which it can be difficult to gain the required access. The data analysis can be difficult and require multiple methods, tools, and entities for triangulation. The researcher may face a lack of control and complications of context and temporal dynamics. Specifically in the area of Operations Management, there is a lack of familiarity among researchers with methods, procedures and consistency (Meredith, 1998).

3.4 Research process

Identifying research gaps is an essential step of any research process. As discussed earlier, product acquisition management is the key for a successful remanufacturing operation, and has recently received more attention (Bulmuş et al., 2014). The literature review was undertaken to identify the current status of the research on product acquisition along with the research gaps and research questions. The mathematical modelling was carried out in line with the research questions. In parallel with the mathematical models, the empirical case studies were designed to deliver more information about the motives and barriers in the practice of remanufacturing, with special attention given to the product acquisition strategies. Finally, findings from both procedures were synthesised to reach a more spherical and well-rounded conclusion. Figure 3—1 illustrates this overview of the research process for this study.

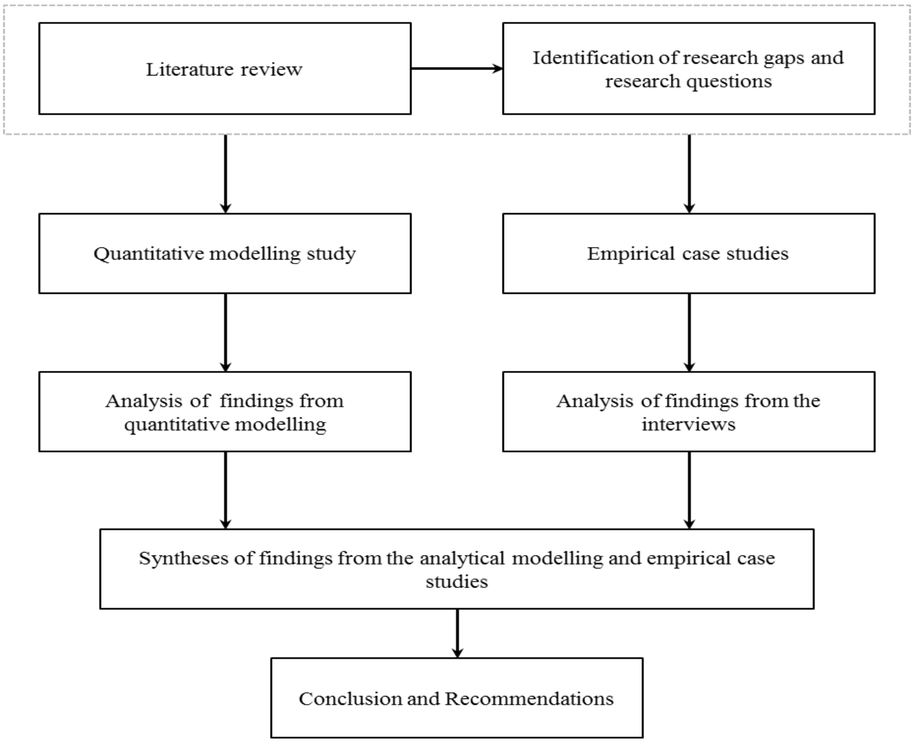

Figure 3—1: Overview of the research process.

3.4.1 The quantitative modelling

In the present study, mathematical models are developed in order to generate insights about the impact of different product acquisition strategies in reverse and closed-loop supply chains. In general, three product acquisition decisions are considered; a proactive strategy (when returns are influenced by offering financial incentives), a closed-loop system (remanufacturing without offering an incentive), and an open-loop system. Quality and quantity based incentives are introduced in the proactive strategy to explore the economic advantages of incentivising the market for remanufacturing operations. The cost savings of the proactive strategies are benchmarked against an open-loop system to show under what conditions offering incentives is beneficial for firms.

The cost structure (in particular, the acquisition cost) is the main element of this study. In contrast to the majority of studies in this area, which simply assume a linear acquisition cost structure (e.g., Majumder and Groenevelt, 2001; Fleischmann et al., 2001; Galbreth and Blackburn, 2006; Vadde et al., 2007; Ghoreishi et al., 2011 and Minner and Kiesmüller, 2012), this thesis proposes a more general acquisition cost functions that allow for a broader investigation into the economics of the proactive strategy. According to Simon (1989), although the presence of a linear relationship in this context is not based on a well-founded theory it often yields a satisfactory fit to empirical data. It has been suggested, however, that a non-linear response function provides a better theoretical foundation for the price-response function (Simon, 1989; Thomson and Teng, 1984 and Klausner and Hendrickson, 2000). In this study, the acquisition cost function is presented in the form of a rational function[2] that can capture the relationships between the acquisition price and the return rate or return quality. It has to be mentioned that as a part of the financial incentives (e.g. cash or discount), the costs of advertising, transportation and handling can be considered within the acquisition cost function. A more general interpretation of the acquisition cost function, therefore, would be the level of effort that firms put into the product acquisition. In practice both economies and diseconomies of scale in the collection cost of used products can be observed. According to Atasu et al., (2013) firms who charge their customers volume-dependent prices and use a drop-off strategy, under which consumers are provided the means to drop off the used product to specified locations, face economies of scale. Atasu et al., (2013) also provide a justification for the convexity in collection costs (a diseconomy of scale) using empirical data of an IT manufacturer that sells print cartridges to end-consumers and provides them with pre-paid envelopes to return their end-of-use cartridges. In this study we investigate OEM's who collect the used products from their customers (either directly or through third-party collectors). In this situation the marginal cost of collecting an additional product is increasing in the collection rate, such that one would observe diseconomies of scale.

For the purposes of this study it was necessary to derive closed-form solutions for cost minimisation problems that allow for a flexible and insightful investigation into how the model behaves under different circumstances and settings while capturing all the essential elements in the research scope. The investigation began

[2] A rational function is a fraction of polynomials. If $f(\rho)$ and $q(\rho)$ are polynomials, then $P(\rho) = \frac{f(\rho)}{q(\rho)}$ is a rational function.

by looking at an infinite planning horizon to explore in more depth the effect of different cost structures (e.g. acquisition cost function and remanufacturing cost function) on the economic attractiveness of the proactive strategy. The model was then extended into the finite planning horizon to investigate both static and dynamic acquisition policies. In the finite horizon model, demand and returns were modelled as a typical unimodal shape of the product life cycle. Although these assumptions are simplistic, they contain all the essential features needed to capture the time-dependent product returns and allow for analytical treatment (Geyer et al., 2007; Kleber, 2005).

The objective functions are formulated as unconstrained and constrained non-linear optimisation problems. The analytical solutions to these problems are derived by first and second order conditions as necessary and sufficient conditions for the unconstrained problem. For the constrained problem, the Lagrangian Multiplier method is used to derive a solution. Based on the properties of the acquisition cost function, however, obtaining the closed-form solution was not always possible. In these cases, a numerical method is used to find an approximation to the optimal solution. These methods have been used in previous product acquisition studies, e.g. Guide et al. (2003b), Galbreth and Blackburn (2006); Galbreth and Blackburn (2010) and Geyer et al. (2007).

Finally, the optimal control theory was utilised to capture the dynamic system of product acquisition. Optimal control is a branch of mathematics that originates from the theory of *calculus of variations*. This method has been developed to find optimal solutions to control a dynamic system that changes over time (Sethi and Thompson, 2000).

One of the standard methods for solving the optimal control theory is the Maximum Principle (for the general formulation of the optimal control problem please see Appendix I). This method provides the fundamental necessary conditions for a controlled trajectory (x, u) to be optimal. The method was developed in the mid-1950s in the Soviet Union by a group of mathematicians (including V.G. Boltyanskii, R.V. Gamkrelidze, and E.F. Mishchenko) under the leadership of L.S. Pontryagin, and is known as the Pontryagin maximum principle (Pontryagin, 1987). By using the maximum principle, the dynamic system can be decoupled into a series of problems that holds at each instant of time. The optimal solution to these instantaneous problems can be proved to give the optimal solution to the overall problem. Although optimal control can provide insights into dynamic systems for optimal production and acquisition, the approach is also useful in problems with a fewer constraints.

The application of optimal control theory ranges from management science, production and inventory, economics, finance, marketing (Sethi and Thompson, 2000) to other field such as aerospace, process control, robotics, bioengineering and consumption of natural resources (Becerra, 2008).

The hybrid manufacturing-remanufacturing environment can be seen as a dynamic control system. The market demand can be viewed as a state, which is continuously satisfied by (re)manufacturing. The cost of remanufacturing depends on the quality and quantity of returns, which can be controlled by the acquisition of used products. Therefore, market demand and the supply of used products (returns) are usually continuously changing with time. As mentioned previously, optimal control theory can provide insights into dynamic decision for the optimal acquisition price and quantity in order to minimise the cost of the operations (or maximizing the profit). Optimal control theory has been applied in previous studies of remanufacturing e.g. (Kleber et al., 2002; Minner and Kiesmüller, 2012; Minner and Kleber, 2001).

3.4.2 Empirical case studies

As mentioned earlier, empirical case studies are conducted to deliver more information about the motives for and barriers to remanufacturing in practice and to complement the quantitative analysis. In this research, the case studies also serve as the motivation for the modelling study and its applicability to a part of real world practice.

The current research in the field of RL and CLSCs is predominately quantitative using mathematical/OR techniques. (Fleischmann et al., 1997; Dekker and Fleischmann, 2004; Rubio and Corominas, 2008; Govindan et al., 2015). It has been suggested that research in this area requires adequate field observations in order to justify the theory and the assumptions, so as to eventually have a practical contribution. Losing connection with the reality in industry may result in the formulation of solutions to problems that do not exist in practice and consequently are of no use to managers and firms (Atasu et al., 2008; Guide and Van Wassenhove, 2009). Applying a case study in parallel to the mathematical modelling has been used in a number of previous studies. In some instances, the case study was conducted initially to understand the context of the problem, and then the mathematical model was built to address that specific problem (e.g. Klausner and Hendrickson (2000); Guide et al. (2003b); Guide et al. (2005). Alternatively, some researchers have developed the model first, with quantitative data then being gathered through case studies in order to validate the model (Teunter and Flapper, 2011; Guide et al., 2006). Finally, some researchers have used case studies in isolation in order to understand the industrial needs and challenges (e.g. Östlin et al. (2008); Seitz (2007). Although the remanufacturing industry is rapidly developing, and these empirical studies remain relatively limited, they do provide an understanding into remanufacturing operations and the challenges being faced by managers.

3.4.2.1 **Interview Questions**

As Eisenhardt (1989) emphasises, a well-defined research focus and well-defined research questions are crucial when collecting data from case studies. The absence of an appropriate focus will cause the researcher to become overwhelmed by the volume of potential data. Hence, in the premises of the present study, the use of case studies is focused on investigating product acquisition strategies with the aim to cover the following topics (for the details of interview questions please see Appendix II).

- Key strategic objectives of the company's reverse logistics operation
- Types of product returns and challenges in managing returns
- Characteristics of the company's return policies
- Reverse logistics network structure
- The company's product acquisition decision
- Demand and returns characteristics
- Product acquisition cost structure and characteristics
- Challenges in managing the product acquisition
- Management trends

3.4.2.2 **Selection of case sectors and companies**

A recent study of remanufacturing and reuse in the UK estimated the economic value for remanufacturing[3] and reuse at £2.4 billion[4] (Centre for Remanufacturing and Reuse, 2010), with the potential to create £5.6 to £8 billion (Lavery et al., 2013). Besides the economic opportunity, remanufacturing typically uses 85% less energy than manufacturing (All Party Parliamentary Sustainable Resource Group, 2014). Regarding the environmental benefits, the carbon saving from remanufacturing in the UK is estimated to be over 10 million tonnes CO_2 per annum (Centre for Remanufacturing and Reuse, 2010). Furthermore, businesses in the UK are required to comply with producer responsibility laws in the UK (e.g. packaging, electrical and electronic equipment (EEE), batteries and end-of-life vehicles (ELVs) (GOV UK, 2014). These figures suggest that remanufacturing has the potential for a greater contribution to businesses, environment and a sustainable future and opens the opportunity for researchers to investigate the UK remanufacturer industry.

Multiple companies who are involved in remanufacturing operations in the UK were selected for the interview. Multiple cases are often considered more compelling (Herriott and Firestone, 1983) than a single case study (Stake, 1995). Multiple cases may reduce the depth of a study, especially when resources are limited, but at the same time increase external validity and help guard against observer bias. The selected cases are globally well-known brands providing a wide

[3] In this study, remanufacturing is also considered to cover refurbishment.

[4] Aerospace industry is not included in this figure.

range of products and services. Throughout this study these companies are referred as '*Company A'*, *'Company B'* and *'Company C'*. .

The first company (Company A) is a large dealer in Caterpillar equipment who also remanufactures engine and power train components for a wide range of applications including both heavy and general construction, and power generation. The interview examines the remanufacturing operation of engines at Company A's Component Rebuild Centre (CRC). The second case (Company B) is a leading company in the information and communication technology (ICT) sector and the research investigates the reverse logistics and product acquisition of used laptops. Finally, the third company (Company C) is a manufacturer of office imaging equipment and printing solutions, and the interview examines the product acquisition strategy in respect to empty toner cartridges. A brief overview of these companies is presented in Table 3—3.

Table 3—3: Overview of the selected case companies.

Case companies	**Company A**	**Company B**	**Company C**
Industry	Industrial Equipment	ICT Equipment	Digital imaging
Country of Origin	Canada	Japan	Japan
Total number of employees	13,550	173,155	108,525
The product focus for the interview	Engine	Laptop and PCs	Toner cartridges

3.4.2.3 **Data collection**

Due to the nature of the interview objectives, a semi-structured interview method was used (see Flynn et al., 1990). Semi-structured interviews are used to explore the meaning of a specific concept (Flynn et al., 1990) Questions are specified by the interviewer, but s/he is free to probe beyond the respondent's initial answer (May, 2011). Relevant position holders in well-known remanufacturing companies were approached with the information requests. A positive response was received from three organizations, which led to the face-to-face interviews.

The interviews were conducted at the offices of the case companies between March 2013 and September 2013, with each lasting for around three hours. All interviews were reordered and transcribed for analysis purposes. Before each interview, the interviewee was informed about the area that would be discussed. The questions were arranged in a particular order, starting with more general questions, and more specific questions were asked according to the respondent answers. Due to confidentiality concerns, participants claimed that they were not allowed to expose any quantitative data since these could potentially be of a sensitive nature. The interviewee from Company A holds the position of *"Life Cycle Solutions Manager"*. He is responsible for coordinating the remanufacturing operation. The interviewee from Company B holds the position of "*Head of Remarketing"* and is responsible for managing returns from the market, and the remarketing and reselling process. Finally, the interview with Company C was conducted with two representatives of the company with positions of *"European Business Development Specialist"* and "*Remanufacturing Process Engineer*".

The data analysis of the interviews includes both within-case and cross-case analysis as suggested by (Eisenhardt, 1989). Within-case analysis is central to the generation of insight from the case studies and cross-case searching tactics enhance the probability that the investigators will capture the novel findings which may exist in the data. (Eisenhardt, 1989). In this study, first, a detailed description of each case company is written in order to become intimately familiar with each case. Next, the cases are compared under a set of categories (categories are identified based on the research objective and existing literature) in order to identify their similarities, differences, and a pattern.

In this chapter, the research methodology was discussed in detail, followed by an outline of the research design and approach to address the research objectives. The research is based on quantitative modelling that falls under the Operational Research (OR) discipline. Besides developing and analysing the quantitative models, empirical case studies are conducted in order to better understand the motives and barriers of remanufacturing and product acquisition in practice. A brief description was given for each of the methods in this research. The next chapter will describe case studies from the UK.

Chapter 4

Empirical Case Studies

4.1 Introduction

This chapter presents the findings from the empirical case studies. The empirical case studies have investigated a number of important strategic and operational issues within three companies in the UK. This chapter is organised as follows. Section 4.2 gives a brief description of each company. Section 4.3 discusses the different strategic views regarding product returns. The Reverse Logistics network structure of each case is presented in section 4.4. In section 4.5 the product acquisition strategy of each company is discussed, followed by the challenges in managing the product acquisition. Finally, the chapter concludes by summarizing the findings of the empirical case studies in section 4.7.

4.2 Description of case companies

Company A is a large dealer in Caterpillar equipment that sells and provides services to customers in various industries such as mining, construction, power systems, petroleum and forestry. The company operates in various countries around the world with over 13,550 employees, and has been operating in the U.K since 1983 under the name of Company A (UK) Ltd. where it serves businesses such as coal mining, quarrying, electric power, petroleum and marine industries. Company

A's Component Rebuild Centre (CRC) remanufactures engine and power train components for a wide range of applications, including both heavy and general construction and power generation. Company A's CRC offers remanufactured products to customers under the "service exchange programme". The concept of this programme is to obtain used products from the customers in exchange for a remanufactured one (used products are referred to as having a "core" value). The quality of the service exchange products are as good as new; however, they are offered to the customers at a lower price compared to the brand new version. The company's sales data for service exchange products shows a significant growth in sales of remanufactured cores since 2005 (Figure 4—1).

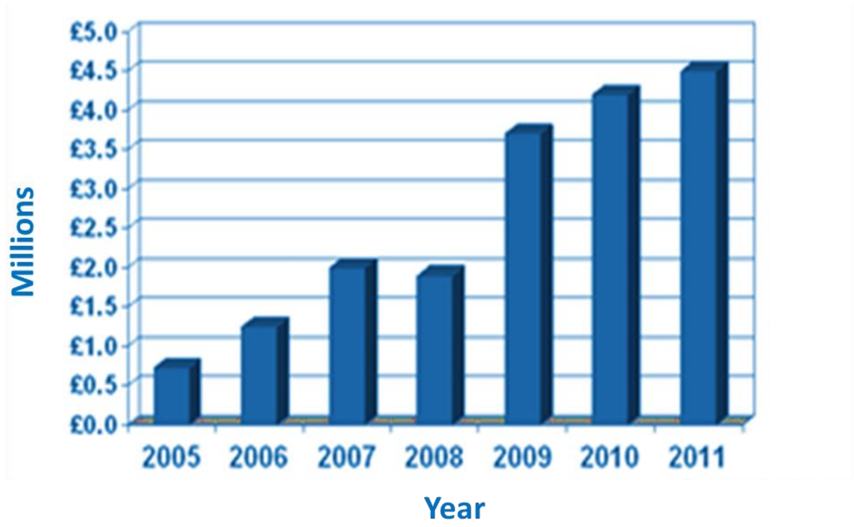

Figure 4—1: Service exchange sales growth.

In this case study, the focus is on the reverse logistics operations of the service exchange programme in respect to Caterpillar engines at Company A's Component Rebuild Centre.

Company B is one of the leading Japanese information and communication technology (ICT) companies offering a full range of technology products, solutions and services such as laptops, PCs, servers and telecommunications equipment. The company operates in more than 100 countries and the consolidated revenues for the fiscal year ending March 31, 2013 were reported as 4.4 trillion yen (US$47 billion). Company B operates in the UK and Ireland (with around 14,000 employees) as a major IT system, product and service provider. This case study focuses on the reverse logistics operations of Company B's notebooks and desktop personal computers (PCs) in the UK.

Company C Group is a leading international corporation supplying products and services in the field of Imaging and Solutions.[5] Company C operates globally in around 200 countries and has a global workforce of 107,421. In the 2013 fiscal year the company's worldwide net sales totalled approximately 1,924.4 billion yen. Company C Europe is a wholly owned subsidiary of Company C Ltd. and has more than 16,000 employees working in 21 countries in the EMEA region.[6] The company's sales, manufacturing and customer support centres throughout the region include three European Green Centres (UK, Netherlands, Germany) and five additional Satellite Spare Part Centres (UK, Netherlands, France, Spain, Italy), allowing Company C to provide a service to their customers in the EMEA area. In 1983, Company C UK Products Ltd (RPL) was established as the first European production subsidiary of Company C. The company has two production facilities that offer the design, development and reconditioning of Office Automation Equipment including MFPs (multifunction printers), production printers and

[5] The Imaging and Solutions segment consists of three sub-segments:

- Office imaging equipment: multifunctional printers, copiers, laser printers, digital duplicators, facsimile, scanners, related parts & supplies, services, support and software.
- Production printing solutions: Cut sheet printer, continuous feed printer, related parts & supplies, services, support and Software.
- Network system solutions: Personal computers, servers, network equipment, related services, support and software.

[6] The EMEA region consists of Europe, the Middle East and Africa.

associated toner products. This case study concentrates on the reverse logistics operations of toner cartridges at one of Company's C remanufacturing centres.

4.3 Strategic view of products return

Company A is engaged in reverse logistics operations mainly for the economic reasons. According to the interviewee, remanufacturing is a profitable business. However, the profitability depends on the product type/model, the quality of the returned product and the time period within which products (engines and power trains) are returned. Providing the maximum uptime[7] for the customers is the next factor that motivates Company A to be involved in reverse logistics operations. The uptime is the crucial factor for Company A's customers since it has a direct impact on the cost of their operations. As mentioned by the interviewee, "*Uptime is one of the key factors in the customer satisfactory metrics*". The service exchange programme for engines allows customers to use their machine for a long time against reasonable costs. Finally, due to the high value of the cores, there is competition in the market to acquire the cores for remanufacturing. Therefore, Company A is under pressure to secure the return of the used core, since it is essential for their remanufacturing business.

Companies B and C, like other manufacturers of electronics equipment in Europe, are bound by WEEE legislation. These legal obligations make companies responsible for the establishment of a take back and recovery system for their products throughout the product life cycle. To fulfil this legal requirement both companies have developed a set of strategies for the collection and recycling of

[7] Uptime refers to the ratio of the actual production time of a machine to the availability time.

used products from both household consumers and businesses in the UK. Beside this legal obligation both companies act beyond the requirements that are set out in the WEEE directive.

Company B believes that profit can be made by reconditioning used products if the returns are handled correctly (refurbishment and remanufacturing typically costs around 65-75% less than a new build replacement). Particularly for client products such as laptops and PCs, the market is highly competitive. Manufacturers in this type of market are making a small margin on new sales (usually between 3-5%). Therefore, if the company efficiently manage the back end of the initial product life cycle a higher percentage can be achieved from the resale of that product provided the sale price of reconditioned models is not much less than the new price.

Company C introduced the concept of a "*Comet Circle*" in 1994 (Figure 4—2), as the company strategy to reduce its environmental impact throughout the entire product life cycle. This strategy is based on the belief that all of Company C's product parts should be designed and manufactured in a way that they can be recycled or reused. Thus, the company attempts to contribute to profit by maximising the reuse of materials and parts (moving towards the left side of the Comet Circle). The competitive advantage that can be achieved by offering this service is another reason why the company engages in reverse logistics activities.

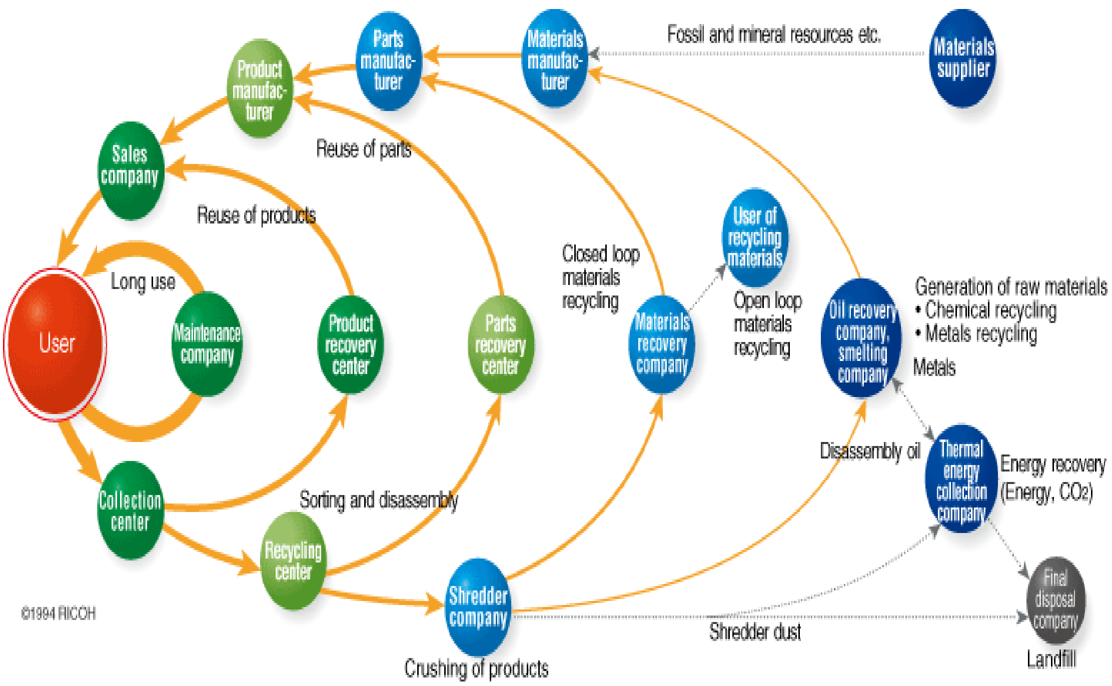

Figure 4—2: Company C's Comet Circle (Source: Company C website).

4.4 Overview of RL operations of case companies

Company A

Company A's reverse logistics for service exchange programme starts when the components of a new Caterpillar machine that has been sold to market fulfil their useful life.[8] These components (engine, power train, etc.) have a core value and can be remanufactured to be as good as new. With the service exchange programme, customers can return their used core in exchange for the remanufactured one, this way they can minimise their machine downtime by paying a lower price.

There are two main factors that enable Company A to provide such a service: First is the durability of the cores. Caterpillar products are designed to be

[8] A typical end-of-use period for an engine is around 15,000 working hours, at this stage the engine is considered as worn out.

remanufactured several times. For instance, some engines that are used in oil and gas are working for 34 years and have been remanufactured around 9 times. The next factor is the cost efficiency of the service exchange products. The price of a new product is significantly higher than the remanufactured one (Table 4—1). Customers are getting the same performance at 40-60% of the cost of new product. Therefore, a service exchange product is the most economical option for customers to maximise the life they get from the complete machine (uptime).

Table 4—1: Example of Company A's service exchange engines prices in 2013.

Machine model	Engine model	New engine price	Remanufactured engine price (service exchange price)
Mining truck 785D	3512	£ 263,739.20	£ 72,091.39
Off-highway truck 773E	3412	£ 104,026.81	£ 51,919.13
Large wheel loaders 988H	C18	£ 63,356.67	£ 35,383.21
Wheel loader 950G	3126	£ 20,698.70	£ 10,410.43

Interestingly, according to the interviewee, the market demand for new machines does not overlap with the market of remanufactured products (due to the price gap). New machines are typically sold to new customers for new projects while remanufactured products are predominantly offered to the existing customers (who had bought a new machine previously). Therefore new and remanufactured products represent parallel market segments.

Customers can return their used core directly to the Component Rebuild Centre (CRC) or drop off them off at one of Company A’s local branches and from there they will be shipped to CRC. In most instances, however, when a service exchange product is sold, Company A’s engineers would go to the customer site, install the new service exchange products and remove the old core to the Company

A facility. Company A applies a deposit-refund system for the service exchange programme in order to secure the return of the used core. Once the old cores have arrived at CRC, they go through inspection to ascertain whether the returned core is damaged or not and based on the quality of the core Company A invoices the deposit to the customer's account.

The used cores are disassembled, washed, batch labelled and moved through the rebuild process. In the rebuild process each component will be tested according to the Caterpillar guidelines and those components that are damaged will be remanufactured.[9] All the remanufactured/rebuilt products are tested before assembly to make sure they work as "like-new" products. Finally, remanufactured products are branded as "service exchange products" to be sold in the market (Figure 4—3).

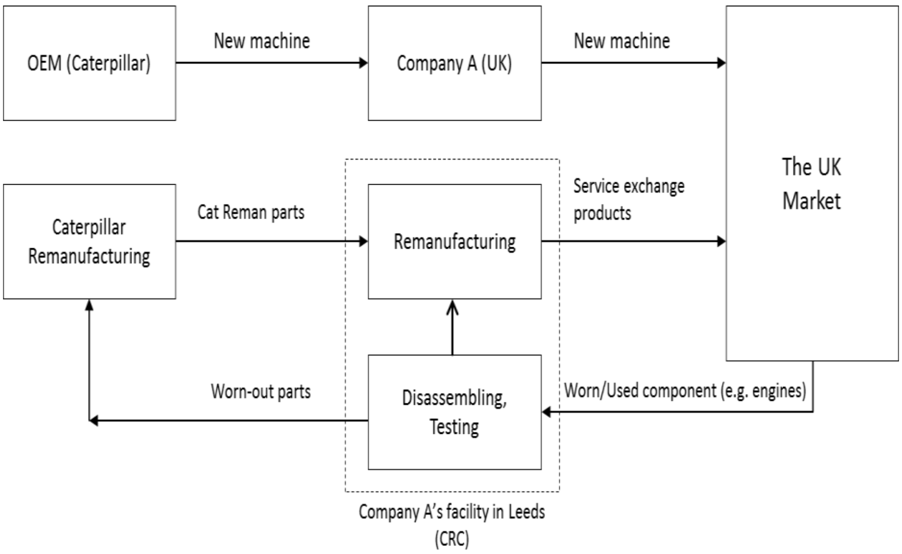

Figure 4—3: The reverse supply chain process at CRC.

[9] Component remanufacturing includes replacement of number of parts such as seals, gaskets and bearings.

Company A uses Caterpillar remanufactured parts (e.g. cylinder head, piston pack) for their service exchange programme. Those worn out parts that cannot be remanufactured at Company A will be sent to Caterpillar to be remanufactured at their facility. Decisions regarding remanufacturing used cores are mainly dependent on the difference between the price of purchasing a new product and the remanufacturing cost. When the gap between these two costs is small, it is prohibitive to justify remanufacturing. The higher the value of the asset, the higher the likelihood that it is returned for remanufacturing. Those cores that cannot be economically remanufactured (due to extensive damage or the low value of the original product) will be scrapped by Company A. According to the interviewee, annually about 500 engines and power trains are returned to CRC to be remanufactured. The relative proportions between the costs of manufacturing a new product and other costs are as follows: remanufacturing cost is around 40%, testing can be between 2-10% and scrapping is only 1% of the cost of manufacturing a new product.

Company B

Company B operates a centralised reverse supply chain for its notebook and desktop returns in Europe. The remarketing division is responsible for managing the returns, i.e. acquiring the products from the market, determining the best reuse option (product disposition), reconditioning, and remarketing the reconditioned products. Apart from the reverse distribution, which is outsourced to a third-party provider, all the other operations are done in-house at the company’s facility in Germany.

The returns arriving at the reconditioning centre are a mix of manufacturing overstocks (when the sales rate is lower than expected), which are usually a mixture of in-built products or at a component level, end-of lease (when the customer decides not to extend the lease into a second term), and end-of-use returns. The end-of-use returns consist of products that are returned due to trade-ins and upgrades or that are bought-back from the customers (this case study focuses on the returns of end-of-use products).

The returned products are sent to the return centre to be disassembled and tested. The quality inspection starts by a visual examination for any physical damage. This part of the inspection is very important for Company B because failure at this stage can influence the total cost of the entire reverse logistics process.[10] After the visual inspection, the products are tested for functionality to establish whether systems are performing according to their original specifications. Once the quality inspection is done, the company grades the products based on product quality (Table 4—2).

Table 4—2: Grades based on the quality level (Source: Company B's asset life cycle management services).

Grade	Product status
1	Working, damage-free
2	Working, with limited damage
3	Working, but physically damaged or with parts missing
4	Dead on bench / Unable to boot up
5	Beyond economic repair

Based on the product's grade, the company then decides what level of reconditioning is required. Those parts that are in a good quality condition will be

[10] For products such as laptops, visible damage might affect the performance considerably

mixed and matched together in order to provide a working unit for the remanufacturing operation. All the reconditioned products are tested and stored at the same location to be sold in the market with the company warranty (at least for 12 month). In addition, there is a recycling centre next to the refurbishment centre where the components that failed the quality inspection are recycled onsite (Figure 4—4).

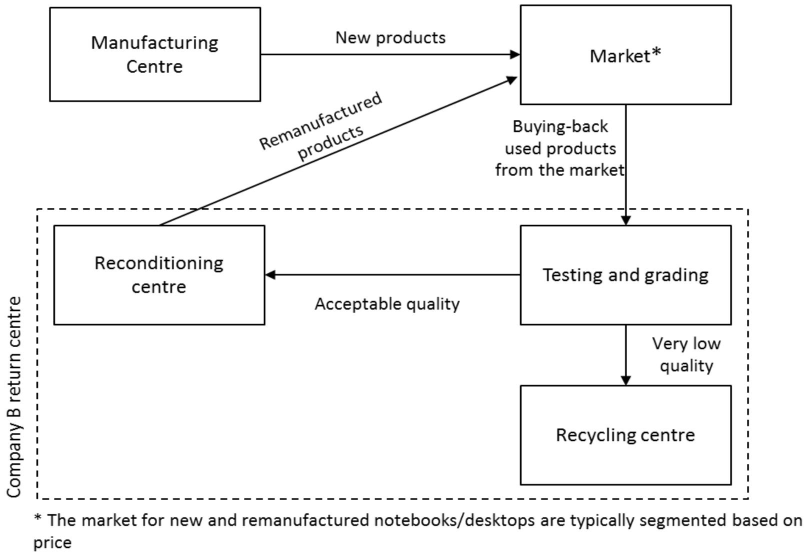

Figure 4—4: Reverse logistics flow of Company B.

Company C

Company C has two strategies to obtain used products (used toner cartridges) back from the market: The company's official route (Green Centre), which is through the company's website, and an informal route which involves third-party brokers for the collection. All the returned products are tested and sorted, either by Green Centre or third-party brokers, and then transferred to Company C for a suitable reconditioning operation. The quality inspection is done in two levels at Company C: the first level is the basic inspection which is performed by the Green

Centre or the third party broker, depending on the channel of return. This level of quality inspection is predominately a visual inspection to assess whether or not the used product is suitable for reconditioning. Those products that cannot be recovered will be incinerated at a cost to the company. Those products that pass the visual inspection will be disassembled into parts and components; they are cleaned, dried and made ready for the enhanced technical test, at the company's facility. Those components that failed the quality specifications will be replaced by new components before entering to the market. This inspection is done to make sure that the remanufactured products are of the same quality level as new products to serve the demand of the primary market.

4.5 Overview of the PA strategies of the case companies:

4.5.1 Company A

Acquisition of cores is the essential aspect of the Company A's service exchange business, since it is the backbone of the remanufacturing process. Typically, a product such as an engine has a life cycle of 60,000 working hours. Commonly, however, engines are considered as worn out after approximately 15,000 working hours[11] and have to be remanufactured.[12] The most desirable time for remanufacturing the engines is when products are at their first life (the first 15,000hrs of working). The cost of remanufacturing increases as the product passes the first life and therefore a lower profit margin can be achieved through

[11] This interval obviously can vary based on the level of maintenance and usage pattern.

[12] At this stage it is very likely that some sub-components of the engine (gaskets, bearing, piston pack and etc.) have failed. When this occurs the whole engine is considered as a non-running core and it is more costly to be remanufactured.

remanufacturing. In order to obtain used cores at the right time, Company A tracks their products periodically (by monitoring the number of working hours, and the amount of litres of fuel that the engine has burnt) and approaches customers to encourage them to buy service exchange products. This is done by the sales agents; they have records of all the machines associated to each customer and have the ability to track the usage pattern of those assets.

As mentioned earlier, the deposit-refund system is the Company A's strategy to secure the return of the used cores. For every unit that is sold, a used core must be returned and then the deposit will be refunded to the customer. The amount that will be refunded to the customer however, depends on the quality of the returned core. Company A completely mirrored the Caterpillar core criteria for their quality inspection in order to determine whether the core is eligible for full core refund, damaged core refund or no core deposit refund (Table 4—3). According to the interviewee, customers prefer to be informed about all the costs prior to their purchase, therefore having these strict criteria for their deposit system gives a clear idea to the customers whether or not they will be receiving full, partial or no core refund.

Table 4—3: Core acceptance criteria (adapted from Caterpillar core acceptance criteria).

Full Core Refund	• Case, housing, splines, and shafts, not visibly cracked, broken, or welded. • Non-failed, running core. • No non-operational damage (mishandling, excessive rust, corrosion, pitting, or fire damage). • Fully assembled and complete. • Must be returned on Caterpillar Remanufactured transmission stand. • Acceptable part number — Caterpillar part.
Damaged Core Refund	• Case, housing, splines, and shafts visibly cracked, broken, or welded. • Failed, non-running core. • Evidence of bearing, carrier, gear, or other internal failure. • Excessive rust, corrosion, or pitting. • Fully assembled and complete. • Must be returned on Caterpillar Remanufactured transmission stand. • Acceptable part number — Caterpillar part.

No Core Refund	• Scavenged cores. • Fire damage. • Disassembled.

4.5.2 Determining the deposit price in Company A

Company A's strategy to determine the deposit level starts by evaluating the remanufacturing cost, referred to as a "dealer net".[13] Company A's engineering teams are responsible for determining the remanufacturing cost. Once this cost is identified, Company A sets the list price for the service exchange product according to the level of profitability they are aiming for (which varies among different products). The last figure that has to be considered is the cost of purchasing a new engine from Caterpillar (in case the customer refuses to return the engine). Therefore, the core deposit for the service exchange product would be the difference between the cost of purchasing a new product from Caterpillar and the Company A list price for selling a remanufactured one. The identification of the core deposit is illustrated in Figure 4—5. As can be seen, the core deposit for service exchange "C" is the difference between the cost of purchasing a new engine "A" and the list price of the service exchange "B" (please refer to Table 4—1 for more details about the price of new and remanufactured).

[13] Dealer net varies based on the product type and age, also the cost of packaging, handling and testing are included in the dealer net.

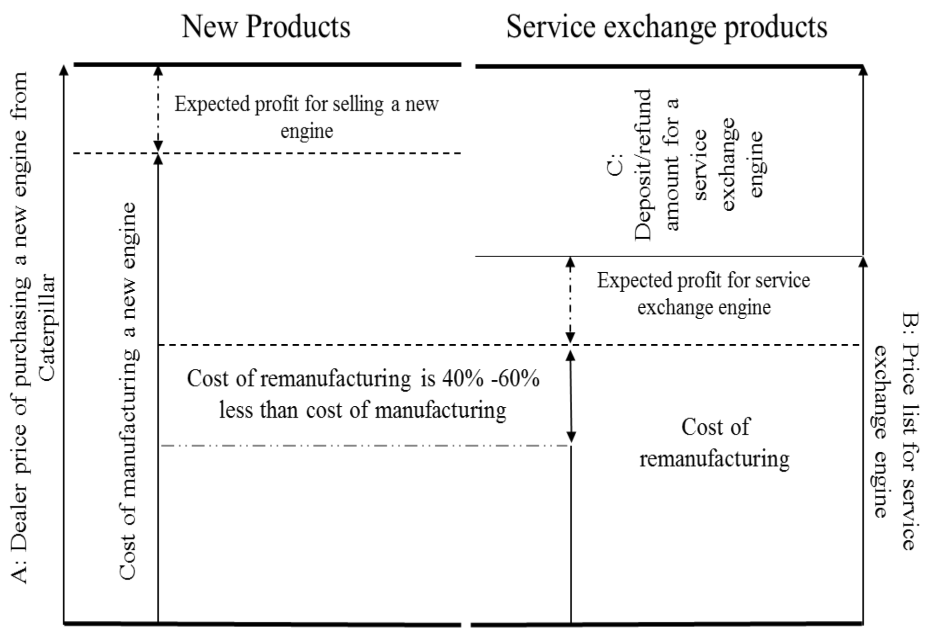

Figure 4—5: Determining full core deposit.

The deposit-refund system allows Company A to eliminate the uncertainty in the returns quantity. This strategy enables Company A to get a used core at the same time as the remanufactured product is sold to customers. This aspect is critical for Company A since the service exchange business is reliant on the supply of the used cores. The amount of the deposit has to be determined carefully because any increases in the deposit will affect the sales rate. In addition, the quality-based deposit strategy helps Company A to reduce the uncertainty in regard to the quality of the returned core significantly, which consequently decreases the risk of refunding a non-reusable core.

4.5.3 **Company B**

Besides the legal obligation (WEEE) that compels Company B to set up a route for collection of the used equipment, the company applies a trade-in rebate and buy back strategy to acquire end-of-use products from the market. In the trade-in programme, customers return an old system[14] against a new purchase with an agreed deduction in the invoice or, the provision of additional products or services to the same value (customers have the option to select cash rebates, additional services or warranty upgrades). If the customer decides to sell old equipment, Company B can provide 'buy-back' solutions for their customers. In a buy-back strategy, Company B purchases the used equipment by offering cash to the customers.

Whether choosing trade-in or buy back services, the first step is that the customer fills in a "trade-in request form". In this form, customers are asked to provide accurate information regarding their used equipment and to send it back to their Company B's local Remarketing contact. After five working days (this time may vary based on the quantity of returns) the customer will be advised if an offer for the equipment can be made. Once the trade-in or buy-back is agreed the customer will need to inform the Company B's Remarketing division to arrange for the collection. The collection service is free of charge and it is done through Company B's logistics partners; however, customers have to ensure that the equipment is packed, palletised and ready for secure transit.

After the equipment has been collected and quality checked, the final value of the offer will be passed to the customers. Any shortfalls in the returned equipment (in quantity or quality) leading to a reduction in the final value and therefore, a new price will be re-invoiced to the customer. As mentioned by the interviewee "We prefer to see what we've got and audit it before we pay the

[14] Customers can trade-in not only Company B's equipment, but also other major IT brands, but Company B only reconditions their own products, and other brands will be shipped to specialised partners for reconditioning.

money”. Therefore, the company either pays the same amount of money as in the initial offer or to offer a new price based on the actual audit outcome. The value of the offer for trade-in or buy-back is closely linked with the quality of the returned products, as well as the second-hand market value of the returned products. There is also a direct link between the price that Company B can sell the remanufactured products for, and the level of incentive they can offer to the customer. If the company believes the returned product still has a good demand in the market, then they will offer a better price to the customer. Company B, therefore, looks at the potential market resale value to guide them on what they should offer to the customer. In the case of laptops, Company B usually aims to make a 10%-15% net margin, and uses this figure as a benchmark to decide how much they should offer to the customers.

4.5.4 **Company C**

The product acquisition strategy at Company C consists of both a passive (waste stream strategy) and a proactive approach (market-driven strategy). Since Company C is bound by the WEEE directive, they are obliged to have a route for customers to return their products (the Green Centre was established to be company’s official channel for returns). The Green Centre works as a centralised acquisition system and accepts all types of used products. Customers can print shipping labels from the Company’s website and send their used products through the Post Office free of charge. All the returns through this route will be transferred to the ‘Green Centre’, to be sorted and tested. Those returns with an acceptable quality are transferred to Company C’s facility for reconditioning, while the other products will be sent to incineration.

In addition to the official route, Company C has developed an informal channel with third-party brokers. This route is predominantly for the acquisition of toner cartridges. In this strategy, the company offers financial incentives to buy-back used cartridges of acceptable condition for remanufacturing. The collection of used products is done by third-party brokers who charge the company a premium for their service. The third parties are informed regarding the required quality specification and they are only paid by Company C if the returns match those specifications. After collecting the used products, cartridges are palletised by brokers on special pallets (provided by Company C) and transferred to Company C's facility for the enhanced quality check and reconditioning operation. The official informal routes are shown in (Figure 4—6).

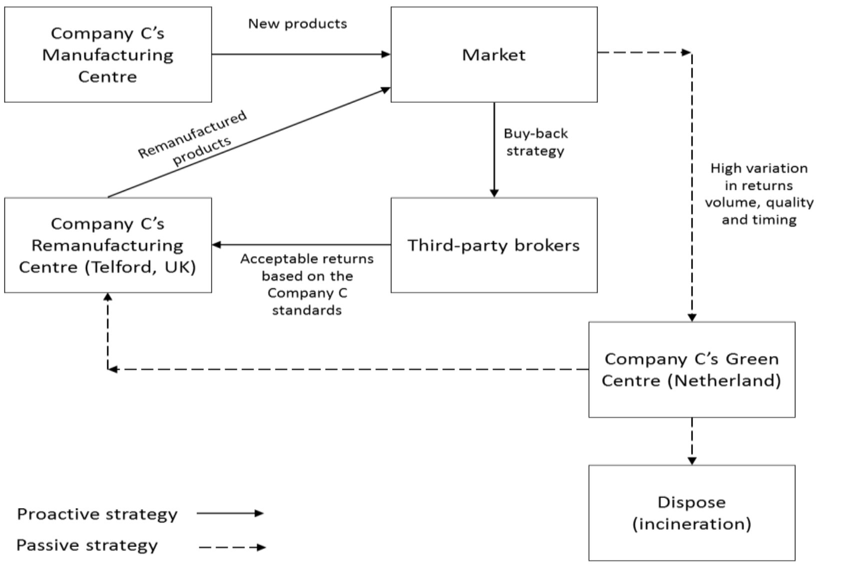

Figure 4—6: Company C's official route vs. informal route for product returns.

The amount of the incentive is mainly determined based on the total cost of remanufacturing[15] and the selling price in the market. Knowing these values enables the company to find a range of price incentives. The price varies, however, based on the broker's location (e.g. the incentive is higher in Western Europe compared to Eastern Europe) and also on the type of cartridges.

According to the interviewees, the acquisition cost (including the cost of reverse distribution) has a major impact on the total cost structure of the company's reverse logistics operations. Interestingly, they believe that the informal route is more cost efficient and more convenient compared to the official route. The transportation cost and administration cost related to the official route are much higher compared to the informal route.

4.5.5 Advantages and disadvantages of official vs. informal routes

Returns through the informal route arrive at Company C's facility in bulk (usually a container) and therefore the company knows exactly how many used products arrive at the facility and from what location. In the official route, the transportation is outsourced to third party contractors and customers can send back one toner cartridge at a time, which makes the transportation cost expensive for the firm. Moreover, in the official route, the information regarding the quality of returns is unknown, since the quality of returns is only revealed when they arrive at the Green Centre. In the informal route, a primary quality inspection is done by a third party, so that the products that arrive at Telford are known to be suitable for reconditioning. Therefore, at Company C UK the attempt is to develop the well-

[15] Total cost of remanufacturing refers to all costs associated with the remanufacturing operation (sorting, testing, disassembly and reconditioning).

established broker route quite aggressively because it is cheaper and more information is available regarding the returned products. It has to be pointed out however, that working with third-party brokers has its own risk. The first issue is that there are some areas in Europe that have no broker coverage (for instance, in Malta there is no broker available so the only option for returning the used product is through the Green Centres).

Another issue regarding the informal route is the possibility of competition between third-party brokers and the operating company. As the manager at Company C pointed out, they have to be very careful in selecting their brokers and their location in order to minimize the competition. Finally, there are some independent re-fillers who divert the cartridges from coming back to the Green Centre or third-party brokers. Therefore, the company attempts to minimize the amount of cartridges that are acquired by independent re-fillers.

4.6 Challenges in managing product acquisition

Company A

With a deposit-refund system, Company A is able to control the uncertainty in the quantity and quality of returns. The uncertainty in the timing of returns is more challenging to deal with, however. The timing of returns is mainly dependent on the usage pattern and maintenance level and so it is possible that cores stay at the customer site for long periods of time. As mentioned by the interviewee, "*we are not worried that we won't get the product back but when we get it back*". Used products that are returned earlier in the life cycle can be remanufactured at a lower cost. Acquiring a used core at the right time might be challenging, however, because there is no definitive way to guarantee when the customers will return the core. For instance, some customers have their own engineers to repair the engine. The uncertainty in the timing might impose other challenges on Company A's operations. It is possible, for example, that a high number of cores are returned to the CRC at the same time, putting the company under the pressure from customer's financial department to inspect the returned core and refund their deposit, and leaving the company with a high inventory of used cores that have to be remanufactured and then resold to the market.

The next factor that makes the managing of the reverse logistics operation challenging is the uncertainty in the customers' businesses. As mentioned earlier, the supply of the service exchange product mainly relies on the sales of the new product, since the latter determine the quantity and timing of used core returns. Therefore, any instability in the customers' businesses will have an effect on Company A's reverse logistics operations. A recent example of this uncertainty happened in the mining sector when the price of coal decreased and mining companies had to reduce their working hours. Incidences like this will affect the timing and forecasts of returns and add an extra complexity to the reverse logistics operation. Finally, due to the high value of the cores, customers may decide to disassemble the product and sell the subcomponents to a third party remanufacturer, or sell the core to another customer. In this situation, Company A has to substitute the unreturned product by purchasing a new product (engine) from Caterpillar and this will damage the service exchange business.

Company B

As the interviewee of company B expressed "*the interesting dynamics within the returns for a manufacturer, is that we don't know what we're going to get, or when we're going to get it, how much we're going to pay for it, how much we're* *going to have to pay to repair it, how long we're going to hold it, who we're going to sell it to, and how much we're going to sell it for, but apart from that it's a great business to be in*". As for other IT manufacturers, therefore, for Company B the inherent uncertainty in different aspects of product return is the major challenge in managing the reverse logistics operation.

Uncertainty in quality

As mentioned earlier, Company B makes an offer to customers based upon the information the customers provide, but the actual quality of the equipment is unknown until the products arrive at the company's facility. It is only then that the company realises exactly which equipment is going to need how much refurbishment or cleaning, or components replaced. For products such as laptops, the uncertainty in quality is greater compared to other IT products because of the nature of their use (mobile devices). This uncertainty will then impose a set of complexities in managing the returns, which eventually increases the total cost of the reverse logistics operation. For instance, one of the major costs in reverse logistics operations is the cost of reverse distribution. Acquiring used products with unknown quality conditions imposes a high shipment cost for the company since all the returns in Europe are shipped to the facility in Germany for quality inspection.

Uncertainty in timing

Uncertainty in timing is another challenge for the company. Since the market for laptops and PCs is very dynamic due to rapid technology changes, it is crucial to get the product back at the right time in order to maximise the potential value of the returns. Price erosion is steep, especially when the products are towards the end of their life cycle. Company B believes that potential value can be obtained from the returns for products such as laptops or PCs by extending the product life cycle for another 24 months if the returns start at the end of 36 months (when the product falls out of warranty). The company refers to this as the "*sweet spot*" in the market place and starts approaching customers around month 30 in order to encourage them to return their products.

One of the major factors that influences the timing of returns is the competition between the manufacturer and other independent brokers in buying back the used products. Quite often the customer makes the decision to sell their equipment to Company B or another remanufacturer very late. As expressed by the interviewee "*Nowadays customers are aware of the potential value of their existing products. So as well as getting an offer from the manufacturer, they will benchmark that against what the market says. So, competing with the independents is one of the key challenges that Company B faces".*

Although Company B offers financial incentives to buy-back or trade-in the old products, the customer may actually receive a competitive offer from another remanufacturer. Company B does not know when the used product will be returned until the deal has actually happened. According to the interviewee "*independent brokers are potentially obtaining a higher return rate than original manufacturers like Company B*." This happens mainly because the independent brokers have a lower cost structure compared to OEMs such as Company B (Company B as a tier one manufacturer has to operate under a standard working environment, whereas independent brokers can operate in different environments with lower standards). The competition between independent brokers and Company B also influences the supply of used products and increases the uncertainty in regard to the quantity of returns. This uncertainty influences the balance of supply and demand and, therefore, the company has to be careful to balance the supply of the used products with the demand for reconditioned products: without that balance the firm faces a warehouse full of equipment that is worth nothing and has to be scrapped.

Company C

The interviewees from Company C also indicated that the uncertainty in the quantity, timing and quality of returns is one of the major challenges in managing their reverse logistics operation. Particularly for empty cartridges, these uncertainties are extremely high since returns are mainly based on the customer usage rate: i.e. some cartridges last for three months and some for nine months. Another approach that is used in Company C is to manage the uncertainty in quantity by keeping a stock of the used products. Company C holds used products for between one and three months (based on the previous demand pattern) in order to provide a buffer against fluctuations in the return rate. According to the managers at Company C, having a flexible manufacturing system also helps them to be more responsive to variations in the return rate (i.e. by changing the manufacturing line from one product to another product).

The major factor that causes challenges in the handling of the remanufacturing operation is the quality of the returned products. The quality varies considerably because different customers have different usage patterns and some products might have been used much more extensively than others. According to the interviewees the primary quality inspection that is done at the collection points is extremely important. Negligence in performing this inspection imposes different challenges in the planning and in remanufacturing operations, as well as on the remanufacturing yield. According to the interviewees, the average remanufacturing yield at Company C is about 95% but this yield will drop to 50% if the handling of the collection is done poorly.

Apart from the aforementioned challenges, matching the supply of used products with the demand in the market is another challenge for Company C. If the company floods the market with remanufactured products, eventually they reach a point where there is not much product left to be remanufactured (since each product can only be remanufactured for a limited time). The company, therefore, has constantly to balance the collection rate of returned products with the demand in the market. The current strategy of the company in order to control the return rate is to institute a gatekeeping policy. When the supply of the used products is greater than predicted demand, collection points send returned products to the incineration centre.

4.7 Summary of the findings from the cases

The empirical case studies have investigated some of the key aspects of the reverse logistics operations and product acquisition strategies of three companies in the UK (Table 4—4).

Table 4—4: Overview of the key insights from the case studies.

<table>
<tr><th></th><th>Company A</th><th>Company B</th><th>Company C</th></tr>
<tr><td>Product</td><td>Engines</td><td>Laptops and Pcs</td><td>Toner Cartridges</td></tr>
<tr><td>Product returns</td><td>End of lease</td><td>• End-of-use
• End-of-life</td><td>• End-of-use
• End-of-life</td></tr>
<tr><td>Product life cycle</td><td>• Long
• low MVT[16]</td><td>• Short
• High MVT</td><td>• Short
• Low MVT</td></tr>
<tr><td>Main characteristics of returns</td><td>• Non-time sensitive
• Very High value
• Durable
• Low risk of obsolescence</td><td>• Time-sensitive
• High value
• High risk of obsolescence</td><td>• Non-time sensitive
• Low value
• Durable
• Low risk of obsolescence</td></tr>
<tr><td>Strategic objectives of reverse logistics operation</td><td>• Economic reasons
• Competition with independent remanufacturers</td><td colspan="2">• Comply with the WEEE directive.
• Economic reasons
• Competition with independent remanufacturers</td></tr>
<tr><td rowspan="2">Product acquisition strategy</td><td rowspan="2">• Proactive:
• Deposit-refund system</td><td colspan="2">• Passive strategy (WEEE-compliant take-back programme)</td></tr>
<tr><td>• Proactive:
• Trade-in rebate and buy-back</td><td>• Proactive:
• Buy-back (through third party brokers)</td></tr>
<tr><td>The major objective in applying proactive strategy</td><td>• To secure returns of the used engines with the acceptable quality</td><td>• Influence returns quality and timing</td><td>• Influence return quantity and quality</td></tr>
<tr><td>The main challenges</td><td>• Variability in returns timing and quality.</td><td colspan="2">• Variability in quality, quantity and timing
• Competition with independent remanufacturer
• Matching supply of used product with demand</td></tr>
<tr><td>The main factor in making a decision regarding incentive price</td><td>• The differences between cost of remanufacturing and buying a new engine</td><td>• Quality of used laptops/PCs
• Potential market value for selling the remanufactured product.</td><td>• Quality of empty cartridges
• Demand for remanufactured cartridges</td></tr>
</table>

[16] Marginal Value of Time

Both Company B and Company C are bound by the WEEE directive and fulfilling this legal obligation is the first priority for both companies, necessitating the companies to develop and setup a route for the return of their used products. Both Company B and Company C, however, act beyond this requirement to consider product returns as a profitable business. Company A, however, is engaged in reverse logistics operations for economic reasons, i.e. to provide the maximum service uptime for their customers. The other factor that drives all three cases to engage in the reverse logistics operations is competition with third-party remanufacturers. For Company A, especially, securing the used core is important due to the high value of the cores.

Although the characteristics of the product returns differ between the interviewed cases, there are some similarities in their reverse logistics operations. Company C and Company B implement a combination of passive and proactive strategies to obtain used products from customers. The purpose of the passive strategy is to fulfil the legal obligation (WEEE), while the proactive strategy is designed for economic reasons. In contrast, Company A applies only the proactive strategy to secure the return of used cores from customers.

The next operation in reverse logistics after the acquisition of used products is testing and sorting. The importance of sorting and grading returned products has been stated by many scholars (e.g. Aras et al., 2004; Ferguson et al., 2009; Galbreth and Blackburn, 2006b; Guide and Wassenhove, 2001; Zikopoulos and Tagaras, 2007; Zikopoulos and Tagaras, 2008). The analysis of the information from the case companies also reveals that quality inspection and sorting is an essential part of reverse supply chain operations, with the level of quality then dictating which value recovery operation should be adopted.

Company C and Company B typically inspect returns in two stages: a visual inspection, and an enhanced quality inspection. Prior to the enhanced inspection, however, used products are disassembled into parts and components, where they are cleaned and dried (in the case of laptops, all the information is removed from the system prior to these operations). Those components that fail the quality test are replaced by new components. Based on the used product quality, companies decide either to remanufacture the returned product or scrap it at their own cost. Finally, the remanufactured products are tested once more to make sure their quality is as good as new so they can be sold in the primary market.

The acquisition of used components is essential for the companies' remanufacturing businesses. Company A uses a deposit-refund system as their product acquisition strategy to secure the return of the used cores. This type of strategy is common in the automotive industry (Östlin et al., 2008). In this strategy, for every unit that is sold, a used core must be returned and then the deposit will be refunded to the customer. The amount that will be refunded depends, however, on the quality of the returned core. The decision regarding the amount of deposit mainly depends on the differences between the cost of remanufacturing and the cost of buying a new product from Caterpillar.

Company B and Company C have developed a return route for their customers so that they can return their used products free of charge. In addition to this, both companies implement a proactive (market-driven) strategy. Company C buys back used cartridges of acceptable condition through third-party brokers. The third-parties are informed of the required quality specifications and are only paid by Company C if the returns match those specifications. The amount of the incentive is mainly determined by the total cost of remanufacturing and the selling price in the market.

Although there are similarities in the nature of the business between Company C and Company B, the product acquisition strategies differ from each other. Company B offers both trade-in and buy-back services to obtain used products from customers. In the buy-back strategy, Company B directly purchases used equipment by offering cash to the customers. Customers who decide to trade-in or sell their used equipment to Company B have to fill in and send the “trade-in” form. In these forms customers are asked to provide accurate information regarding their used equipment (quality, model, age, etc.). Once the trade-in or buy-back is agreed, Company B’s remarketing division collects the used item(s) free of charge; although customers have to ensure that the equipment is packed, palletised and ready for secure transit. After the equipment has been collected and inspected, the final value of the offer is passed to the customers. Any shortfalls in the returned equipment (in either quantity or quality) lead to a reduction in the final value, and customers will be re-invoiced with a new price. This finding is contrary to Li et al. (2009) and Teunter and Flapper (2011) who maintain that it is not possible to differentiate the acquisition price based on the quality of the returned products.

The incentive price for trade-in or buy-back is closely linked to the quality of the returned products, as well as the market appetite to resell remanufactured products. There is, therefore, a direct link between the value at which Company B can sell the refurbished products, and the level of incentive they can offer to the customer. Company B looks at the potential market resale value to guide them on incentive price. In the case of laptops, Company B usually aims to make a 10%-15% net margin, and uses this figure as a benchmark to decide on how much they should offer to the customers. Analogous to Company C, Company B only reconditions products of the company brand, however; customers can trade-in or sell other major IT brands, and in these cases, Company B ship the equipment to their specialised partners for reconditioning operations.

The analysis from the case studies indicates several challenges in current product acquisition management practice. One of the biggest challenges is managing uncertainty in the quantity, timing and quality of returned products. These uncertainties impose extra complexity in managing reverse logistics operations, but their nature differs between the cases. Company A is able to control the variability in the quantity and quality of returns with a deposit-refund system, however the major challenge is controlling the timing of returns. The timing of the returns is mainly dependent on the usage pattern and maintenance level and therefore it is possible that cores (engines) stay at the customer site for long periods of time. Uncertainty in timing might not directly affect the cost of Company A’s reverse logistics operations but does impose several complexities (material matching, inventory control) to their service exchange programme. For Company B, however, the quality of returns (laptops) is very important since it has a direct impact on the cost of the remanufacturing operations. Company B’s acquisition strategy (trade-in and buy-back) enables it to manage the reverse logistics operation more efficiently. According to Guide et al. (2005), companies whose products have a short life cycle lose a lot of money if they treat time-sensitive returns as a nuisance, and this research confirms that the life cycle stage of returned products is also a crucial factor for Company B. Laptops that return late in their life cycle (after 36 months from the beginning of the life cycle) are not suitable for remanufacturing since there is no demand for them in the market. To overcome this challenge, Company B offers a discount to customers who return their products earlier in the life cycle (before the warranty ends).

Finally, the competition between the third-party remanufacturer and OEMs has been identified in the literature as one of the challenges in reverse logistics (Ferguson and Toktay, 2006; Heese et al., 2005; Lebreton, 2007; Majumder and Groenevelt, 2001). The information from the interviews also shows that the competition between case companies and independent remanufacturers is an important issue that adds extra complexities to the companies' remanufacturing operations. According to the managers at both Company C and Company B, independent remanufacturers are able to offer a better incentive price to customers and divert a proportion of the returns to themselves. This competition influences the balance of supply and demand, which consequently leads to warehouses being full of equipment that has to be scrapped. In addition, the case companies state that, typically, the quality of the used products that are remanufactured by third-parties is low, and this can have a negative influence on customer perceptions of remanufactured products.

4.8 Conclusion

As mentioned earlier this research primarily seeks to develop models to provide a general understanding of the important trade-offs involved in product acquisition decisions. One of the major challenges among all the cases is the uncertainty in the quantity, timing and quality of returned products. These uncertainties impose extra complexity in managing RL operations and seem to be the main reason that all the case companies operate a proactive acquisition strategy. A combination of passive with proactive strategies is observed in Companies B and

C as a response to the legal regulatory requirements of the sector they operate in. The acquisition costs (including the cost of collection and incentive price) seem to be the major factor affecting the total cost of the RL operations in all cases.

The quantitative models in the following chapters aim to address some of the key issues that emerge from the empirical case studies. In Chapter 5 and 6, we investigate the economic attractiveness of a proactive strategy over a passive strategy by considering a more general acquisition cost function in the form of a rational function. This model enables us to explore how the acquisition efforts can stimulate returns volume or quality under different scenarios (e.g. when company faces diseconomies of scale in their acquisition costs). In particular, the models of Chapter 5 can provide insights into the optimal buy-back price and the quality level of used products for which operating a proactive strategy becomes economically viable.

The findings from Company C acknowledge that beside the quality of used products, market demand for remanufactured products is also a critical factor in making a product acquisition decision. This is an important issue specifically for companies who offer consumer technological products (e.g. laptops and desktops). Facing a high value erosion implies that any postponement in processing returns will impact on the viability of the remanufacturing operations. In Chapter 6, the product life cycle is considered as a basis for balancing the supply of used products and market demand. The aim of the models in Chapter 6 is to provide insights into important issues such as the return's lead time and synchronisation of product acquisition strategy throughout the product life cycle.

Finally, market demand and supply of used products can be determined upon time dependent elements such as seasonal effects. The intensity in the usage pattern, maintenance level, and changes of technology impact on both the quality and timing of returns. Therefore, a hybrid manufacturing-remanufacturing system may be defined as a dynamic control system upon predication of said elements and the acquisition control can be dynamically changed with time, so that timing uncertainties can be managed to a certain extent. The model in Chapter 7 aims to provide insights into a dynamic manufacturing-remanufacturing system and buy-back acquisitioning in which the condition of the products in the market decays continuously over time.

Chapter 5

The Economics of Proactive Product Acquisition Strategies under an Infinite Planning Horizon

5.1 Introduction

The aim of the work presented in this chapter is to provide insights into different product acquisition strategies and the impact of some important cost components on the economic attractiveness of these strategies. As discussed in Section 2.4.4, there are two main options for obtaining used products from the final user, namely the waste stream and the market-driven strategy (Guide and Van Wassenhove, 2001). In the waste stream system, firms passively accept all product returns, and therefore have no control on the quality and quantity of those returns. A market-driven strategy, on the other hand, relies on financial incentives to motivate end users to return their products for recovery. The financial incentives could include a deposit system, credit towards a new product, or cash paid for a specified level of quality. Firms would then be able to control the quantity and quality of the returned products since the acceptance of returns is conditioned by the firm (Guide and Van Wassenhove, 2001; Jayaraman, 2006; Atasu et al., 2008).

In the UK, for instance, used EEE returns via the “official” collection system are controlled by WEEE compliance schemes. This official route, however, seems to divert too many products from remanufacturing to simply being shredded for recycling (Haig et al., 2011). In parallel with the legal obligation, there are manufacturers that proactively acquire higher quality used products for their remanufacturing operations. Good examples are manufacturers of toner cartridges and ink jets such as Xerox, HP and Ricoh. According to Xerox, remanufactured cartridges can contain up to 90% reused and recycled content and are tested to the same specifications as new products (Xerox, 2010b). Considering that cartridges can be remanufactured up to four times, the savings associated with remanufacturing cartridges are substantial.

This chapter presents economic models to investigate the optimal product acquisition strategy for firms in a CLSC, and the economic attractiveness of the market-driven strategy over the passive strategy. Within the market-driven strategy, the first scenario investigated is that of a firm offering incentives to influence the returns rate for the remanufacturing operation (quantity-based incentives). Exemplary cases for the quantity-based incentive can be found in products such as single-use cameras, heavy vehicle tyres, packaging and empty containers. In the tyre industry, for instance, the remanufacturing[17] of used tyres[18] typically starts with the purchase of used tyres from tyre dealers or fleet operators, which are then sent to the remanufacturing facility. In this model, the relationship between the

[17] There are two different remanufacturing processes for used tyres: Re-grooving or Re-treading.

[18] In the UK approximately 920,000 truck tyres, 33% of the total, are annually remanufactured (Centre for Remanufacturing & Reuse, 2009).

acquisition cost and the cost difference between manufacturing new tyres and remanufacturing is crucial for the profitability of this business.

The next model explores the impact of quality-based incentives, i.e. when firms offer incentives to obtain a higher quality of returns. The cost savings of the market-driven strategies are then benchmarked against an open-loop system to illuminate the economic advantage of the remanufacturing operation. The quality-based incentives are commonly used for consumer products such as, printers, mobile phones, toner cartridges and car engines.

This chapter is arranged as follows. In Section 5.2, the quantity-based incentive model is presented by describing the networks associated with passive and proactive strategies and the main assumptions made. In Section 5.3, the quality-based incentive model is presented. Section 5.3.6 investigates a case where both acquisition and remanufacturing costs are a function of quality. Finally, in Section 5.4 the chapter is concluded by discussing the summary and outcomes.

5.2 Quantity-based model

Consider a firm with a hybrid manufacturing-remanufacturing system that can manage product returns through passive or proactive strategies. In an open-loop strategy, demand is satisfied by manufacturing new products, and returned products will be scrapped in order to comply with the relevant environmental legislation (e.g. WEEE or ELT). Alternatively, the firm can go beyond the open-loop strategy and proactively engage in remanufacturing operations. In this case, returns of used products act as a source of supply for the firm's remanufacturing operations. The firm can influence the return rate by offering appropriate financial incentives. When returns arrive at the firm's return centre, they will be tested and sorted into two categories: remanufacturing for those returns that retain value and scrap for those that do not meet the firm's quality standards, meaning that market demand can be satisfied through both the manufacture of new products and the remanufacture of used products (Figure 5—1).

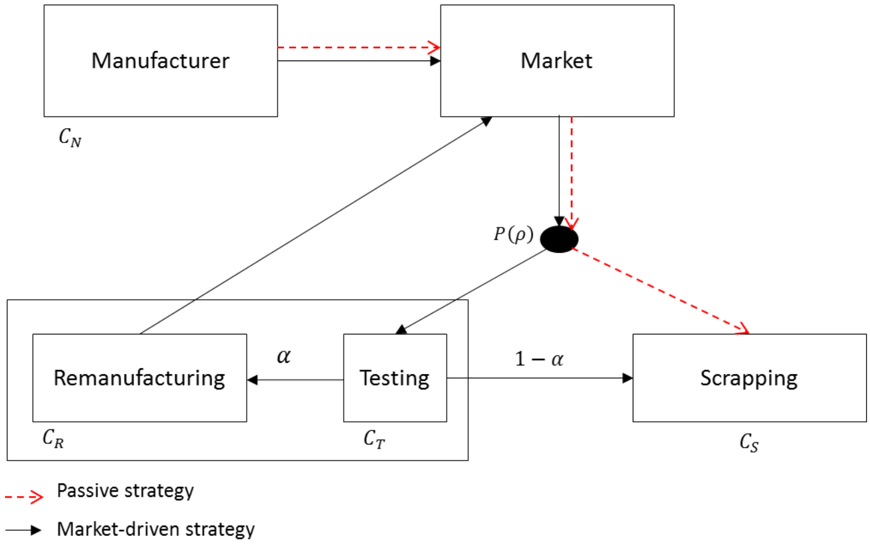

Figure 5—1: Quantity-based market-driven structure.

The remanufacturing of used tyres can exemplify the quantity-based model. A tyre is a one-piece product wherein 75% of value is added by the casing, which hardly deteriorates during its first life. Hence, tyre remanufacturing presents the opportunity to recover all of this value-added, at a certain remanufacturing cost (Ferrer, 1997). The used tyres that are collected from the market will be inspected to identify the ones with the best remanufacturing potential.[19] The fraction of used tyres that are considered to be suitable for remanufacturing will be recovered until they are as good as new,[20] whereas those that failed to meet the quality standards

[19] The collection of used tyres is mainly achieved through tyre retailers, who work with OEMs under a contract (Flapper et al., 2006).

[20] In the UK, remanufactured tyres are considered as good as new since they must comply with the same standards that are imposed on new tyres (WRAP, 2012).

will be scrapped.[21] Tyre manufacturers apply different acquisition strategies to control and influence the return of used tyres. For instance, Michelin applies a leasing strategy under a pay-per-kilometre programme, while Bandvulc operates an incentivised return model for both heavy goods vehicle and smaller van vehicle tyres (WRAP, 2012). In Bandvulc's business model, the company sells tyres to heavy goods vehicle dealers and encourages customers to return their used tyres in exchange for a financial incentive (e.g. cash, a voucher, or a discount on a new purchase). The returned products are then remanufactured and resold or reused in service contracts. According to WRAP (2012), the incentivised model has enabled Bandvulc to generate £10 million in extra revenue (in its first three years), and to have a positive environmental impact in terms of resource use and carbon emission reduction.

In more general terms the present quantity based model can provide insights into the optimal buy back levels for used products.

5.2.1 Model description and assumptions

It is assumed that remanufactured products are identical to the original products in term of quality. Therefore, there is no distinction between a manufactured and a remanufactured product; both are sold in a primary market to satisfy demand. The assumption of perfect substitution between new and remanufactured products has been widely used in both pure remanufacturing environment (e.g. Geyer et al. 2007 and Xiong et al., 2014) and hybrid

[21] Such tyres are used as feedstock for other tyre-rubber based products. They are often shredded and crumbed or used as incinerator or cement kiln fuel. As tyre disposal at landfill sites is becoming prohibited, numerous other applications are being developed (WRAP, 2006).

manufacturing-remanufacturing studies (e.g. Minner and Kiesmüller 2012; Cai et al., 2014). The list of notations used in the models is presented in Table 5—1.

Table 5—1: Model Notations.

C_N	Cost of manufacturing a new product.
C_R	Cost of refurbishing/remanufacturing.
C_T	Cost of testing the returned products.
C_S	Cost of scrapping/disposal.
ρ	Return rate as fraction of demand ($0 \leq \rho \leq 1$).
ρ_{max}	Maximum amount of return rate.
ρ_{min}	The price-independent return rate.
P_{max}	Maximum incentive that firm has to offer to attract maximum return rate
b	Price sensitivity of the acquisition cost function
d	Demand rate per unit time.
$P\ (\rho)$	Acquisition cost function as a function of the return rate.
VR	Value Recovery (the cost advantage of operating a market-driven strategy).
α	Quality level of returned product.
$P(\alpha)$	Acquisition cost function as a function of the return quality.
TC_M	Total cost of market-driven strategy.
TC_O	Total cost of passive strategy (open-loop system).

The cost of manufacturing new products is denoted by C_N and the unit cost of remanufacturing and scrapping are denoted by C_R and C_S, respectively. Note that $(C_N + C_S) - C_R$ denotes the remanufacturing cost advantage. If $(C_N + C_S) - C_R < 0$ then remanufacturing is not economically beneficial and will not take place. Therefore, to avoid trivial solutions, it is assumed that $(C_N + C_S) - C_R > 0$ i.e. remanufacturing a unit is always cheaper than manufacturing a new one and scrapping the return. A similar assumption of the cost structure has been made in Minner and Kiesmüller (2012). In contrast to their model in which scrapping occurs when the returns are more than the required amount for remanufacturing, we consider a testing operation that evaluates the quality of returns and returns with low quality are sent for scrapping.

Demand d is assumed to be constant and deterministic over the infinite planning horizon. A similar assumption has been used in other remanufacturing models (Richter, 1996; Dobos and Richter, 2003; Dobos and Richter, 2004 and Rubio and Corominas, 2008). This assumption will be relaxed in Chapter 6 in which demand is a deterministic continuously differentiable function of time.

Thereturns r are a function of demand ($r = \rho d$), where a constant value ρ ($0 \leq \rho_{min} \leq \rho \leq \rho_{max} \leq 1$) represents the return rate that can be influenced by offering financial incentives. One of the fundamental elements of the market-driven model is offering financial incentives as part of the product acquisition process. We denote the quantity-based acquisition cost function by $P(\rho)$ which is a deterministic, increasing and convex function of ρ. The main difference between our model and previous studies (e.g. Rubio and Corominas, 2008; Kaya 2010; Minner and Kiesmüller 2012; Cai et al., 2014) is that we incorporate a general acquisition cost function that can capture both linear and non-linear relationships (i.e. diseconomies of scale) in the acquisition volume and a testing phase that evaluates the quality of returns for remanufacturing operation. The specifications of $P(\rho)$ are discussed further in section 5.2.2. The quality parameter α represents a fraction of the returns that meet the quality standard and can be remanufactured. Therefore, $\alpha\rho d$ represents the remanufacturing rate and $(1-\alpha)\rho d$ is the rate of scrapping. Also, the firm has to manufacture new products at a rate $(1-\alpha\rho)d$ to satisfy all market demand. Hence, the total cost of the market-driven strategy can be written as the sum of the following costs:

- Cost of manufacturing new products: $C_N\,(1-\alpha\rho)d$.
- Cost of remanufacturing returned products that pass the quality test: $C_R\alpha\rho d$.
- Cost of testing all the returns: $C_T\rho d$.
- Cost of scrapping those that failed the quality inspection: $C_S(1-\alpha)\rho d$.

- Acquisition cost of the used products : $P(\rho)\rho d$.

Therefore, the total cost of the market driven strategy, can be obtained from:

$$TC_M(\rho) = C_N\,(1-\alpha\rho)d + C_R\alpha\rho d + C_T\rho d + C_S(1-\alpha)\rho d + P(\rho)\rho d. \tag{5-1}$$

where $TC_M(\rho)$ is a continuous and twice differentiable function of ρ on the interval $[\rho_{min}, \rho_{max}]$. The objective is to find the optimal return rate that minimises the total cost of the market-driven strategy i.e., $TC_M(\rho)$.

Alternatively, the firm can operate an open-loop system. In this case, no incentive is offered to attract more returns, however, due to environmental obligations the firm has to scrap any returns at a cost C_S and all the market demand has to be satisfied by manufacturing new products at a cost of C_N. Therefore, the total cost of the open-loop strategy will be:

$$TC_O = C_N d + C_S\,\rho d.$$

From the above expression it is clear that the cost of the open-loop system increases as the return rate increases, therefore, the minimum cost of the open-loop system is achieved when $\rho = \rho_{min}$:

$$TC_O^* = C_N d + C_S\,\rho_{min} d. \tag{5-2}$$

The decision regarding the economic strategy can be made based on a cost comparison between the market-driven strategy and the open-loop strategy. Let VR be the cost advantage of operating a market-driven strategy, i.e. $VR = TC_O - TC_M$. When $VR > 0$ offering an incentive to influence return rate becomes appropriate, from an economic point of view:

$$C_N d + C_S\, \rho_{min} d > C_N\,(1-\alpha\rho^*)d + C_R\alpha\rho^* d + C_T\rho^* d + C_S(1-\alpha)\rho^* d + P(\rho^*)\rho^* d,$$

where ρ^* is the optimal return rate that minimises (5-1). Simplifying the above, gives:

$$-\alpha(C_N - C_R + C_S) + C_S(1-\rho_{min}) + C_T + P(\rho^*) < 0.$$

Rewriting the above for the quality parameter α gives the following quality threshold:

$$\alpha > \frac{P(\rho^*) + C_S(1-\rho_{min}) + C_T}{(C_N - C_R + C_S)}, \rho \in [\rho_{min}, \rho_{max}]. \tag{5-3}$$

The threshold (5-3) suggests that the remanufacturing operation is economically attractive when the quality of returns is higher than $\frac{P(\rho^*)+C_S(1-\rho_{min})+C_T}{(C_N-C_R+C_S)}$. Otherwise, the open-loop strategy should be operated.

The objective is to find the optimal return rate that minimises (5-1), i.e.

$$\min_{\rho_{min} \le \rho \le \rho_{max}} TC_M(\rho).$$

Let ρ^* denote the optimal solution for the above minimisation problem, therefore, $TC_M(\rho)$ has an isolated strict local minimum at ρ^* if $\frac{dTC_M(\rho)}{d\rho} = 0$ and $\frac{d^2TC_M(\rho)}{d\rho^2} > 0$.

Where the first order condition is:

$$\rho P'(\rho) + P(\rho) - \alpha(C_N - C_R + C_S) + C_T + C_S = 0, \;\; \rho \in [\rho_{min}, \rho_{max}], \tag{5-4}$$

and the following second order condition is sufficient for the optimality condition:

$$\frac{d^2TC_M(\rho)}{d\rho^2} = 2P'(\rho) + P''(\rho)\rho > 0. \tag{5-5}$$

Therefore, $TC_M(\rho)$ is convex in ρ if the acquisition cost function is convex.

The following section discusses the specification of the acquisition cost function.

5.2.2 Specification of the quantity-based acquisition cost function

Different types of the price-response function (linear, non-linear) have been presented in the marketing and economics literature (Simon, 1989; Thomson and Teng, 1984). In this study, the acquisition cost function is presented in the form of a rational function that can capture the relationships between the acquisition price and the return rate. It has to be mentioned that as a part of the financial incentives (e.g. cash or discount), the costs of advertising, transportation and handling can be considered within the acquisition cost function. A more general interpretation of the acquisition cost function, therefore, would be the level of effort that firms put into the product acquisition (a similar interpretation is used in Minner and Kiesmüller, 2012).

Let $P(\rho)$ denote the quantity-based acquisition cost function; $P(\rho)$ is defined as:

$$P(\rho) = \frac{P_{max}(\rho - \rho_{min})}{(\rho_{max} - \rho)^b \Delta\rho}. \tag{5-6}$$

where $\Delta\rho$ denotes the difference between minimum and maximum return rate i.e. $\Delta\rho = \rho_{max} - \rho_{min}$.

When $P(\rho)$ is linear ($b = 0$) the firm can obtain the maximum amount of returns (ρ_{max}) by offering the incentive price (P_{max}). However, as b increases ($b > 0$) it becomes more expensive to increase return rates, i.e. the marginal cost of acquisition of a unit increases as the return rate increases (e.g. if there is a lot of competition for obtaining used products, acquiring more products yields a higher cost). The value of ρ_{min} represents the price-independent return rate, i.e. those used products that are returned without offering any incentive ($0 \leq \rho_{min} < \rho_{max} \leq 1$).

Differentiating $P(\rho)$ with respect to ρ gives:

$$\frac{dP(\rho)}{d\rho} = \frac{P_{max} \frac{d}{d_\rho}\left(\frac{(\rho - \rho_{min})}{(\rho_{max} - \rho)^b}\right)}{\Delta\rho},$$

hence:

$$= \frac{P_{max}.\left((\rho_{max} - \rho)^b - b(-1)(\rho_{max} - \rho)^{b-1}(\rho - \rho_{min})\right)}{\Delta\rho(\rho_{max} - \rho)^{2b}}.$$

simplifying the above, it is easy to see that:

$$\frac{dP(\rho)}{d\rho} = \frac{P_{max}\big((\rho_{max} - \rho) + b(\rho - \rho_{min})\big)}{(\rho_{max} - \rho)^{b+1}\Delta\rho}. \tag{5-7}$$

(5-7) implies that acquisition cost function is an increasing function in ρ for $\forall\rho \in [\rho_{min}, \rho_{max})$.

The second derivative is now derived. Rewriting equation (5-7) as follows:

$$\frac{d^2P(\rho)}{d\rho^2} = \frac{d}{d_\rho}\left(\frac{P_{max}\big((\rho_{max} - \rho) + b(\rho - \rho_{min})\big)}{(\rho_{max} - \rho)^{b+1}\Delta\rho}\right),$$

which gives:

$$\frac{d^2P(\rho)}{d\rho^2} = \frac{2bP_{max}.(\rho_{max} - \rho) - (-b - 1)bP_{max}(\rho - \rho_{min})}{(\rho_{max} - \rho)^{b+2}\Delta\rho}. \tag{5-8}$$

Hence, $\frac{d^2P(\rho)}{d\rho^2} \geq 0$ if

$$bP_{max}\big(2(\rho_{max} - \rho) - (-b - 1)(\rho - \rho_{\mathrm{min}})\big) \geq 0.$$

Which is always positive for $\forall b \geq 0$ .Therefore the function $P(\rho)$ is a monotonically increasing and convex function ρ for $\forall \rho \in [\rho_{min}, \rho_{max})$.

This implies that the return rate increases by giving higher incentives to customers. Assuming the convexity of the acquisition cost function is reasonable since the acquisition cost can be affected by different factors such as location and transportation (Ferguson and Toktay, 2006; Rubio and Corominas, 2008). In practice both economies and diseconomies of scale in the collection cost of used products can be observed. According to Atasu et al., (2013) firms who charge their customers volume-dependent prices and use a drop-off strategy, under which consumers are provided the means to drop off the used product to specified locations, face economies of scale. Atasu et al., (2013) also provide a justification for the convexity in collection costs (a diseconomy of scale) using empirical data of an IT manufacturer that sells print cartridges to end-consumers and provides them with pre-paid envelopes to return their end-of-use cartridges.

In this study we investigate OEMs who collect the used products from their customers (either directly or through third-party collectors). In this situation the marginal cost of collecting an additional product is increasing in the collection rate, such that one would observe diseconomies of scale. In our model the diseconomies of scale in the acquisition cost are captured when b>0. Similar assumptions have been used in other remanufacturing models (Guide et al., 2003; Savaskan et al., 2004 and Atasu et al., 2013). Figure 5—2 illustrates the relationships between the return rate and the acquisition cost.

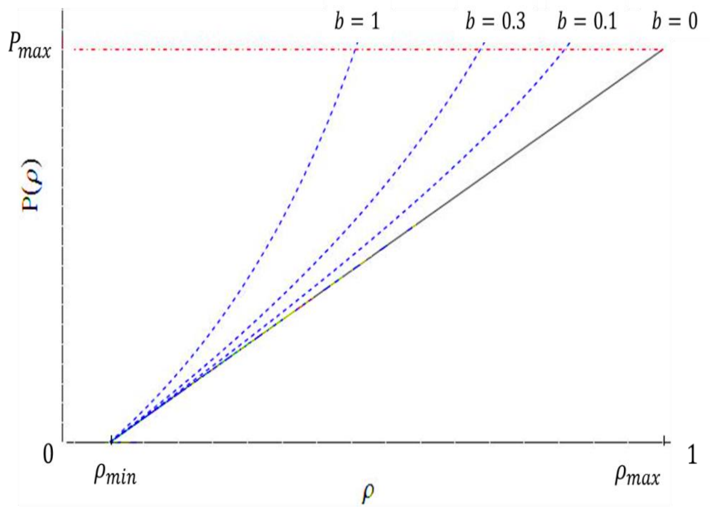

Figure 5—2: The quantity-based acquisition cost function

Given (5-7) and (5-8), the second order condition (5-5) is always satisfied, hence the objective function is convex in ρ and a unique optimal solution exists, which can be derived by solving the first order condition (5-4).

The optimality condition can be obtained by substituting (5-6) and (5-7) into the first order condition (5-4), as follows:

$$\frac{\rho P_{max}\big((\rho_{max}-\rho)+b(\rho-\rho_{min})\big)}{(\rho_{max}-\rho)^{b+1}\Delta\rho}+\frac{P_{max}(\rho-\rho_{min})}{(\rho_{max}-\rho)^{b}\Delta\rho}-\alpha(C_N-C_R+C_S)+C_T + C_S = 0.$$

The above can be rewritten as:

$$\frac{\rho P_{max}\big((\rho_{max}-\rho)+b(\rho-\rho_{min})\big)+P_{max}(\rho-\rho_{min})(\rho_{max}-\rho)}{(\rho_{max}-\rho)^{b+1}\Delta\rho} - \alpha(C_N-C_R+C_S)+C_T+C_S=0.$$

Factoring out P_{max} gives:

$$\frac{P_{max}\big(\rho(2\rho_{max}-2\rho+b\rho)-\rho_{min}(b\rho-\rho+\rho_{max})\big)}{(\rho_{max}-\rho)^{b+1}\Delta\rho}-\alpha(C_N-C_R+C_S)+C_T + C_S = 0.$$

Rearranging the above, gives:

$$\frac{\rho(2\rho_{max} - 2\rho + b\rho) - \rho_{min}(b\rho - \rho + \rho_{max})}{(\rho_{max} - \rho)^{b+1}} = \frac{\Delta\rho(\alpha(C_N - C_R + C_S) - C_T - C_S)}{P_{max}}. \tag{5-9}$$

The optimal return rate that minimises the total cost of the market driven strategy can therefore be obtained by solving (5-9).

The following sections analytically derive the optimality condition for linear and non-linear acquisition cost functions when $b = 0$ and $b = 1$. For higher values of b, however, (5-9) becomes a polynomial equation of a high degree, making it extremely difficult to obtain the analytical solution[22]. For b>1, therefore, the optimal solution is obtained numerically.

The optimality condition for the linear acquisition cost function is analysed first. In a remanufacturing environment, linear acquisition, transportation and handling costs are commonly assumed in the literature (e.g., Majumder and Groenevelt, 2001; Fleischmann et al., 2001; Galbreth and Blackburn, 2006; Vadde et al., 2007; Ghoreishi et al., 2011 and Minner and Kiesmüller, 2012). According to Simon (1989), although the presence of a linear relationship in this context is not based on a well-founded theory it often yields a satisfactory fit to empirical data. It has been suggested, however, that a non-linear response function provides a better theoretical foundation for the price-response function (Simon, 1989; Thomson and Teng, 1984 and Klausner and Hendrickson, 2000). Section 5.2.4, therefore, investigates the impact of the nonlinear acquisition cost function on the optimal return rate and cost saving of the market-driven strategy.

[22] According to Évariste Galois' theory, there is no exact solution for polynomial equations of degree 5 and greater.

5.2.3 Optimal strategy with linear acquisition cost function

Let $\overline{\rho}$ represent the solution to (5-9) when the acquisition cost function is linear i.e. $b=0$. Therefore, the optimal return rate will be:

$$\rho^* = \overline{\rho} = \frac{\Delta\rho(\alpha(C_N - C_R + C_S) - C_T - C_S)}{2P_{max}} + \frac{\rho_{min}}{2}, \rho \in [\rho_{min}, \rho_{max}]. \tag{5-10}$$

The corresponding quality interval for the optimal solution can be obtained as follows:

The lower bound for the quality parameter α can be obtained when $\rho_{min} \leq \overline{\rho}$. Hence:

$$\rho_{min} \leq \frac{\Delta\rho(\alpha(C_N - C_R + C_S) - C_T - C_S)}{2P_{max}} + \frac{\rho_{min}}{2},$$

which simplifies to:

$$P_{max}\rho_{min} \leq \Delta\rho(\alpha(C_N - C_R + C_S) - C_T - C_S).$$

Rewriting above for α gives the lower bound for the quality interval:

$$\frac{\frac{P_{max}\rho_{min}}{\Delta\rho} + C_T + C_S}{(C_N - C_R + C_S)} \leq \alpha. \tag{5-11}$$

Similarly the upper bound of quality parameter α can be obtained when $\overline{\rho} \leq \rho_{max}$. Hence:

$$\frac{\Delta\rho(\alpha(C_N - C_R + C_S) - C_T - C_S)}{2P_{max}} + \frac{\rho_{min}}{2} \leq \rho_{max},$$

which simplifies to:

$$\Delta\rho(\alpha(C_N - C_R + C_S) - C_T - C_S) \leq (2\rho_{max} - \rho_{min})P_{max}.$$

Rewriting above for α gives the upper bound of the quality interval:

$$\alpha \leq \frac{\frac{(2\rho_{max}-\rho_{min})P_{max}}{\Delta\rho}+C_T+C_S}{(C_N-C_R+C_S)}. \tag{5-12}$$

Hence when $\rho^* = \overline{\rho}$ the quality parameter α should be on the interval of $[\frac{\frac{P_{max}\rho_{min}}{\Delta\rho}+C_T+C_S}{(C_N-C_R+C_S)}, \frac{\frac{(2\rho_{max}-\rho_{min})P_{max}}{\Delta\rho}+C_T+C_S}{(C_N-C_R+C_S)}]$.

If $\overline{\rho} > \rho_{max}$, then the optimal solution reaches the value of the upper bound i.e. $\rho^* = \rho_{max}$. This situation implies that the maximum incentive should be offered to attract the maximum return. Also, if $\overline{\rho} < \rho_{min}$, then the optimal solution occurs at the lower bound, i.e. $\rho^* = \rho_{min}$. This implies that offering an incentive to attract more returns is not economically attractive. In this situation two strategies can be followed:

1) If $\frac{C_T}{(C_N-C_R+C_S)} < \alpha < \frac{\frac{P_{max}\rho_{min}}{\Delta\rho}+C_T+C_S}{(C_N-C_R+C_S)}$, remanufacturing the price-independent returns (ρ_{min}) yields a cost advantage for the firm compared to the open-loop system, but no incentive should be offered to attract more returns.

2) If $\alpha < \frac{C_T}{(C_N-C_R+C_S)}$, the returns quality is not suitable for remanufacturing and therefore it is economically viable to scrap all the returns and satisfy the market demand by manufacturing new products (i.e. open-loop system).The above strategies are illustrated in Figure 5—3 based on the quality parameters α.

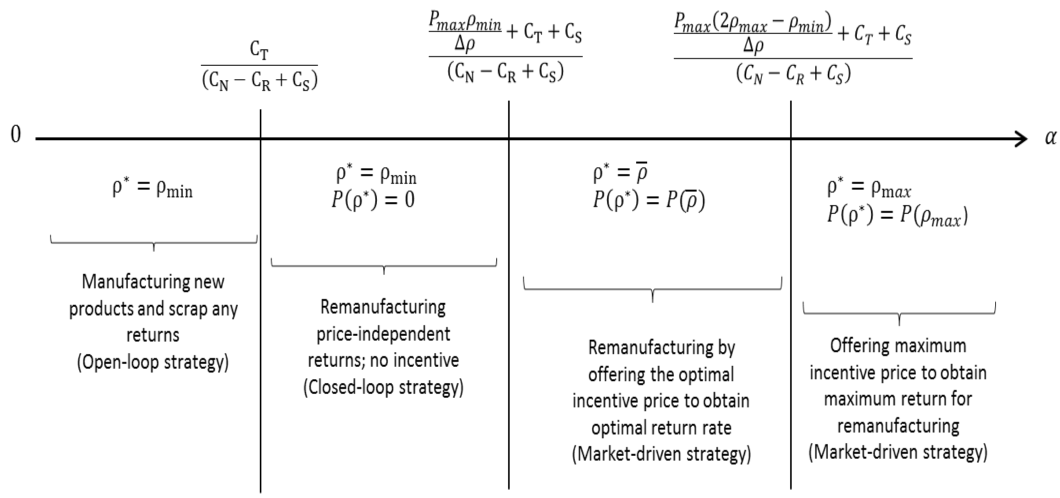

Figure 5—3: Optimal acquisition strategy based on the quality parameter α when $b=0$.

5.2.4 Optimal strategy with non-linear acquisition cost function

As discussed earlier in section 5.2.2 the cost of advertising and promotional activities can be considered within the acquisition cost function. Non-linear response functions have been widely used in advertising response models of consumer retention and product awareness (Lilien et al. 1992, Fruchter and Kalish 1997, Zhao 2000). In the remanufacturing context Savaskan (2004) used a simple quadratic cost structure[23] to capture the diminishing returns to total investment in promotional/ advertising activities. In our model the non-linear acquisition cost function can be captured when $b > 0$. For the purpose of this study we required a closed-form solution for the optimality condition when the acquisition cost is non-linear. Therefore we analyse the non-linear case when $b = 1$. However, we numerically investigate the scenarios when $0 < b < 1$.

[23] The cost structure is presented as $I = C_L\tau^2$, where I denote the total investoment in advertising/promotional activities, τ represent the return rate, i.e., $0 \leq \tau \leq 1$ and C_L is scaling parameter.

The optimal return rate when the acquisition cost function is non-linear can be obtained by substituting *b=1* into (5-9), to give:

$$\frac{-\rho^2+2\rho\rho_{max}-\rho_{min}\rho_{max}}{(\rho_{max}-\rho)^2}=\frac{\Delta\rho(\alpha(C_N-C_R+C_S)-C_T-C_S)}{P_{max}},$$

adding $+\rho_{max}^2$ and $-\rho_{max}^2$ to the left hand side of the above, and rewriting gives:

$$\frac{-(\rho_{max}-\rho)^2+\rho_{max}^2-\rho_{min}\rho_{max}}{(\rho_{max}-\rho)^2}=\frac{\Delta\rho(\alpha(C_N-C_R+C_S)-C_T-C_S)}{P_{max}},$$

which simplifies to:

$$\frac{\rho_{max}^2-\rho_{min}\rho_{max}}{(\rho_{max}-\rho)^2}=\frac{\Delta\rho(\alpha(C_N-C_R+C_S)-C_T-C_S)}{P_{max}}+1.$$

Factoring out ρ_{max} gives:

$$\frac{\rho_{max}\Delta\rho}{(\rho_{max}-\rho)^2}=\frac{\Delta\rho(\alpha(C_N-C_R+C_S)-C_T-C_S)+P_{max}}{P_{max}},$$

which can be rewritten as:

$$(\rho_{max}-\rho)^2=\frac{P_{max}\rho_{max}\Delta\rho}{\Delta\rho(\alpha(C_N-C_R+C_S)-C_T-C_S)+P_{max}}.$$

Solving the above equation for ρ, gives

$$\rho=\rho_{max}\pm\sqrt{\frac{P_{max}\rho_{max}\Delta\rho}{\Delta\rho(\alpha(C_N-C_R+C_S)-C_T-C_S)+P_{max}}},\rho\in[\rho_{min},\rho_{max}].$$

Let $\bar{\bar{\rho}}$ represent the feasible solution to the above equation, since $\rho\in[\rho_{min},\rho_{max}]$ for $\bar{\bar{\rho}}$, we obtain:

$$\bar{\bar{\rho}}=\rho_{max}-\sqrt{\frac{P_{max}\rho_{max}\Delta\rho}{\Delta\rho(\alpha(C_N-C_R+C_S)-C_T-C_S)+P_{max}}}. \qquad (5\text{-}13)$$

Hence $\rho^* = \bar{\bar{\rho}}$ is the optimal solution for the return rate. It is clear from (5-13) that when the acquisition cost function is non-linear ($b = 1$), it is infinitely expensive to obtain the maximum used products (ρ_{max}) from the market. Also, when $\bar{\bar{\rho}} < \rho_{min}$ we have:

$$\Delta\rho < \sqrt{\frac{P_{max}\rho_{max}\Delta\rho}{\Delta\rho(\alpha(C_N - C_R + C_S) - C_T - C_S) + P_{max}}}.$$

Since $\forall\rho \in [0, 1]$ $\Delta\rho \geq 0$, we can square both sides of the above inequality, which gives:

$$\Delta\rho^2 < \frac{P_{max}\rho_{max}\Delta\rho}{\Delta\rho(\alpha(C_N - C_R + C_S) - C_T - C_S) + P_{max}}.$$

Cancelling out the $\Delta\rho$, gives:

$$\Delta\rho < \frac{P_{max}\rho_{max}}{\Delta\rho(\alpha(C_N - C_R + C_S) - C_T - C_S) + P_{max}}.$$

Rewiring the above for α, we obtain:

$$\alpha < \frac{\frac{(P_{max}\rho_{max})}{\Delta\rho} + \Delta\rho(C_T + C_S) - P_{max}}{\Delta\rho(C_N - C_R + C_S)}. \quad (5\text{-}14)$$

The above threshold suggests that when the quality of returns is higher than $\frac{\frac{(P_{max}\rho_{max})}{\Delta\rho} + \Delta\rho(C_T + C_S) - P_{max}}{\Delta\rho(C_N - C_R + C_S)}$ we have $\rho^* = \bar{\bar{\rho}}$. This implies that offering an incentive is economically attractive, i.e. that the market-driven strategy is optimal.

For $\frac{C_T}{(C_N - C_R + C_S)} \leq \alpha \leq \frac{\frac{(P_{max}\rho_{max})}{\Delta\rho} + \Delta\rho(C_T + C_S) - P_{max}}{\Delta\rho(C_N - C_R + C_S)}$ we have $\rho^* = \rho_{min}$. This suggests that the firm should remanufacture the price-independent returns and that no incentive should be offered to attract more returns (a closed-loop strategy). Obviously, when $\alpha < \frac{C_T}{(C_N - C_R + C_S)}$ it implies that the quality of the returns is not sufficient for remanufacturing operations and an open-loop strategy should be operated (Figure 5—4).

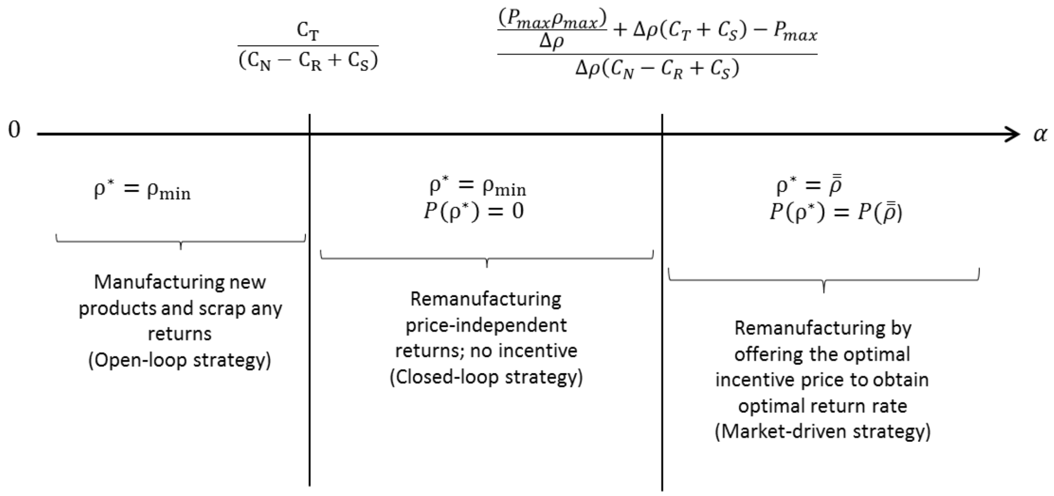

Figure 5—4: Optimal acquisition strategy based on the quality parameter α when $b=1$.

5.2.5 **Numerical example**

This section conducts a numerical study to investigate the impact of the model's parameters on the optimal acquisition decision, and to illustrate the insight gained from the analytical solutions. The following base case parameters are considered for the numerical test and the effect of the parameters in the model are studied by varying one parameter at a time. It has to be mentioned that the main objective of these numerical tests is to investigate the relationships between the model's parameters and their effect on the optimality conditions. This means that the precise value for each parameter is not a concern, since the magnitude of the values does not affect the relationships between the model's parameters. Nonetheless, the relative proportions between the parameters were based on the available information in the literature and knowledge gained from the empirical case studies (e.g. Dowlatshahi (2000) reported that cost of remanufacturing is between 40-60% of the cost of manufacturing a new product; as reported in Section 4.4 cost of testing can varies between 2-10% of the manufacturing cost) in an effort to maintain realism.

Table 5—2: The base set parameters for the numerical examples.

Parameter	d	C_N	C_R	C_S	C_T	P_{max}	ρ_{min}	ρ_{max}
Base values	100	100	40	10	10	20	0.2	1

The impact of the quality parameter α on the optimal strategy for linear and non-linear acquisition cost functions for b=0 and b=1 is investigated first (Figure 5—5 and Figure 5—6). As can be seen from the figures, three strategies can be optimal based on the quality of returns. For the quality parameters $\alpha = 0.1$ and 0.2, the optimal return rate that minimises the cost of the market driven strategy is equal to $\rho_{min} = 0.2$.

For $\alpha = 0.2$, however, the remanufacturing of price independent returns (a closed-loop strategy with no incentive) yields a marginal cost improvement compared to an open-loop system. While for a lower quality of returns ($\alpha = 0.1$) an open-loop system should be used. This decision can be made based on the quality thresholds presented in Section 5.2.2 and 5.2.3. The value of the quality thresholds is calculated as shown in Figure 5—3 for $b = 0$ and in Figure 5—4 for $b = 1$ according to (Table 5—3).

Table 5—3: The optimal strategy based on the quality thresholds.

	$\alpha < 0.14$	$0.14 \leq \alpha < 0.35$	$0.35 \leq \alpha \leq 0.92$	$\alpha > 0.92$
$b = 0$	$\rho^* = \rho_{min} = 0.2$ Open-loop	$\rho^* = \rho_{min} = 0.2$ Closed loop (remanufacturing with no incentive)	$\rho^* = \overline{\rho}$ Market-driven (optimal incentive)	$\rho^* = \rho_{max} = 1$ Market-driven (maximum incentive)
	$\alpha < 0.14$	$0.14 \leq \alpha \leq 0.37$	$\alpha > 0.37$	
$b = 1$	$\rho^* = \rho_{min} = 0.2$ Open-loop	$\rho^* = \rho_{min} = 0.2$ Closed loop (remanufacturing with no incentive)	$\rho^* = \bar{\bar{\rho}}$ Market-driven (optimal incentive)	

As α increases (the quality of returns are sufficiently high) the market-driven strategy becomes more economically attractive. For $\alpha = 0.6$ and the linear acquisition cost ($b = 0$) the minimum cost from remanufacturing can be achieved by offering an incentive price that corresponds to $\rho = 0.5$. When the acquisition cost function is non-linear, however (i.e. it is more expensive to increase the return rate), a lower return rate is obtained for remanufacturing ($\rho = 0.32$ will minimise the cost of the market driven strategy). Finally, when the quality of returns is high ($\alpha = 0.8$), the optimal return rate occurs at the upper bound ($\rho = \rho_{max}$). This implies that the maximum incentive should be offered to yield the maximum return rate for remanufacturing operations. For $b = 1$ and $\alpha = 0.8$ the optimal return rate increases, but, as can be seen from equation (5-13), the optimal return rate will not reach the endpoint value. This indicates that when b increases it becomes extremely expensive for firms to increase the return rate and obtain ρ_{max}. This result shows the significance of the acquisition cost function's shape parameter (b) on the optimal policy. When the acquisition cost function is linear (i.e. $b = 0$) the cost structure of the market driven strategy is less sensitive to change in the return rate ρ. While for $b = 1$ the cost of market driven strategy become much more sensitive to the change in ρ.

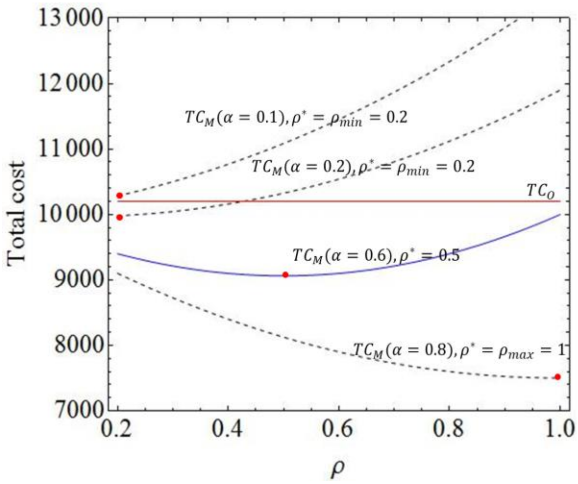

Figure 5—5: Impact of α on ρ^* when $b = 0$.

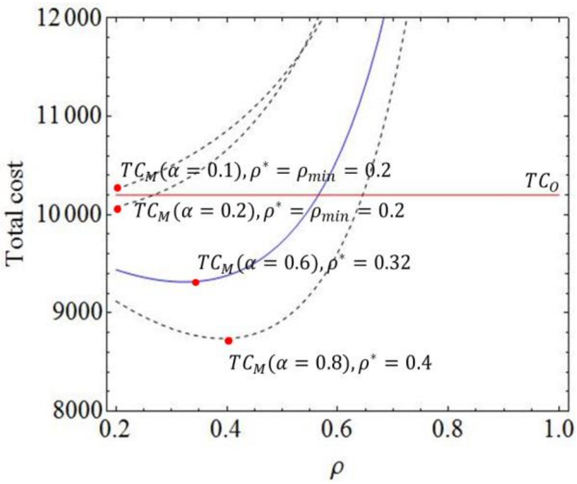

Figure 5—6: Impact of α on ρ^* when b=*1* .

5.2.6 Sensitivity analysis

This section first analyses the effect of changes in the model parameters C_R, C_T, C_S, P_{max} and α on the optimal return rate ρ^* and the optimal cost improvement from the market-driven strategy. It then illustrates these effects on the optimal solution with a numerical study. The percentage-cost improvement of the market-driven strategy over the passive strategy is denoted by the Value Recovery (VR) function and can be expressed as:

$$VR^*\% = \frac{TC_O^* - TC_M^*}{TC_O^*} * 100\% \ ,$$

where TC_M^* and TC_O^* represent the optimal cost of operating market-driven strategy and passive strategy respectively.

Substituting (5-1) and (5-2) into above, we obtain:

$$VR^* = \frac{\rho^*(\alpha(C_N - C_R + C_S) - C_T - C_S - P_{max}\rho^*(1-\rho^*)^{-b})}{C_N}, \rho^* \in [\rho_{min}, \rho_{max}],$$

and ρ^*can be obtained from (5-9).

Table 5—4 shows the details of the sensitivity analyses for parameters C_R, C_T, C_S, P_{max} and α on optimal return rate (ρ^*) for both linear and nonlinear acquisition cost function.

Table 5—4: The effect of models parameters on optimal return rate for $b = 0$ and $b = 1$.

$b = 0$	
$\frac{\partial \rho^*}{\partial C_R} =$	$-\frac{\alpha}{2P_{max}} < 0$
$\frac{\partial \rho^*}{\partial C_T} =$	$-\frac{1}{2\,P_{max}} < 0$
$\frac{\partial \rho^*}{\partial C_S} =$	$\frac{(\alpha-1)}{2\,P_{max}} < 0$
$\frac{\partial \rho^*}{\partial P_{max}} =$	$-\frac{C_S+C_T-(C_N-C_R+C_S)\alpha}{{P_{max}}^3} < 0, \forall\alpha \geq \frac{C_S+C_T}{C_N-C_R+C_S}$
$\frac{\partial \rho^*}{\partial \alpha} =$	$\frac{C_N-C_R+C_S}{2P_{max}} > 0$
$b = 1$	
$\frac{\partial \rho^*}{\partial C_R} =$	$-\frac{{P_{max}}^2\alpha}{2\left(P_{max}(P_{max}-C_S-C_T+(C_N-C_R+C_S)\alpha)\right)^{3/2}} < 0.$
$\frac{\partial \rho^*}{\partial C_T} =$	$-\frac{{P_{max}}^2}{2\left(P_{max}(P_{max}-C_S-C_T+(C_N-C_R+C_S)\alpha)\right)^{3/2}} < 0.$
$\frac{\partial \rho^*}{\partial C_S} =$	$\frac{{P_{max}}^2(-1+\alpha)}{2(P_{max}(P_{max}-C_S-C_T+(C_N-C_R+C_S)\alpha))^{3/2}} < 0.$
$\frac{\partial \rho^*}{\partial P_{max}} =$	$\frac{P_{max}(C_S+C_T-(C_N-C_R+C_S)\alpha)}{2(P_{max}(P_{max}-C_S-C_T+(C_N-C_R+C_S)\alpha))^{3/2}} < 0, \forall\alpha \geq \frac{C_S+C_T}{C_N-C_R+C_S}.$
$\frac{\partial \rho^*}{\partial \alpha} =$	$\frac{{P_{max}}^2(C_N-C_R+C_S)}{2(P_{max}(P_{max}-C_S-C_T+(C_N-C_R+C_S)\alpha))^{3/2}} > 0.$
For$\rho_{min} = 0$ and $\rho_{max} = 1$.	

It can be seen from the Table 5—4 that if the remanufacturing cost C_R increases, the optimal acquisition rate for remanufacturing (ρ^*) decreases. This leads to an increase in the amount of manufacturing and a decrease in the cost improvement offered by the market-driven strategy. The effect of C_T, C_s and P_{max} on ρ^* and $VR^*$are similar to the effect of C_R. An increase in α, however, leads to an increase in ρ^*, implying that more returns pass the quality test and can be remanufactured. Consequently, the amount of manufacturing and scrapping decreases and more of the demand can be satisfied by remanufacturing used products at a lower cost.

The second derivative of ρ^* with respect to C_R, C_T, C_S, P_{max} and α is taken to further investigate the rate of change in the optimal return rate (Table 5—5).

Table 5—5: The second-order analysis for optimal return rate for $b = 0$ and $b = 1$.

$b = 0$
$\frac{\partial^2 \rho^*}{\partial P_{max}^2} = \frac{(C_S+C_T)-(C_N-C_R+C_S)\alpha}{2{P_{max}}^2} < 0, \forall \alpha \geq \frac{C_S+C_T}{C_N-C_R+C_S}.$
$b = 1$
$\frac{\partial^2 \rho^*}{\partial C_R^2} = -\frac{3{P_{max}}^3\alpha^2}{4(P_{max}(P_{max}-C_S-C_T+(C_N-C_R+C_S)\alpha)))^{5/2}} < 0$.
$\frac{\partial^2 \rho^*}{\partial C_T^2} = -\frac{3{P_{max}}^3}{4(P_{max}(P_{max}-C_S-C_T+(C_N-C_R+C_S)\alpha)))^{5/2}} < 0.$
$\frac{\partial^2 \rho^*}{\partial C_S^2} = -\frac{3{P_{max}}^3(-1+\alpha)^2}{4(P_{max}(P_{max}-C_S-C_T+(C_N-C_R+C_S)\alpha)))^{5/2}} < 0.$
$\frac{\partial^2 \rho^*}{\partial P_{max}^2} = \frac{-4P_{max}(C_S+C_T)+4P_{max}(C_N-C_R+C_S)\alpha+(C_S+C_T-(C_N-C_R+C_S)\alpha)^2}{4P_{max}(-P_{max}+C_S+C_T-(C_N-C_R+C_S)\alpha)^2\sqrt{P_{max}(P_{max}-C_S-C_T+(C_N-C_R+C_S)\alpha)}} < 0.$
$\frac{\partial^2 \rho^*}{\partial \alpha^2} = -\frac{3{P_{max}}^3(C_N-C_R+C_S)^2}{4(P_{max}(P_{max}-C_S-C_T+(C_N-C_R+C_S)\alpha)))^{5/2}} < 0.$
For $\rho_{min} = 0$ and $\rho_{max} = 1$.

Table 5—5 shows that, ρ^* is concave in C_R, C_T ,C_S, P_{max} and α. This implies that the rate of change (i.e. decrease) in the optimal return rate (ρ^*) increases when C_R, C_T, C_S, and P_{max} increase; the rate of increase in the optimal return rate (ρ^*) decreases as α increases.

The effect of model's parameters on VR^* when $b = 0$ is presented in Table 5—6. Please note that due to the complexity of the closed-form solution for VR^* when $b = 1$, the impact of model parameters is shown numerically in the following section.

Table 5—6: The first and second-order analysis for optimal value recovery when b=0

First derivative
$\frac{\partial VR^*}{\partial C_R} = \quad -\frac{(C_N - C_R - C_T)\alpha^2}{2(C_N - 1)P_{max}} < 0.$
$\frac{\partial VR^*}{\partial C_T} = \quad -\frac{C_S + C_T - 2(C_S + C_T)\alpha + (C_N - C_R + C_S)\alpha}{2(C_N - 1)P_{max}} < 0\ .$
$\frac{\partial VR^*}{\partial C_S} = \quad -\frac{(C_S + C_T)(-1+\alpha)^2}{2(C_N - 1)P_{max}} < 0.$
$\frac{\partial VR^*}{\partial P_{max}} = \quad \frac{(C_S + C_T)^2(1-2\alpha) + (C_N - C_R + C_S)(-C_N + C_R + C_S + 2C_T)\alpha^2}{4(-1+C_N){P_{max}}^2} < 0\ .$
$\frac{\partial VR^*}{\partial \alpha} = \quad \frac{(-C_N + C_R - C_S)(C_S + C_T - (C_N - C_R + C_S)\alpha)}{2C_N P_{max}} > 0\ ,\ \forall \alpha \geq \frac{C_S + C_T}{C_N - C_R + C_S}.$
Second derivative
$\frac{\partial^2 VR^*}{\partial C_R^2} = \quad \frac{\alpha^2}{2(-1+C_N)P_{max}} > 0.$
$\frac{\partial^2 VR^*}{\partial C_T^2} = \quad \frac{1-2\alpha}{2P_{max}(1-C_N)} > 0.$
$\frac{\partial^2 VR^*}{\partial C_S^2} = \quad \frac{(\alpha-1)^2}{2P_{max}(1-C_N)} > 0.$
$\frac{\partial^2 VR^*}{\partial P_{max}^2} = \quad \frac{(C_S + C_T - (C_N - C_R + C_S)\alpha)(-C_S - C_T - (C_N - C_R - C_S - 2C_T)\alpha)}{2(-1+C_N){P_{max}}^3} \geq 0,\ \forall \alpha \geq \frac{C_S + C_T}{C_N - C_R + C_S}$
$\frac{\partial^2 VR^*}{\partial \alpha^2} = \quad \frac{(C_N - C_R + C_S)^2}{2P_{max}C_N} > 0.$
For $\rho_{min} = 0$ and $\rho_{max} = 1$.

As Table 5—6 shows, the effect of model parameters on VR^* are similar to the effect of ρ^*. The second derivative analysis shows that VR^* is convex in the model parameters C_R, C_T ,C_S, P_{max} and α. This implies that when the quality of returns meets the threshold $\alpha > \frac{C_S + C_T}{(C_N - C_R + C_S)}$ (i.e. the market-driven strategy is economically viable), the rate of change (i.e. decrease) in the optimal cost improvement from the market-driven strategy (VR^*) decreases as C_R, C_T ,C_S,and P_{max} increases. On the contrary, an increase in α leads to a faster increase in the optimal cost saving from the market-driven strategy (VR^*). Table 5—7 summarises the effect of model parameters on the optimal return rate and cost improvement from the market-driven strategy.

Table 5—7: Effect of an increase in the parameters on the optimal solution (↑: increasing, ↓: decreasing).

	C_R	C_T	C_S	P_{max}	α
ρ^*	↓	↓	↓	↓	↑
VR^*	↓	↓	↓	↓	↑

A further sensitivity analysis is now conducted to illustrate the impact of the model parameters and their combined effects on the optimal solutions. The base set parameters are the same as those in presented in Table 5—2. Here, however, it is assumed that $\rho \in [0,1]$ and $\alpha \in [0.1,1]$, i.e. α =0.1 implies that only 10% of returns will pass the quality test and α =1 implies that all the used products can be remanufactured. The impact of parameters C_R, C_T and P_{max} are also investigated when the acquisition cost is non-linear (i.e. b=1).

As discussed in section 5.2.2, obtaining the closed-form solution for the optimal return rate and the VR function for $b > 1$ is extremely difficult. The following numerical example is therefore presented to investigate the impact of the price sensitivity of the acquisition cost function on the optimal return rate.

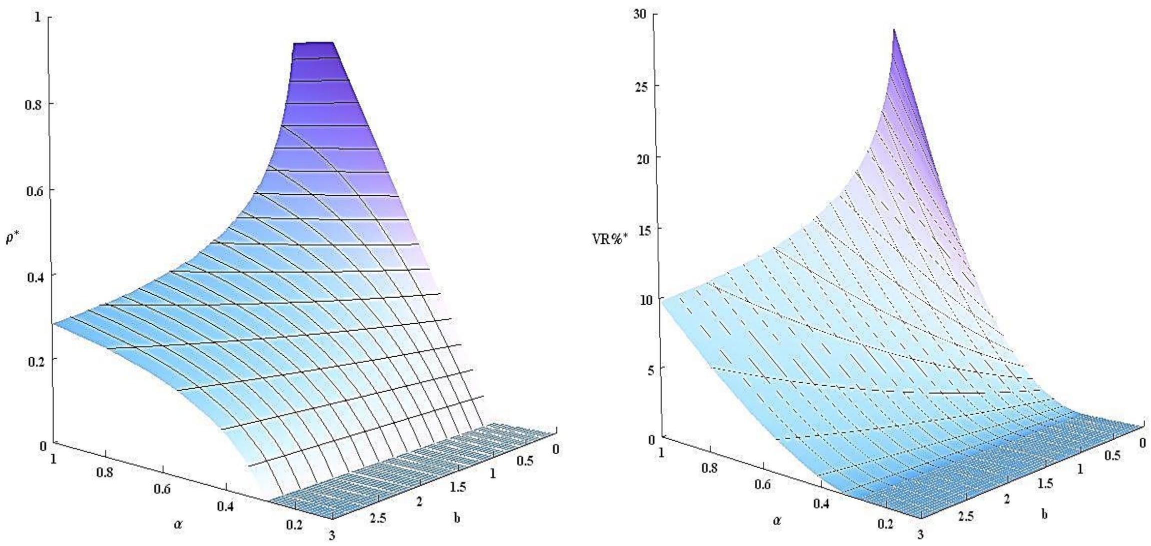

Figure 5—7: Relationship between ρ*, α and b.

Figure 5—7, illustrates the impact of b and α on the optimal return rate ρ^* and optimal cost improvement $VR^*\%$. For $0 \leq \alpha \leq 0.285$[24] the $\rho^* = \rho_{min} = 0$ and therefore the closed-loop strategy has no cost advantage over the open-loop system. When α increases, ρ^* increases, leading to an increase in the remanufacturing amount and a decrease in manufacturing, which in turn results in higher $VR^*\%$. The maximum cost improvement is achieved when the acquisition cost function is linear ($b = 0$). When b increases (i.e. the acquisition cost function shifts from linear to non-linear) it becomes more expensive to acquire more returns and therefore both ρ^* and $VR^*\%$ decrease. When $b = 3$ (i.e. it is very expensive to increase the number of returns), however, the market-driven strategy will still yield a significant cost improvement over the open-loop system for high quality of returns. This result suggests that a lower return rate due to the expensive acquisition cost can be partially compensated when the quality of returns is higher.

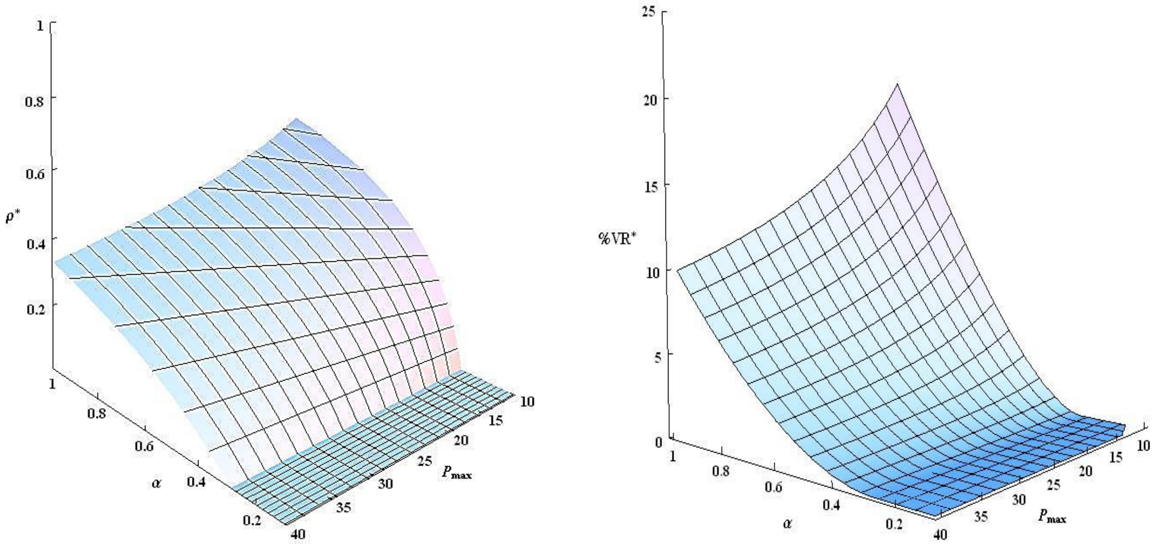

Figure 5—8: Impact of P_{max} on the optimal return rate and optimal *VR* when *b=1*.

[24] When $\rho_{min} = 0$ and $\rho_{max} = 1$, the quality threshold for both $b = 0$ and $b = 1$ cases becomes $\frac{C_T+C_S}{(C_N-C_R+C_S)} = \frac{20}{70} = 0.285$ (refer to Section 5.2.3 and 5.2.4 for the quality thresholds formula).

Figure 5—8 illustrates that, as the acquisition price increases, implying that a higher price has to be offered to the market to attract used products, this leads to a decrease in ρ^*. This suggests that, as P_{max} increases, fewer products are purchased from the market and the number of used products available for the remanufacturing operation decreases, resulting in less cost improvement being achieved from the market-driven strategy.

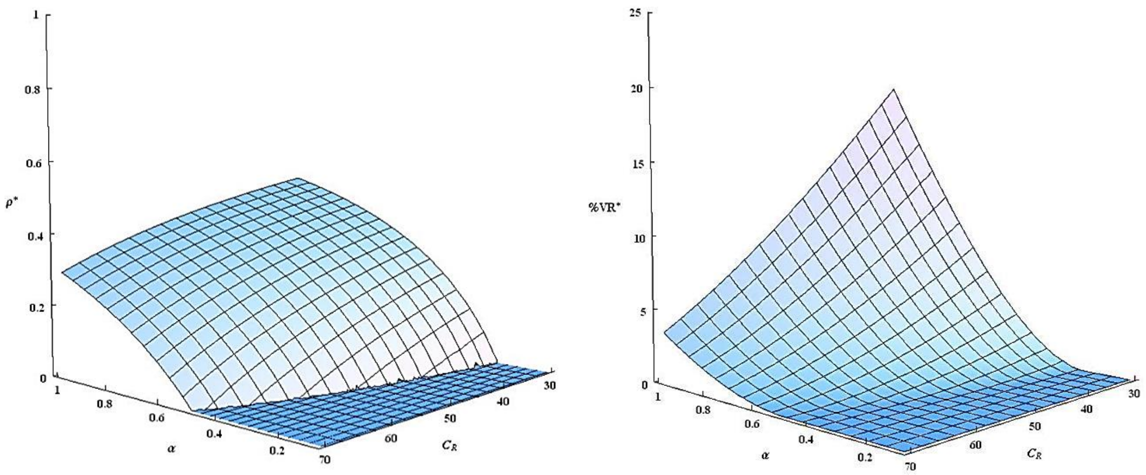

Figure 5—9: The impact of C_R on ρ^* and $VR^*$when *b=1*.

Figure 5—9 illustrates that the optimal return rate (ρ^*) decreases as the cost of remanufacturing increases. This suggests that when the remanufacturing cost C_R increases, then the number of used products acquired for remanufacturing decreases. This leads to an increase in the amount of manufacturing and a decrease in the cost improvement offer by the market-driven strategy. Therefore, the economic advantages of the market-driven strategy weaken when the remanufacturing cost advantage ($(C_N + C_S) - C_R$) decreases. When the quality of returns are high ($0.5 \leq \alpha \leq 1$), however, it is economically attractive to operate the market-driven strategy, even when remanufacturing is expensive (C_R=70). When the quality of returns is low, however, the open-loop system is a better option.

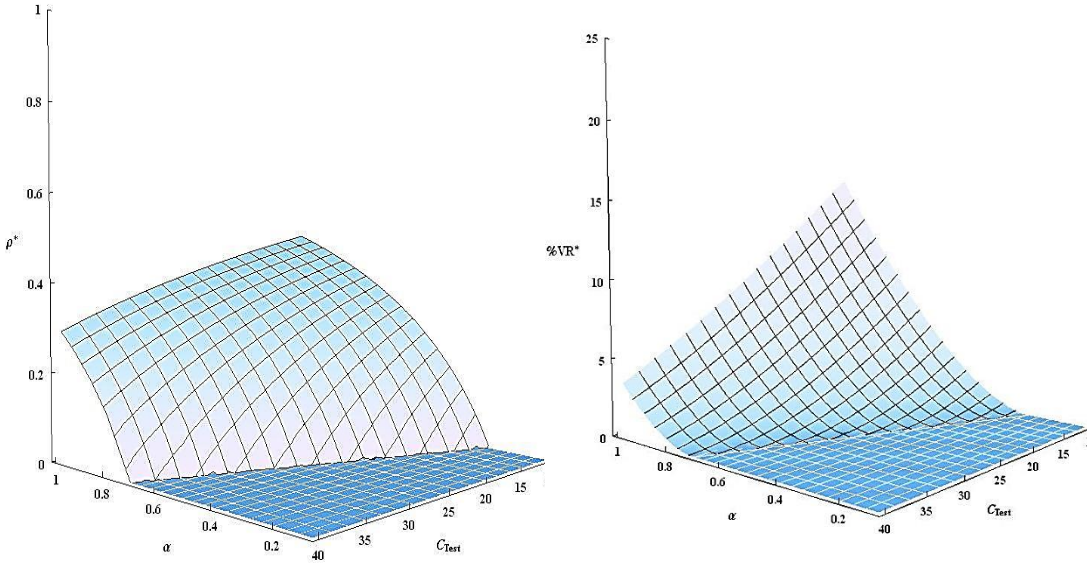

Figure 5—10: The impact of C_T on the return rate when *b=1.*

A similar effect can be seen when the cost of testing increases (Figure 5—10). When the cost of testing is high (C_T=40), the market-driven strategy is economically attractive for a higher quality of returns $(0.7 \leq \alpha \leq 1)$ but an increase in C_T leads to a decrease in ρ^* and in remanufacturing quantity. To compensate for this, the firm has to increase the amount of manufacturing, which leads to a decrease in the cost improvement offered by the market-driven strategy. The cost of scrapping, C_S, has a similar effect on $\rho^*$and VR^*%.

This result implies that when enhanced testing is needed for the quality inspection (i.e. the testing operation is expensive) firms should be especially careful when obtaining returns, since the acquisition of low quality returns has a considerable impact on the economics of the market-driven strategy.

The impact of C_T is particularly important since, in this model, it is assumed that firm offers incentives to influence the return rate and that the acquired returns are in unsorted slots, so testing occurs until after the remanufacturing has reconceived the items. The quality of returns therefore has a considerable influence on the optimal acquisition strategy. The next section investigates the scenario in which the firm offers an incentive that corresponds to the quality of returns, allowing some control over the quality of returns for the remanufacturing operation.

5.3 Quality based incentive model

The analyses in the previous section illuminate the importance of the used products in remanufacturing operations and the cost saving of the market-driven strategy. In this section the acquisition cost function is modified and a scenario is investigated in which firms give a financial incentive in order to obtain better quality used products. The initial case investigated is where the acquisition cost is a function of the quality condition and the remanufacturing cost is constant. This assumption is then relaxed to investigate the optimality condition when both acquisition and remanufacturing costs are a function of the quality condition.

Quality-based incentives are commonly used for consumer products such as toner cartridges, laptops, printers, mobile phones, car engines etc., where a certain amount of cash is offered to customers based on the quality of the used items.

As discussed in section 4.5, Company C is a manufacturer of toner cartridges that satisfies the market demand through both new and remanufactured products (used products are remanufactured to serve in a primary market). The company has two strategies to obtain used products back from the market: 1) an official route (to comply with the WEEE directive), which is done through the company’s website, and 2) an informal route whereby the company pays a certain amount of cash (through third-party brokers) to collect those empty toner cartridges that are complying with the company's standards. The returned products then will be tested and sorted by the third-party brokers before being transferred to the company for the remanufacturing operation. This quality inspection is performed to assess whether the used product is suitable for remanufacturing. Those products that cannot be recovered will be scrapped at a cost for the company. This phase is very important for the firm since it can influence the remanufacturing operation as well as the remanufacturing yield. The collected items will go through a technical inspection (parts and components will be tested) before the remanufacturing operation.

The model present in the following section is investigating the quality-based incentive approach which can be insightful for Company C.

5.3.1 Model assumptions

Most of the assumptions made in this section are the same as for the previous model. The main difference between this model and previous one, however, is that here it is assumed that the remanufacturer pays an incentive to influence the quality of returns. This way, the process of sorting/grading is effectively transferred to the suppliers of the used products (e.g. the collector). This implies that the uncertainty in the quality of returns reduces once they have arrived at the remanufacturing facility. In this case, the acquisition price will increase for products with a higher quality; therefore, having a good inspection prior to purchasing the used product is crucial in order to avoid accepting used products with poor quality. When the used products arrive at the firm's return centre, they have to be disassembled and all the parts and components are tested to identify the re-manufacturability of that used product.

It is assumed that the quality parameter α is independent from the return rate (ρ) and that it can be influenced by giving the appropriate financial incentive, i.e. the return rate ρ is constant in the interval of [0, 1]. The cost of quality-based acquisition is denoted by $P(\alpha)$, which is a deterministic, increasing and convex function of α where $\alpha \in [\alpha_{min}, \alpha_{max}]$ (the specification of the quality-based acquisition cost function is discussed further in the following section). Given the above assumptions, all the costs remain the same as in section 5.2.1, except the acquisition cost, which is $P(\alpha)\rho d$.

Let TC_Q represent the total cost of the market-driven strategy with a quality-based incentive, then we obtain:

$$TC_Q(\alpha) = C_N\,(1-\alpha\rho)d + C_R\alpha\rho d + C_T\rho d + C_S(1-\alpha)\rho d + P(\alpha)\rho d\,, \tag{5-15}$$

and for the open-loop system we obtain:

$$TC_O = d(C_N + C_S\rho)\,. \tag{5-16}$$

Therefore, the decision regarding the best strategy can be made based on a cost comparison of this strategy with the open-loop model. When $\mathrm{TC_Q} < TC_O$ investing in the remanufacturing operation is economically attractive:

$$C_N\,(1-\alpha\rho)d + C_R\alpha\rho d + C_T\rho d + C_S(1-\alpha)\rho d + P(\alpha)\rho d \le d(C_N + C_S\rho)\,,$$

simplifying above, we obtain:

$$C_T + P(\alpha) - \alpha(C_N - C_R + C_S) \le 0\,.$$

Rewriting above for α gives:

$$\alpha > \frac{C_T + P(\alpha)}{(C_N - C_R + C_S)} \,. \tag{5-17}$$

The above threshold suggests that when the quality of returns is higher than $\frac{C_T+P(\alpha)}{(C_N-C_R+C_S)}$, then a cost saving can be achieved by incentivising the market and performing the remanufacturing operation. The objective, therefore, is to find the optimal quality rate that minimises the total cost of market driven strategy (5-15), i.e.:

$$\min_{\alpha_{min} \leq \alpha \leq \alpha_{max}} TC_Q(\alpha) \,.$$

Let α^* denote the optimal solution to the above minimisation problem, therefore, $TC_Q(\alpha)$ has an isolated strict local minimum at α^* if $\frac{dTC_Q(\alpha)}{d\alpha} = 0$ and $\frac{d^2TC_Q(\alpha)}{d\alpha^2} > 0$.

Differentiating the objective function with respect to α gives:

$$\frac{dTC_Q(\alpha)}{d\alpha} = \rho\big(-(C_N - C_R + C_S) + P'(\alpha)\big) \,, \tag{5-18}$$

and the following second order condition is sufficient for the optimality condition:

$$\frac{d^2TC_Q(\alpha)}{d\alpha^2} = P''(\alpha) > 0 \,. \tag{5-19}$$

Therefore, $TC_Q(\alpha)$ is convex in α if the acquisition cost function is convex. Assuming the convexity of the acquisition cost function, i.e. increasing marginal cost for acquisitions of a higher quality is reasonable and has been used in other studies (e.g. Guide et al., 2003). The following section discusses the specification of the acquisition cost function.

5.3.2 The specification the quality-based incentive cost function:

Similar to the quantity-based incentive cost function, we propose a general acquisition cost function in a form of rational function to capture the relationship between acquisition effort and quality yield rate. Let $P(\alpha)$ represent the quality incentive function, where $P(\alpha)$ is a continuous, increasing and twice differentiable function of α :

$$P(\alpha) = \frac{P_{max}(\alpha - \alpha_{min})}{\Delta\alpha(\alpha_{max} - \alpha)^{b}}, \qquad (5\text{-}20)$$

where $\Delta\alpha$ denotes the difference between minimum and maximum quality of returns i.e. $\Delta\alpha = \alpha_{max} - \alpha_{min}$.

The value of b represents the price sensitivity of the acquisition cost function. In other words, when b increases it becomes more expensive to obtain products with a better quality (i.e. the marginal cost of acquisition increases for a higher quality of returns as α increases). When $b = 0$ the relationship between cost function and the quality parameter is linear and for $b > 0$ this becomes non-linear. It is assumed that when the acquisition cost function is linear ($b = 0$) firms can obtain the returns with the highest quality (α_{max}) by offering an incentive price of P_{max}. The value of α_{min} represents the price-independent return quality.

Differentiating $P(\alpha)$with respect to α gives:

$$\frac{dP(\alpha)}{d\alpha} = \frac{P_{max}\frac{d}{d_{\alpha}}\left(\frac{(\alpha - \alpha_{min})}{(\alpha_{max} - \rho)^{b}}\right)}{\Delta\alpha},$$

and hence, we get:

$$= \frac{\dfrac{P_{max}.\left((\alpha_{max}-\alpha)^b \dfrac{d}{d_\alpha}(\alpha-\alpha_{min}) - \dfrac{d}{d_\alpha}((\alpha_{max}-\alpha)^b).(\alpha-\alpha_{min})\right)}{((\alpha_{max}-\alpha)^b)^2}}{\Delta\alpha}$$

$$= \frac{P_{max}.\left((\alpha_{max}-\alpha)^b - b(\alpha_{max}-\alpha)^{b-1}\dfrac{d}{d_\alpha}(\alpha_{max}-\alpha)(\alpha-\alpha_{min})\right)}{\Delta\alpha(\alpha_{max}-\alpha)^{2b}}$$

$$= \frac{P_{max}.\left((\alpha_{max}-\alpha)^b - b(-1)(\alpha_{max}-\alpha)^{b-1}(\alpha-\alpha_{min})\right)}{\Delta\alpha(\alpha_{max}-\alpha)^{2b}}.$$

Simplifying the above, it is easy to see that:

$$P'(\alpha) = \frac{P_{max}((\alpha_{max}-\alpha)+b(\alpha-\alpha_{min}))}{(\alpha_{max}-\alpha)^{b+1}\Delta\alpha}. \tag{5-21}$$

Equation (5-21) implies that the acquisition cost function is an increasing function with respect to the α on the interval of $\alpha \in [\alpha_{min}, \alpha_{max})$.

Now we derive the second derivative:

$$\frac{d}{d\alpha}\left(\frac{P_{max}((\alpha_{max}-\alpha)+b(\alpha-\alpha_{min}))}{(\alpha_{max}-\alpha)^{b+1}\Delta\alpha}\right),$$

which gives:

$$P''(\alpha) = \frac{2bP_{max}.(\alpha_{max}-\alpha)-(-b-1)bP_{max}(\alpha-\alpha_{min})}{(\alpha_{max}-\alpha)^{b+2}\Delta\alpha}. \tag{5-22}$$

Hence, $\frac{d^2P(\alpha)}{d\alpha^2} > 0$ if:

$$2bP_{max}.(\alpha_{max}-\alpha)-(-b-1)bP_{max}(\alpha-\alpha_{min}) \geq 0\,.$$

Rewriting the above, we get:

$$2bP_{max}(2\alpha_{max}-\alpha+b\alpha-b\alpha_{min}-\alpha_{min}) \geq 0.$$

which by inspection is always positive for $\forall\alpha \in [\alpha_{min}, \alpha_{max}]$. Since, $\frac{dP(\alpha)}{d\alpha} > 0$ and $\frac{d^2P(\alpha)}{d\alpha^2} > 0$, then we can conclude that $P(\alpha)$ is a monotonically increasing and convex function α for $\forall\alpha \in [\rho_{min}, \rho_{max})$ $\forall b \geq 0$. This implies that the marginal cost of obtaining an additional used product with a higher quality continually increases. Figure 5—11 illustrates the relationships between the quality parameter α and the acquisition cost.

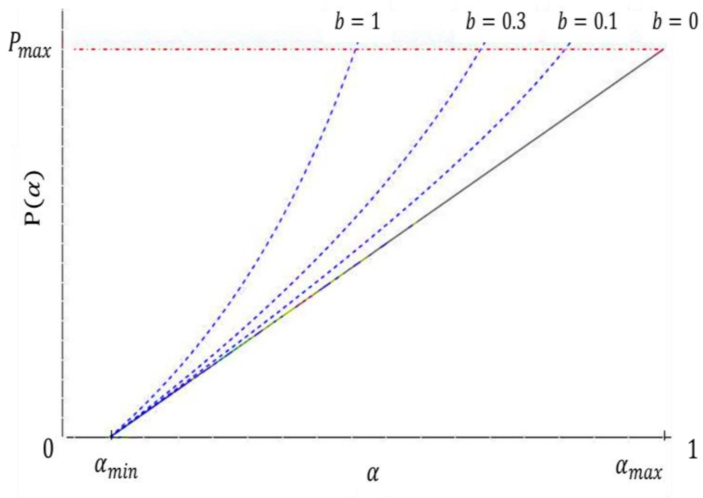

Figure 5—11: The quality-based acquisition cost function.

Given the equation (5-22), the second order condition is always satisfied, hence the objective function is convex in α and there exists a unique optimal solution derived by the first order condition, i.e. (5-18), which gives:

$$P'(\alpha) - (C_N + C_S - C_R) = 0\,. \tag{5-23}$$

From (5-23) it is clear that the optimal quality that minimises the total cost of the market-driven strategy depends on the marginal cost of acquiring a better quality of returns $P'(\alpha)$ and the remanufacturing cost advantage $(C_N - C_R + C_S)$.

Replacing $P'(\alpha)$ from (5-21) into (5-23), we obtain:

$$\frac{P_{max}((\alpha_{max}-\alpha)+b(\alpha-\alpha_{min}))}{(\alpha_{max}-\alpha)^{b+1}\Delta\alpha}-(C_N+C_S\ -C_R)\ =0\,. \tag{5-24}$$

The following section analytically obtains the optimality conditions for both the linear and non-linear acquisition cost function i.e. $b=0$ and $b=1$.

5.3.3 Optimal strategy with linear acquisition cost function

For $b=0$ the acquisition cost function is linear and increases with a rate of $\frac{P_{max}}{\Delta\alpha}$ (i.e. $P'(\alpha)=\frac{P_{max}}{\Delta\alpha}$). Therefore two cases can be distinguished: first, when the rate of change in the acquisition cost is less than the remanufacturing cost advantage, i.e. $P'(\alpha)<(C_N-C_R+C_S)$, second, when the rate of change in the acquisition cost is greater than or equal to the remanufacturing cost advantage, i.e. $\mathrm{P}'(\alpha)\geq(\mathrm{C_N}-\mathrm{C_R}+\mathrm{C_S})$.

- ***(Case 1):*** $\boldsymbol{P'(\alpha)<(C_N-C_R+C_S)}$***:***

When the incremental cost of acquisition is less than the remanufacturing cost advantage from (5-23) we have:

$$\frac{P_{max}}{\Delta\alpha}-(C_N-C_R+C_S)<0\ \ or\ \Delta\alpha>\frac{P_{max}}{C_N-C_R+C_S}\,.$$

In this situation, the total cost function is a decreasing function with respect to α (as the quality of returns increases the total cost decreases). Let $\tilde{\alpha}$ denote the optimal quality level that minimises the total cost of the market driven strategy when $b=0$, hence $\tilde{\alpha}\ =\alpha_{max}$.

The decision regarding the open-loop strategy vs. market driven strategy can be made by substituting $\tilde{\alpha}$ into (5-17), giving:

$$\alpha_{max} > \frac{C_T + P_{max}}{(C_N - C_R + C_S)}. \tag{5-25}$$

The above threshold implies that for remanufacturing to be economically rewarding the α_{max} should be greater than $\frac{C_T+P_{max}}{(C_N-C_R+C_S)}$. In this situation, the firm should offer the maximum incentive price, i.e. P_{max}, in order to obtain the best quality of used products. Therefore, when (5-25) holds true, we obtain $\alpha^* = \tilde{\alpha} = \alpha_{max}$.

- ***(Case2): $P'(\alpha) \geq (C_N - C_R + C_S)$:***

When the slope of the incentive function is greater than the remanufacturing cost advantage, we obtain:

$$\frac{P_{max}}{\Delta\alpha} \geq (C_N - C_R + C_S) \quad or\ \Delta\alpha \leq \frac{P_{max}}{C_N - C_R + C_S}.$$

In this situation, the total cost function is an increasing function with respect to α (as the quality of return increases the total cost increases). Hence the optimal cost of the market-driven system occurs when α reaches the values of the lower-bound $\tilde{\alpha} = \alpha_{min}$.

Replacing $\tilde{\alpha}$ into (5-17) we obtain:

$$\alpha_{min} \geq \frac{C_T}{(C_N - C_R + C_S)}. \tag{5-26}$$

Equation (5-26) implies that when the minimum acceptable quality level is higher than the value of $\frac{C_T}{(C_N-C_R+C_S)}$ it is economically attractive for the firm to engage in the remanufacturing operation. In this situation we have $\alpha^* = \tilde{\alpha} = \alpha_{min}$, where $\alpha^* = \alpha_{min}$ suggests no incentive should be offered and therefore only remanufacturing is economically attractive, i.e. a closed-loop strategy.

The summary of the above cases is as follows:

$$\text{When } P'(\alpha) < (C_N - C_R + C_S) \rightarrow \begin{cases} \alpha^* = \alpha_{max}, \; if \; \alpha_{max} > \frac{C_T + P_{max}}{(C_N - C_R + C_S)} \\ \alpha^* = 0, \; if \; \alpha_{max} < \frac{C_T + P_{max}}{(C_N - C_R + C_S)} \end{cases},$$

and

$$\text{when } P'(\alpha) \geq (C_N - C_R + C_S) \rightarrow \begin{cases} \alpha^* = \alpha_{min}, \; if \; \alpha_{min} > \frac{C_T}{(C_N - C_R + C_S)} \\ \alpha^* = 0, \; if \; \alpha_{min} < \frac{C_T}{(C_N - C_R + C_S)} \end{cases}.$$

Figure 5—12a illustrates the scenario in which incremental cost of acquisition is less than the remanufacturing cost advantage, i.e. $P'(\alpha) < (C_N - C_R + C_S)$. In this case we have $\alpha_{max} > \frac{C_T + P_{max}}{(C_N - C_R + C_S)}$ $(1 > \frac{35}{70})$, therefore the firm should offer P_{max} in order to obtain the highest quality of returns from the market, i.e. $\alpha^* = \alpha_{max}$. For higher values of P_{max}, however, at which $\alpha_{max} < \frac{C_T + P_{max}}{(C_N - C_R + C_S)}$ inequality is not satisfied, the open-loop strategy becomes an appropriate option from an economic perspective.

Figure 5—12b illustrates the scenario, where the slope of the acquisition cost function is greater than the remanufacturing cost advantage, i.e., $P'(\alpha) \geq (C_N - C_R + C_S)$. In this case, when $\alpha_{min} > \frac{C_T}{(C_N - C_R + C_S)}$, no incentive should be offered to attract a high quality of returns, i.e. the firm should only seek to remanufacture price-independent returns with the quality of α_{min}. When $\alpha_{min} < \frac{C_T}{(C_N - C_R + C_S)}$, however, then the open-loop strategy will yield a lower cost compared to the closed-loop system. It is also clear that the economic case for remanufacturing is weakened when the cost of testing increases to 20. The impact of testing is particularly important in the quality-based model since the incentive price has to be paid according to the quality of returns in order to avoid accepting used products with poor quality. Failing to do so will increase the cost of testing when the used products arrive at the firm's facility, with a consequent impact on the remanufacturing decisions.

a. Case (1) when $P'(\alpha) < (C_N - C_R + C_S)$. b. Case (2) when $P'(\alpha) \geq (C_N - C_R + C_S)$.

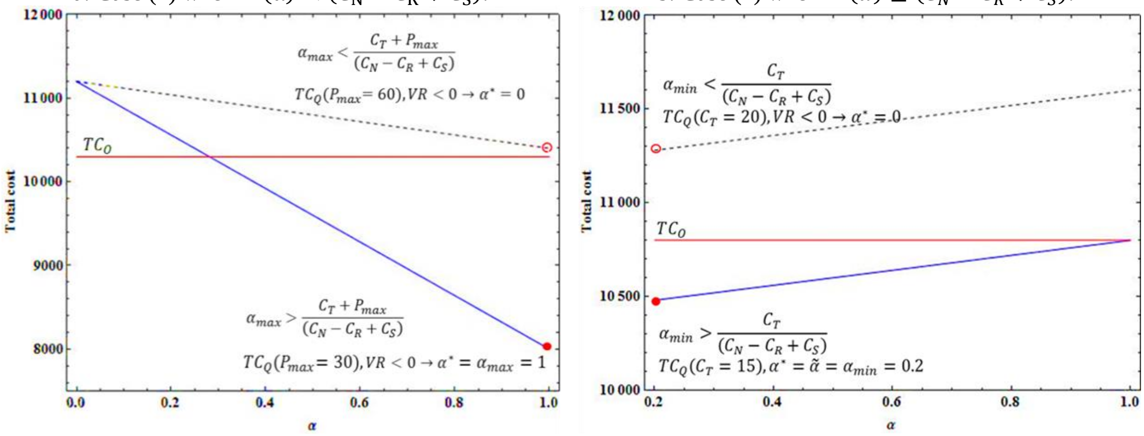

Figure 5—12: Optimal strategy with linear acquisition cost function ($b = 0$) when $C_N = 100;\ C_R = 40; C_S = 10; P_{max} = 30; \rho = 0.8; \alpha_{min} = 0.2; \alpha_{max} = 1$.

5.3.4 Optimal strategy with non-linear acquisition cost function

Let $\overline{\alpha}$ denote the feasible solution to (5-24) when the acquisition cost function is non-linear, i.e. $b = 1$. For $\overline{\alpha}$ we obtain:

$$\overline{\alpha} = \alpha_{max} - \sqrt{\frac{P_{max}}{(C_N - C_R + C_S)}},\ \overline{\alpha} \in [\alpha_{min}, \alpha_{max}]. \tag{5-27}$$

When $\overline{\alpha} < \alpha_{min}$, the optimal solution reaches the value of the lower bound, i.e. $\alpha^* = \alpha_{min}$. This implies that offering an incentive to obtain a higher quality of returns is not economically attractive and the firm should only operate a closed-loop system without incentive, i.e. $P(\alpha^*) = 0$. The decision regarding the optimal strategy, however, should be based on the quality threshold (5-17). When the remanufacturing cost advantage for those returns that pass the quality inspection is higher than the cost of acquisition and testing, i.e.

$$(C_N - C_R + C_S)\alpha^* > P(\alpha^*) + C_T \ or \ \alpha^* > \frac{P(\alpha^*) + C_T}{(C_N - C_R + C_S)},$$

then offering an incentive is economically attractive. From the above expression it is easy to see that for $\alpha^* = \alpha_{min}$ we obtain:

$$\alpha_{min} \geq \frac{C_T}{(C_N - C_R + C_S)}.$$

This implies that the closed-loop strategy will yield a lower cost compared to the open-loop system when the minimum cost advantage from remanufacturing returns is higher than the cost of testing.

Based on the above analysis it is possible to distinguish the following three strategies:

- *Open-loop strategy*

  If $\overline{\alpha} < \alpha_{min}$ and $\alpha_{min} < \frac{C_T}{(C_N - C_R + C_S)}$ then $\alpha^* = 0$ i.e. no cost improvement can be achieved by remanufacturing returned products. In this situation, it is more economical for the firm to satisfy market demand by manufacturing new products and scrapping the returns.

- *Remanufacturing with no incentive (closed-loop system)*

  If $\overline{\alpha} < \alpha_{min}$ and $\alpha_{min} \geq \frac{C_T}{(C_N - C_R + C_S)}$ then $\alpha^* = \alpha_{min}$ i.e. no incentive should be offered to obtain a higher quality of returns ($P(\alpha^*) = 0$). In this scenario, the closed-loop strategy with no incentive will yield a higher cost saving compared to the open-loop system.

- *Incentivise market and remanufacturing (market-driven strategy)*

  If $\alpha_{min} \leq \overline{\alpha} \leq \alpha_{max}$ and $\overline{\alpha} > \frac{P(\overline{\alpha}) + C_T}{(C_N - C_R + C_S)}$ then $\alpha^* = \overline{\alpha}$ i.e. it is economically justified to incentivise the market to obtain a higher quality of returns. Please note that the second condition should be satisfied to ensure that the minimum cost of the market-driven strategy is less than the cost of the open-loop system. In this situation, the firm obtains the acquisition cost of $P(\alpha^*)$ to attract a higher quality of returns, thereby increasing the (re)manufacturability of returns. The higher acquisition cost will be offset by a reduction in the manufacturing quantity, which leads to the lower overall cost of this strategy.

5.3.5 **Sensitivity analysis**

This section first analyses the effect of changes in the parameters C_R, C_T, C_S and P_{max} on the optimal quality rate α^* and the optimal cost improvement from the market-driven strategy. It then illustrates these effects on the optimal solution with a numerical study. The percentage-cost improvement of the market-driven strategy over the passive strategy is denoted by the Value Recovery (VR) function and can be expressed as:

$$VR^*\% = \frac{TC_O^* - TC_Q^*}{TC_O^*} * 100\%\,.$$

Substituting (5-15) and (5-16) into above, we obtain:

$$VR^* = \rho\left(\frac{\alpha^*(C_N\ - C_R + C_S) - C_T - P(\alpha^*)}{C_N + C_S\rho}\right), \alpha \in [\alpha_{min}, \alpha_{max}],$$

and, α^* can be obtained by getting the first derivative of (5-15) and equated to zero.

The impact of the model's parameters on the optimal quality rate and cost improvement is obtained by taking the first derivative of α^* and VR^* with respect to C_R, C_T, C_s, and P_{max}. Table 5—8 presents the details of the sensitivity analyses for the nonlinear acquisition cost function, (i.e. $b = 1$) when $\alpha_{min} = 0$ and $\alpha_{max} = 1$. Please note that for $b = 0$ the optimality condition (Eq.5-23) becomes constant in α (i.e. α^* can be either α_{max} or α_{min}); see section 5.3.3 for a detailed analysis.

Table 5—8: The effect of model parameters on optimal quality rate when $b = 1$.

First derivative	
$\frac{\partial \alpha^*}{\partial C_R} =$	$-\frac{P_{max}^2}{2\left((C_N - C_R + C_S)P_{max}\right)^{3/2}} < 0$
$\frac{\partial \alpha^*}{\partial C_T} =$	0
$\frac{\partial \alpha^*}{\partial C_S} =$	$\frac{P_{max}^2}{2((C_N - C_R + C_S)P_{max})^{3/2}} > 0$
$\frac{\partial \alpha^*}{\partial P_{max}} =$	$-\frac{1}{2\sqrt{(C_N - C_R + C_S)P_{max}}} < 0$
Second derivative	
$\frac{\partial^2 \alpha^*}{\partial C_R^2} =$	$-\frac{3\sqrt{(C_N - C_R + C_S)P_{max}}}{4(C_N - C_R + C_S)^3} < 0$
$\frac{\partial^2 \alpha^*}{\partial C_T^2} =$	0
$\frac{\partial^2 \alpha^*}{\partial C_S^2} =$	$-\frac{3\sqrt{(C_N - C_R + C_S)P_{max}}}{4(C_N - C_R + C_S)^3} \leq 0$
$\frac{\partial^2 \alpha^*}{\partial P_{max}^2} =$	$\frac{1}{4P_{max}\sqrt{(C_N - C_R + C_S)P_{max}}} > 0$

The effect of model parameter on VR^* when $b = 1$ is presented in Table 5—9.

Table 5—9: The effect of model parameters on optimal value recovery when $b = 1$.

First derivative	
$\frac{\partial VR^*}{\partial C_R} =$	$-\frac{\rho\left(1-\frac{P_{max}}{\sqrt{(C_N-C_R+C_S)P_{max}}}\right)}{C_N+C_S\rho} < 0$
$\frac{\partial VR^*}{\partial C_T} =$	$-\frac{\rho}{C_N+C_S\rho} < 0$
$\frac{\partial VR^*}{\partial C_S} =$	$\frac{\rho((C_N+C_S\rho)(1-\frac{P_{max}}{\sqrt{(C_N-C_R+C_S)P_{max}}})+\rho(-C_N+C_R-C_S+C_T-P_{max}+2\sqrt{(C_N-C_R+C_S)P_{max}}))}{(C_N+C_S\rho)^2} > 0$
$\frac{\partial VR^*}{\partial P_{max}} =$	$\frac{\rho(1-\frac{\sqrt{(C_N-C_R+C_S)P_{max}}}{P_{max}})}{C_N+C_S\rho} < 0$, $\forall\, P_{max} \le C_N - C_R + C_S$
Second derivative	
$\frac{\partial^2 VR^*}{\partial C_R^2} =$	$\frac{\rho P_{max}^2}{2(C_N+C_S\rho)((C_N-C_R+C_S)P_{max})^{3/2}} > 0$
$\frac{\partial^2 VR^*}{\partial C_T^2} =$	0
$\frac{\partial^2 VR^*}{\partial C_S^2} =$	$\rho(\frac{P_{max}^2}{2(C_N+C_S\rho)((C_N-C_R+C_S)P_{max})^{3/2}} - \frac{2\rho(1-\frac{P_{max}}{\sqrt{(C_N-C_R+C_S)P_{max}}})}{(C_N+C_S\rho)^2} + \frac{2\rho^2(C_N-C_R+C_S-t+P_{\max}-2\sqrt{(C_N-C_R+C_S)P_{\max}})}{(C_N+C_S\rho)^3}) < 0$, $\forall \alpha^* > \frac{P(\alpha^*)+C_T}{(C_N-C_R+C_S)}$
$\frac{\partial^2 VR^*}{\partial P_{max}^2} =$	$\frac{\rho\sqrt{(C_N-C_R+C_S)P_{max}}}{2(C_N+C_S\rho)P_{max}^2} > 0.$

As can be seen from the above tables, when C_R increases the optimal quality rate decreases. An increase in C_R leads to a decrease in the remanufacturing cost advantage ($C_N - C_R + C_S$), meaning that remanufacturing becomes less attractive for the firm. In this situation, less effort should be devoted to obtaining a higher quality of returns (i.e. α^* decreases). A decrease in α^* suggests that the amount of remanufacturing decreases and that more new products have to be manufactured to compensate for this decrease. The overall cost improvement derived from the market-driven strategy therefore decreases (i.e. $VR^*\%$ decreases). The effects of P_{max} on the optimal quality rate (α^*) and the cost improvement are similar to the effect of C_R. The analysis of the second derivative shows that α^* is concave in C_R, and convex in P_{max}. This implies that the rate of decrease in α^* increases when C_R

increases. This effect is reverse when P_{max} increases (i.e. the rate of decrease in α^* decreases when P_{max} increases).

On the contrary, an increase in the cost of scrapping (C_S) leads to an increase in the remanufacturing cost advantage ($C_N - C_R + C_S$), which then leads to an increase in α^*. When C_S increases, the total cost of the open-loop system also increases, therefore the cost difference between open-loop strategy and the market-driven strategy increases (i.e. VR^*% increases). Also, the concavity of α^* in C_S implies that the rate of increase in the α^* decreases as C_S increases.

Finally, an increase in C_T does not affect the optimal quality rate, but does lead to an increase in the total cost of the market-driven strategy, hence VR^*% decreases.

Table 5—10 summarises the effect of the model parameters on the optimal return rate and the cost improvement achieved by the market-driven strategy.

Table 5—10: Effect of an increase in the parameters on the optimal solution (↑: increasing, ↓: decreasing: ↔ constant).

	C_R	C_T	C_S	P_{max}	b	$\Delta\alpha$
α^*	↓	↔	↑	↓	↓	↑
VR^*	↓	↓	↑	↓	↓	↑

The optimal strategies and the effect of costs on the optimality condition are now discussed numerically, taking into account the following base set parameters and studying the effect of these parameters in the model by varying one parameter at a time.

Let $C_N = 100;\ C_R = 40;\ \ C_S = 10;\ C_T = 5; P_{max} = 20;\ \ \rho = 0.8.\ ; b = 1$ $\alpha_{min} = 0.2$ and $\alpha_{max} = 1$ i.e. $\Delta\alpha = 0.8$.

Figure 5—13 shows that the optimal strategy is sensitive to the value of $\mathrm{P_{max}}$. For $\mathrm{P_{max}}$=10, the market-driven strategy is economically attractive. In this situation, the maximum cost saving can be achieved by incentivising the market to obtain the quality rate of $\alpha^* = 0.625$. An increase in the incentive price will reduce this cost saving, but the market-driven strategy is still economically attractive ($P_{max=20}, \alpha^* = 0.465$). When $P_{max} = 40$, however, the market-driven strategy is no longer justified, and the optimal strategy would be remanufacturing without offering an incentive, $\alpha^* = \alpha_{min}$.

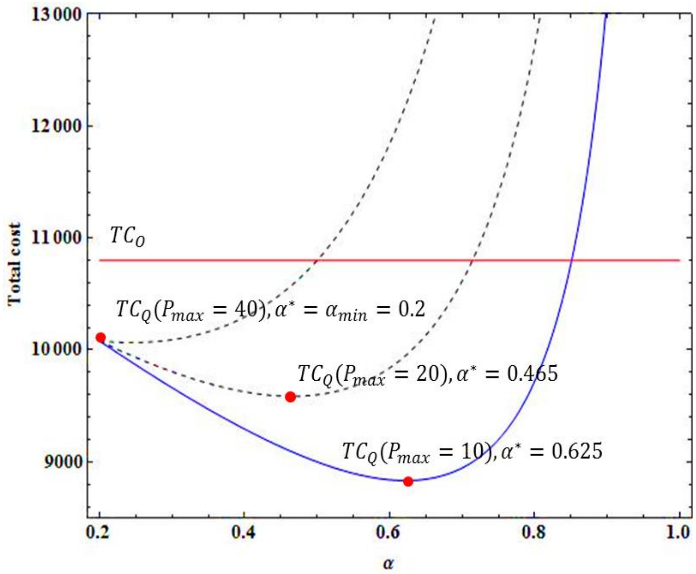

Figure 5—13: Impact of P_{max} on α^* and optimal acquisition strategy.

Figure 5—14 illustrates that the optimal quality rate is not influenced by the cost of testing. When C_T increases, the optimal quality rate, which minimises TC_Q, remains the same at $\alpha^* = 0.465$. An increase in C_T, however, leads to an increase in the total cost of the market-driven strategy which then leads to a decrease in the total cost improvement. For $C_T = 25$ we obtain $VR < 0$, which suggests that operating the open-loop system yields a lower cost compared to the market-driven strategy, hence $\alpha^* = 0$. The economic case for remanufacturing, therefore, is weakened when the cost of testing increases to 25.

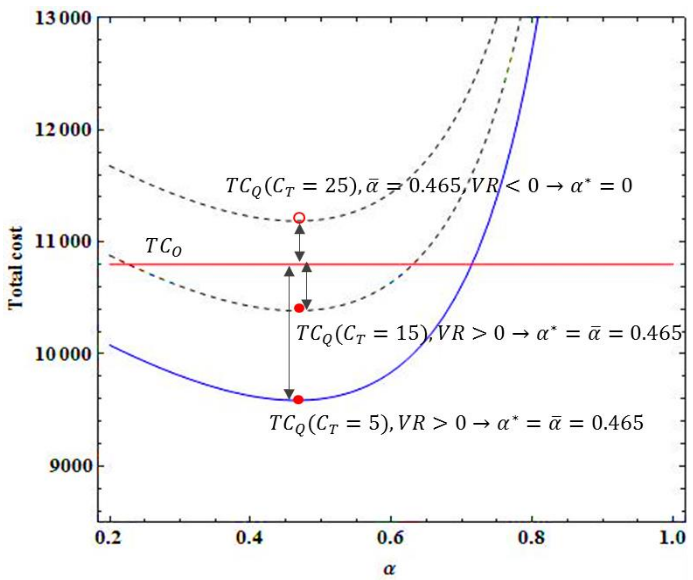

Figure 5—14: Impact of C_T on $\alpha^*$and optimal acquisition strategy.

The effect of C_T on the quality-based model is different from what we see in section 5.2.6. The impact of testing is particularly important in the quality-based model since the process of sorting/grading is effectively transferred to the suppliers of the used products (e.g. the collector). This implies that the uncertainty in the quality of returns reduces when they arrive at the remanufacturing facility. The cost of testing should, therefore, be low for those returns that are acquired. This means that having a good inspection process prior to purchasing the used product is crucial in order to avoid accepting used products with poor quality. Failure to do so will increase the cost of testing when the used products arrive at the firm's facility with a consequent impact on the remanufacturing decisions.

Figure 5—15 shows that the economic advantage of the market-driven strategy is reduced when the remanufacturing cost increases, i.e. the remanufacturing cost advantage $(C_N + C_S) - C_R$ decreases. When it is expensive to remanufacture returns, C_R increases to 80, incentivising the market to obtain a higher quality of returns is not appropriate from an economic point of view. Moreover, in contrast to the effect of P_{max}, for high values of C_R, operating a closed-loop strategy, i.e. remanufacturing with no incentive, only yields a marginal cost improvement over the open-loop strategy.

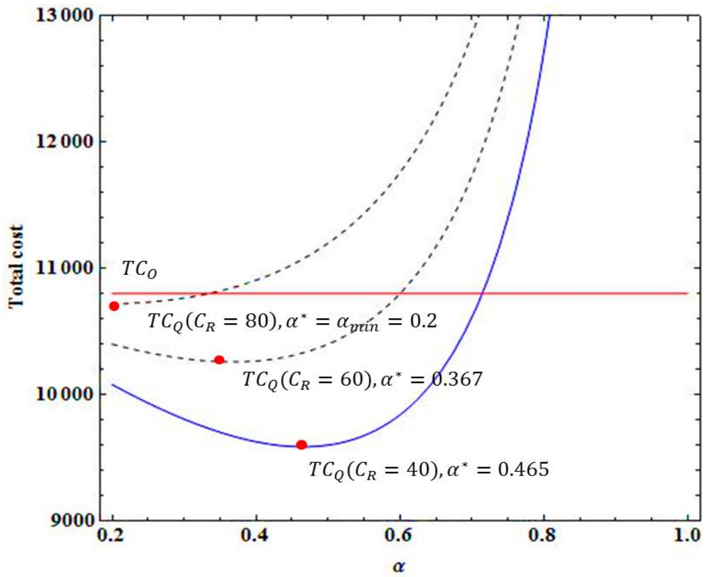

Figure 5—15: Impact of C_R on α^* and optimal acquisition strategy.

On the other hand, an increase in C_S leads to an increase in α^* (Figure 5—16). An increase in C_S, therefore, implies that the remanufacturing cost advantage increases, i.e. $C_N - C_R + C_S$ increases. Therefore, it becomes more economically attractive to exploit incentives to obtain a higher quality of returns for the remanufacturing operation. Although increases in C_S lead to a higher cost of operating the market driven strategy, the cost saving over the open-loop system actually increases. This occurs because an increase in C_S also leads to higher costs for the open-loop system.

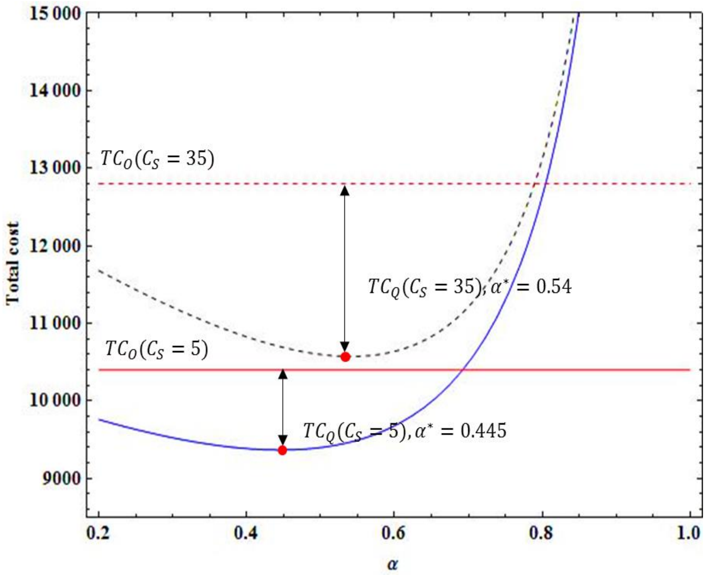

Figure 5—16: Impact of C_S on α^* and optimal acquisition strategy.

Finally, Figure 5—17 shows the impact of parameter b on the optimal quality rate. When the price sensitivity of the acquisition cost function is low, $b = 0.2$, the firm can afford to obtain a high quality of returns by offering a higher incentive price $\alpha^* = 0.854$. When b increases, however, it becomes more expensive to obtain a high quality returns, which leads to a decrease in α^*. This implies that more new products have to be manufactured to satisfy market demand, and therefore the cost improvement offered by the market-driven strategy decreases.

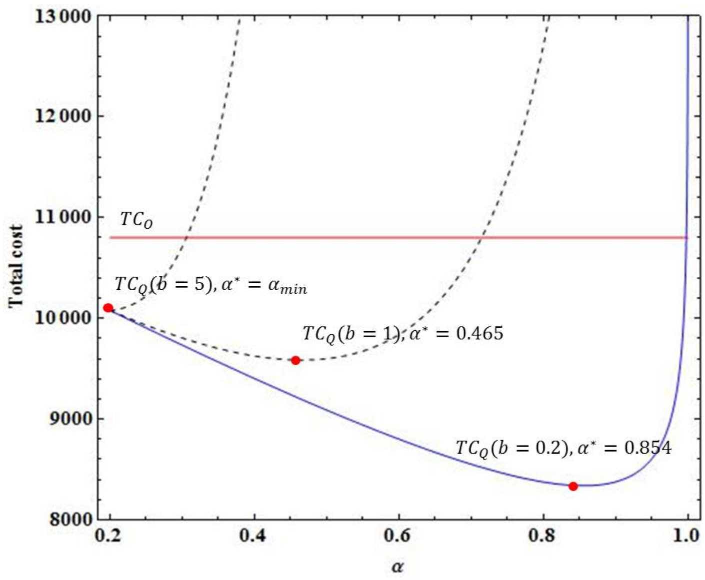

Figure 5—17: Impact of b on α^* and optimal acquisition strategy.

5.3.6 Analysis for the linear remanufacturing cost function

This section investigates the economics of the market-driven strategy when the remanufacturing cost increases as the quality level decreases. Similar to the previous section, it is assumed that the firm can obtain a higher quality of returns by offering a higher financial incentive. Since it is less expensive to remanufacture returns with higher quality, the main decision regarding the optimal acquisition strategy is based on a trade-off between the reduced remanufacturing cost and the increased acquisition cost. Please note that in the quality-based incentive model, the firm pays a higher price incentive to obtain better quality items. This implies that a primary visual inspection/grading process (e.g. inspecting for physical damage) occurs prior to the acquisition process. All products that pass the visual inspection are disassembled into parts and components; cleaned, dried and made ready for the enhanced technical test, at the firm's facility. Since the quality of acquired products is unknown until after this formal procedure is carried out, it is reasonable to keep the cost of testing constant and not a function of quality.

As pointed out by Ferguson et al. (2009), the exact expression for remanufacturing cost is difficult to estimate. In that paper the authors present a general function for the remanufacturing cost that could capture convex, linear and concave relationships between the cost of remanufacturing and the quality condition. In this section a similar assumption is made, and the remanufacturing cost function is presented as a linear function of quality. The linear relationship between remanufacturing cost and quality condition has been used in several remanufacturing studies (e.g. Galbreth and Blackburn, 2006 and Galbreth and Blackburn, 2010).

Let $C_R(\alpha)$ denote the remanufacturing cost function, we define $C_R(\alpha)$ as

$$C_R(\alpha) = \frac{C_R^{min} - C_R^{max}}{\Delta\alpha}(\alpha - \alpha_{min}) + C_R^{max} \tag{5-28}$$

where C_R^{max} denotes the remanufacturing cost for the worst possible quality of returns. Likewise, C_R^{min} represents the remanufacturing cost for the highest quality of returns (Figure 5—18).

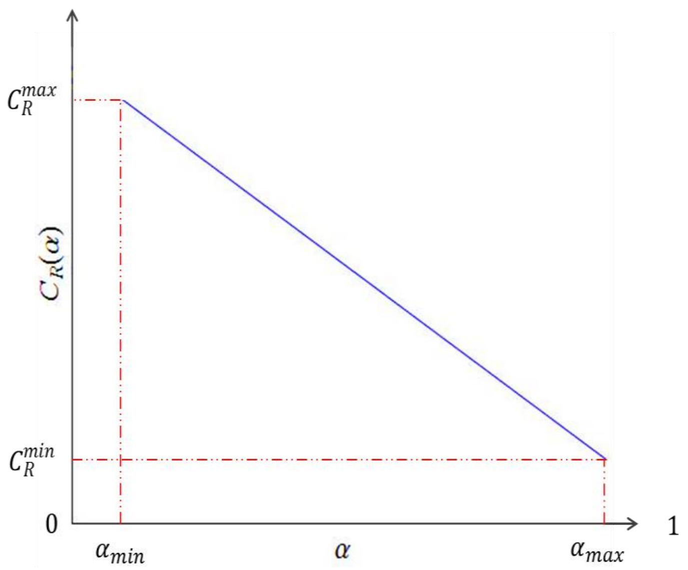

Figure 5—18: Remanufacturing cost function.

Furthermore, for the analysis in this section it is assumed that the marginal cost of the acquisition of a better quality of returns increases with the quality condition, i.e. the acquisition cost function is a convex function of α (i.e. b=1).

Rewriting $TC_Q(\alpha)$ from (5-15) with the remanufacturing cost function (5-28), gives:

$$TC_Q(\alpha) = d\left(C_N + \rho\big(\alpha(-C_N + C_R(\alpha) - C_S) + C_T + C_S + P(\alpha)\big)\right), \tag{5-29}$$

where $TC_Q(\alpha)$ is a continuous and twice differentiable function of α on the interval $[0,1]$. If $\frac{dTC_Q(\alpha^*)}{d\alpha} = 0$ and $\frac{d^2TC_Q(\alpha^*)}{d\alpha^2} > 0$ then $TC_Q(\alpha)$ has a isolated strict local minimum at α^*.

For the first order necessary condition we have:

$$\frac{dTC_Q(\alpha)}{d\alpha} = C_R(\alpha) + C_R'(\alpha)\alpha + P'(\alpha) - (C_N + C_S) = 0\,, \tag{5-30}$$

the following second order condition is sufficient for the optimality condition

$$\frac{d^2TC_Q(\alpha)}{d\alpha^2} = 2C_R'(\alpha) + C_R''(\alpha)\alpha + P''(\alpha) > 0\,. \tag{5-31}$$

The first derivative of the acquisition cost function for $\alpha \in [0\,,1]$ can be obtained by replacing b=1 into (5-21) :

$$P'(\alpha) = \frac{P_{max}}{(1-\alpha)^2}\,, \tag{5-32}$$

where the second derivative is:

$$P''(\alpha) = \frac{2P_{max}}{(\alpha_{max}-\alpha)^3}\,. \tag{5-33}$$

Let ΔC_R denote the remanufacturing cost difference $C_R^{max} - C_R^{min}$. The first derivative of the remanufacturing cost function when $\alpha \in [0\ ,1]$ is therefore:

$$C_R'(\alpha) = -\Delta C_R\ . \tag{5-34}$$

Replacing (5-28), (5-32) and (5-34) into (5-30) gives:

$$(-2\Delta C_R)\,\alpha + \frac{P_{max}}{(1-\alpha)^2} - (C_N - C_R^{max} + C_S) = 0.$$

Let $(C_N - C_R^{max} + C_S) = Z$ and we obtain:

$$(1-\alpha)^2(-2\Delta C_R)\alpha + P_{max} - Z(1-\alpha)^2\ ,=0$$

which can be written as the following polynomial equation

$$\alpha^3 + \left(-2 + \frac{Z}{2\Delta C_R}\right)\alpha^2 + \left(1 - \frac{Z}{\Delta C_R}\right)\alpha + \frac{(Z - P_{max})}{(2\Delta C_R)} = 0\ . \tag{5-35}$$

The above equation is a general cubic function[25] in α where the coefficients are:

$a = 1$, $b = \left(-2 + \frac{Z}{2\Delta C_R}\right)$, $c = \left(1 - \frac{Z}{\Delta C_R}\right)$ and $d = \frac{(P_{max} - Z)}{(-2\Delta C_R)}$.
and can be solved using Cardano’s formula or other suitable methods (Wituła and Słota, 2010).

Let $\hat{\alpha}$ denote the real root of the equation (5-35) on the interval [0, 1], therefore $\hat{\alpha}$ is the local minimum, i.e. $\alpha^* = \hat{\alpha}$ if

$$-2\Delta C_R + P''(\hat{\alpha}) > 0\ . \tag{5-36}$$

[25] The general cubic function has a form of $y = ax^3 + bx^2 + cx + d$

Replacing (5-33) into the above equation gives the following sufficient condition for the minimisation problem (5-29):

$$\hat{\alpha} \geq 1 - \sqrt[3]{\frac{P_{max}}{\Delta C_R}}. \tag{5-37}$$

5.3.7 Numerical example

Numerical tests are performed here to illustrate the result of the analysis for the linear remanufacturing cost function and this result is compared with the constant remanufacturing cost case. The same values are used as in section 5.3.5.

Let $C_N = 100$; $C_R^{max} = 50$; $C_R^{min} = 10$; $C_S = 10$; $C_T = 5$; $P_{max} = 20$; $\rho = 0.8.$; $b = 1$ $\alpha_{min} = 0$ and $\alpha_{max} = 1$. Therefore, we obtain $Z = 60$ and $\Delta C_R = 40$.

Replacing the corresponding values in (5-35) gives:

$$\alpha^3 + \left(-2 + \frac{60}{80}\right)\alpha^2 + \left(1 - \frac{60}{40}\right)\alpha + \frac{(20-60)}{(-80)} \rightarrow \alpha^3 - 1.25\alpha^2 - 0.5\alpha + 0.5 = 0.$$

Solving the above gives three real roots; $= -0.659$, $\alpha = 0.564$ and $\alpha = 1.345$. However, $\hat{\alpha} = 0.564$ is the only feasible solution on interval $[0, 1]$. Since $\hat{\alpha}$ satisfies the second order condition i.e. $\hat{\alpha} > 1 - \sqrt[3]{0.5} = 0.26$, therefore $\alpha^* = \hat{\alpha} = 0.586$.

The optimal quality for the constant remanufacturing cost, i.e. $C_R^{constant} = 40$ can be obtained from (5-27), which gives $\overline{\alpha} = 1 - \sqrt{\frac{20}{70}} = 0.465$.

Figure 5—19 shows that it is more economically attractive for the firm to absorb a higher acquisition cost in order to obtain a higher quality of returns when the cost of remanufacturing for returns with a better quality condition is less. In other words, the increase in the acquisition cost is offset by the decrease in the remanufacturing cost. In this situation, a higher quality of used items can be purchased from the end-users which then lead to an increase in the remanufacturing quantity. The amount of new products that need to be manufactured to satisfy demand therefore decreases; i.e. VR increases.

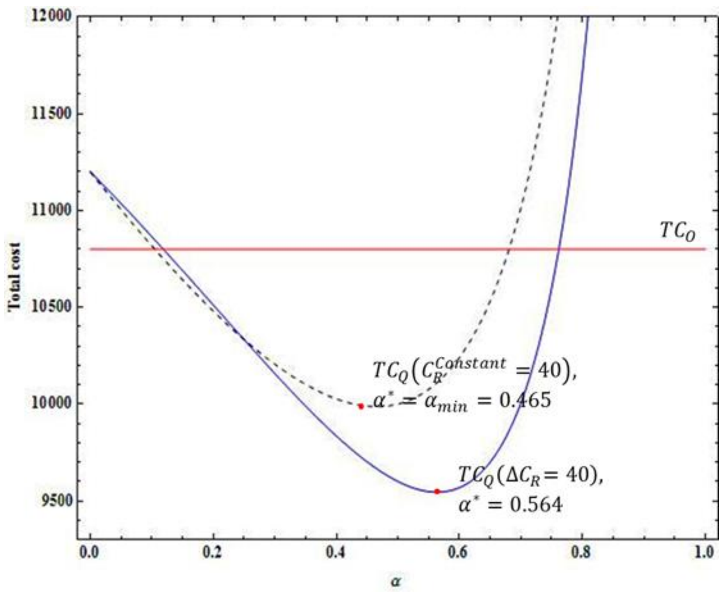

Figure 5—19: Total cost function of linear vs. constant remanufacturing cost.

5.4 Conclusion

Remanufacturing is one of the main recovery operations in the CLSC that aims to bring used products up to the quality of new products that can ultimately satisfy the market demand. One of the key factors that influences the cost saving offered by the remanufacturing operation is the acquisition of the right quantity and quality of used products. This chapter has considered a firm with a hybrid manufacturing-remanufacturing system who can manage the product returns through either passive or proactive strategies. In the proactive strategy (market-driven strategy) two scenarios are considered: first, when the firm exploits financial incentives to influence the rate of returns. In this case, used products are unsorted and the testing and grading process occurs after the firm has received them. After the testing operation, a fraction of returns that have passed the quality test will be remanufactured and those that fail will be scrapped. Remanufacturing of used tyres and empty packaging are examples of this quantity-based model. The second scenario explores the effect of quality–based incentives, where offering a higher incentive price leads to the acquisition of a better quality of used products. The quality-based model was then extended to investigate a case where both acquisition and remanufacturing costs are a function of the quality condition. One of the key considerations of this model is to have a good inspection prior to purchasing the used product in order to avoid accepting used products with poor quality. The quality–based model is common with consumer products (e.g. toner cartridges, mobile phones, laptops, etc.).

The acquisition cost function was introduced in the form of a rational function that can capture the different relationships between the acquisition cost and returns rate, as well as returns quality. The optimality condition was analytically determined and a closed-form solution derived for the optimal solution when the acquisition cost is linear (i.e. the marginal cost is constant), and non-linear (i.e. the marginal cost of acquisition is increasing). The optimal cost of operating proactive strategies was then benchmarked against the passive strategy (the open-loop system) to illuminate the economic advantages of operating the remanufacturing operation and offering incentives (market-driven). Finally, a numerical study and sensitivity analysis were performed to explore the effect of the model parameters on the optimal solution and the optimal cost saving.

The results show that the economic-oriented decision making about operating a closed-loop or open-loop strategy is affected to a great extent by the remanufacturing cost advantage and the acquisition cost structure.

Furthermore, a diseconomy of scale in the acquisition cost ($b > 0$) leads to a decrease in the remanufacturing amount, with more new products having to be manufactured to satisfy the market demand. It is possible to conclude, therefore, that the cost saving from the market-driven strategy is counteracted to a certain extent when a high effort is needed to increase the collection rate or quality. In this case, the scrapping of returns becomes more and more efficient despite the remanufacturing cost advantage

The analysis of the quality–based incentive provides interesting insights regarding the relationship between the marginal cost of obtaining a used product with higher quality and the remanufacturing cost advantage. In this model, the decision regarding the optimal acquisition strategy is based on a trade-off between the remanufacturing cost and the acquisition cost. We show that when the remanufacturing cost depends on the quality condition of returns, it is more economically attractive to acquire a higher quality of returns despite the increase in the acquisition cost.

The sensitivity analysis shows that an increase in C_R, P_{max}, and b negatively influences the optimal solution and VR in both the quality-based and quantity based incentive models. In the quantity-based incentive model, an increase in C_S leads to a decrease in the optimal return rate and VR. Interestingly, this effect is reversed for the quality based model. This implies that when the cost of scrapping is high it is economically beneficial for the firm to obtain a higher quality of returns. This, of course, will increase the total cost of the market-driven strategy but there will still be a higher cost saving since the total cost of the open-loop system also increases.

Finally, an increase in the cost of testing does not affect the optimal quality rate, but does lead to an increase in the total cost of the market-driven strategy, which then leads to a decrease in the total cost improvement. This effect is different from what we see in the quantity-based model. The impact of testing is particularly important in the quality-based model since the process of sorting/grading is effectively transferred to the suppliers of the used products (e.g. the collector). This implies that the uncertainty in the quality of returns has reduced by the time they arrive at the remanufacturing facility. The cost of testing, therefore, should be low for those returns that are acquired. This means that having a good inspection process prior to purchasing the used product is crucial in order to avoid accepting used products with poor quality. Failure to do this will increase the cost of testing when the used products arrive at the firm's facility, with a consequent impact on the remanufacturing decisions.

It has to be mentioned that one assumption we made throughout this chapter is for the demand rate to be constant over the infinite planning horizon. Although this assumption has been used in other remanufacturing models (Richter, 1996; Dobos and Richter, 2003; Dobos and Richter, 2004 and Rubio and Corominas, 2008), it might not reflect real life settings appropriately. In the next Chapter we will relax this assumption and investigate a proactive acquisition strategy over the finite planning horizon in which demand is a function of time.

Chapter 6

The Impact of Returns Quality and Lead-Time on the Firm’s Product Acquisition Decisions

6.1 Introduction

The previous chapter considered both quantity-based and quality–based incentive approaches to investigate the economic advantages of a proactive acquisition strategy. The result of the analysis provides interesting insights regarding the relationship between the acquisition cost function and the remanufacturing cost advantage, and acknowledges that the quality of returns is one of the major factors that directly affects the economic attractiveness of the remanufacturing operation.

The aim of this chapter is to investigate the economic impact of a proactive strategy vs. a passive strategy by simultaneously considering both quality of returns and elements of the product life cycle such as returns lead time.

Technological innovation has influenced the return rate and shortened the life cycle for many products. Previous studies have shown that the product life cycle and the issues related to the return of used products, have a major effect on the ability to balance the returns and demand for remanufactured products and the cost savings from the remanufacturing operation. At the early stage of the product life cycle there are not enough returns for remanufacturing, whereas at the end of the life cycle there is no demand for remanufactured products. The characteristics of the life-cycle therefore affect the possibilities of acquiring used products suitable for remanufacturing. The product life cycle is, therefore, an important issue that has to be considered when making product acquisition decisions (Guide et al., 2005).

The impact of the product life cycle is a major focus in studies that address inventory control problems (Dobos, 2003; Ahiska and King, 2010; Chung and Wee, 2011 and Hsueh, 2011) and marketing issues for remanufactured products (Debo et al. 2006 and Gakan et al., 2013) but not studies regarding product acquisition decisions (Fleischmann et al., 2010). The economics of remanufacturing operations over the product life cycle have been studied by Geyer (2007). In that study a finite product life cycle is introduced to create a constraint on the market demand for remanufactured products. Kleber (2005) proposes a generic dynamic environment for investment decisions of product recovery based on simple assumptions regarding the product life cycle and the availability cycle for returns. In both Geyer (2007) and Kleber (2005) it is assumed that returns are exogenous i.e. remanufacturing yield is constant over the life cycle. In contrast to the above papers, we consider a proactive acquisition strategy over the product life cycle in which the firm offers financial incentives to obtain a higher quality of returns for its remanufacturing operations.

In this chapter the product life cycle is used as a basis for balancing supply and demand, and the effect of used product quality, as well as returns lead time, on the firm's product acquisition decisions is explored. Balancing the product returns and demand for remanufactured products is an important factor for a successful remanufacturing system (Östlin et al. 2008). For instance, even when the remanufacturing cost is lower than the cost of manufacturing a new product, it makes no sense to remanufacture the used product after the life cycle.

The chapter is organized as follows: section 6.2 describes the problem addressed in this chapter along with the assumptions governing the model; section 6.3 presents the static acquisition policy by investigating different demand profiles; section 6.4 presents the dynamic acquisition policy, where firms adjust the acquisition of used products according to different life cycle stages; finally, the main insights are summarised in the conclusion in section 6.5.

6.2 Model description and assumptions

As in the previous chapter, the model is based on a firm with a hybrid manufacturing-remanufacturing system who can manage product returns through either passive or proactive strategies. In a passive strategy, the firm scraps all returned products and demand is satisfied by manufacturing new products (an open-loop system). In the proactive strategy, the firm exploits financial incentives in order to influence the quality of returned products, and thus market demand is satisfied by both manufacturing new products and remanufacturing used products (Figure 6—1). Remanufactured products are assumed to be identical to the original products in terms of quality, so there is no distinction between a manufactured and a remanufactured product and both are sold in a primary market to satisfy demand. Also, it is assumed that products are designed for reuse, therefore used products might be remanufactured several times, i.e. used products have unlimited (or at least sufficient) durability. We refer the readers to Geyer et al. (2007) for the discussion on the impact of limited durability on the economics of remanufacturing operations. Furthermore, remanufacturing a unit is always cheaper than manufacturing a new one and disposing of a return, i.e. the remanufacturing cost advantage complies with $C_N - C_R + C_S > 0$, otherwise the market-driven strategy would not take a place. For many remanufactured products, especially electronic items, prices fall rapidly, and the rate of obsolescence is high, which means that there is little interest in holding inventory of products that can be remanufactured (Galbreth and Blacknurn, 2006). Thus items are rarely remanufactured to stock, and we can realistically limit our analysis to a single-period model.

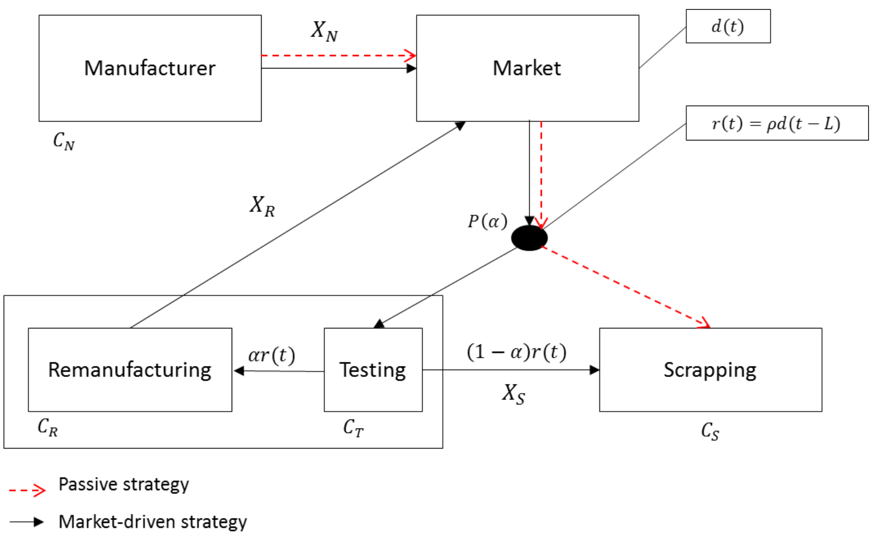

Figure 6—1: The passive and market-driven strategies.

The demand and return profile is illustrated in Figure 6—2 which complies with assumptions A.1 to A.5, below:

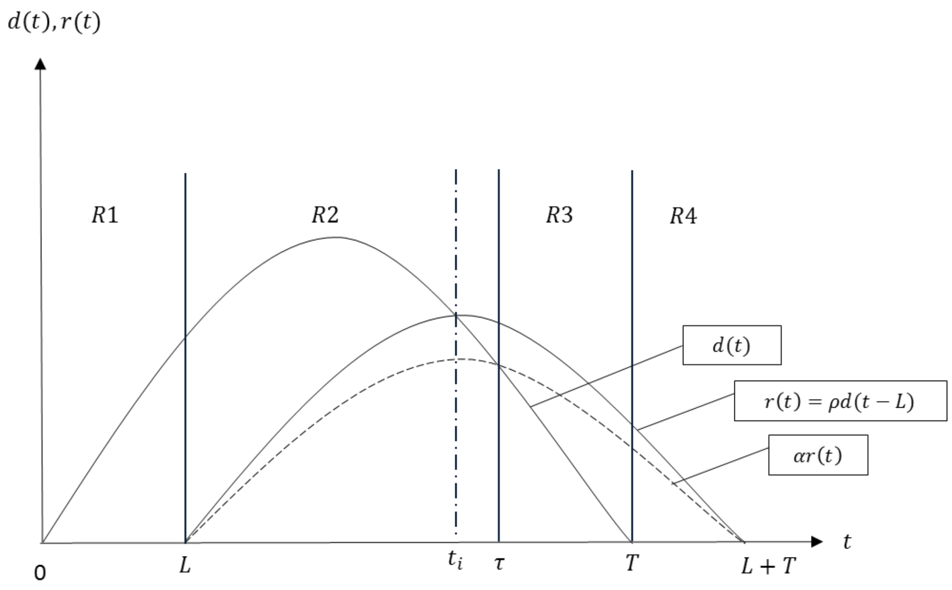

Figure 6—2: Dynamic policy with unimodal demand and return functions.

- A.1.) Similar to Geyer et al. (2007) and Kleber (2005) we assume that demand $d(t)$ is a deterministic continuously differentiable function of time with a unimodal shape over the product life cycle of length T. Geyer et al. (2007) modelled the product life cycle as an isosceles triangle and provide a justification for the unimodality of demand and returns based on sales data from two photocopier companies. Different from Geyer et al., (2007) who assumed that the return rate is exogenous (i.e. the return rate is constant over product life cycle) we assume that the firm can offer quality-based incentives to influence remanufacturing yields by acquiring a higher quality of returns.
- A.2.) Returns $r(t)$ is a function of demand and occur with a time lag (L) from the beginning of the product life cycle ($r(t) = \rho d(t-L)$), i.e. returns are not available prior to a time point L ($r(t) = 0 \; \forall \; t < L$). The constant value ρ ($0 \leq \rho \leq 1$) represents the return rate and is not affected by any incentives, i.e. the returns ρ is constant over time. Also, a time point t_i exists when the returns exceed demand $r(t) < d(t) \; \forall \; t < t_i$ and $r(t) > d(t) \; \forall \; t > t_i$.

- A.3.) After the testing operation a fraction of the returns that pass the quality inspection can be remanufactured ($\alpha\, r(t)$), with those failing this inspection being scrapped $(1-\alpha)\, r(t)$.

- A.4.) Based on the quality of returns (α), there exists at most one single intersection point τ ($\tau \in [t_i, T]$) for which $\alpha r(t) < d(t)\ \forall\ t < \tau$ and $\alpha r(t) > d(t)\ \forall\ t > \tau$. Note that $t_i \in [L, T]$, therefore it is possible that t_i occurs at point L (e.g. when $\rho = 1$) or at the end of the life cycle T. When the latter happens (e.g. constant demand or an increasing demand profile) we have $t_i = \tau = T$. This case will be investigated in section 6.3.1.

- A.5.) It is assumed that the firm offers a quality-based incentive throughout the product life cycle $t \in [0, T]$ in order to obtain better quality products. Moreover, acquired returns are disassembled and tested prior to the remanufacturing operations (i.e. testing occurs in the interval of $[L, T]$).

The list of notations used in the models is presented in Table 6—1.

Table 6—1: Notation summary.

C_N	Unit cost of manufacturing a new product.
C_R	Unit cost of refurbishing/remanufacturing.
C_T	Unit cost of testing.
C_S	Unit cost of scrapping.
$TC_O(t)$	Total cost of the passive strategy
$TC_Q(\alpha, t)$	Total cost of the market-driven strategy
X_N	Number of manufactured new products.
X_R	Number of remanufactured products.
X_S	Number of scrapped units.
$P\ (\alpha)$	Quality-based incentive acquisition cost function.
ρ	Constant return rate as fraction of demands.
α	The fraction of returns that passes the quality check successfully.
$d(t)$	Demand for product at time t.
$r(t)$	Product returns at time t.
T	The total life-cycle length of the product.
L	Returns lead time .
t_i	The point in time where returns exceed demands.
τ	The point in time where acceptable returns exceed demands.

It is intuitively clear that in the passive strategy the market demand $d(t), t \in [0, T]$ will be satisfied by manufacturing new products, and returns $r(t), t \in [L, T+L]$ will be scrapped. Therefore, the corresponding cost of the passive strategy can be expressed as:

$$TC_O(t) = C_N \int_0^T d(t)\, dt + C_S \int_L^{T+L} r(t) dt. \tag{6-1}$$

Where $TC_O(t)$ is considered as a benchmark against which the cost improvements of the market-driven strategy have to be compared.

6.3 Static quality level for the remanufacturing operation

In this section we first assume that the firm sets a static quality level for the remanufacturing operation, i.e. the quality level is fixed throughout the life cycle ($\alpha(t) = \alpha$). Please note that although α is constant over time, the manufacturing-remanufacturing policy is dynamic over the product life cycle. In this situation, for the market-driven strategy, remanufacturing is available after the acquisition of returns at time L. For $t < L$ only manufacturing can be used to satisfy demand. The dynamic policy for $t \geq L$ is to obtain used products in a good quality condition for remanufacturing and to manufacture new products (if required) for excess demand. Also, scrapping is in place for those returns that failed the quality test and/or for the surplus returns.

Using L, T and τ we can distinguish four different regions and the corresponding strategy for each region (Figure 6—3).

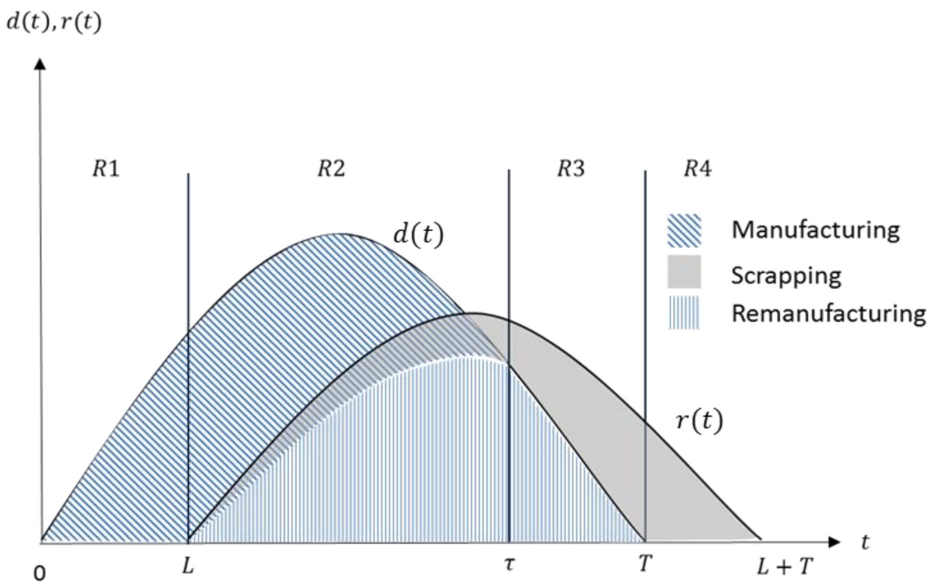

Figure 6—3: Dynamic decision of market-driven strategy: $X_N(t) = max\,[d(t) - \alpha r(t), 0],\ X_R(t) = min[d(t), \alpha r(t)], and\ \ X_S(t) = max[r(t) - d(t), (1-\alpha)r(t)]$.

In (R1) only manufacturing can be used to satisfy demand (the remanufacturing option is only available after time L). The corresponding cost in R1 is independent of α and can be calculated as:

$$C_N \int_0^L d(t)\, dt\,.$$

In (R2), i.e. $t \in [L, \tau]$, some of the demand can be satisfied by the remanufacturing of those returns that pass the quality inspection, $\alpha r(t)$, and also by manufacturing new products to satisfy the remaining demand. In addition those returns that failed the quality inspection, $(1-\alpha)r(t)$, have to be scrapped. The corresponding cost of R2 is:

$$C_N \int_L^\tau \big(d(t) - \alpha r(t)\big)\, dt + C_R \int_L^\tau \alpha r(t)\, dt + C_S \int_L^\tau (1-\alpha) r(t)\, dt + C_T \int_L^\tau r(t) dt\,.$$

In (R3), $t \in (\tau, T]$, returns exceed demand, and therefore, the firm remanufactures only to satisfy the residual demand and excess returns will be scrapped, therefore, we obtain:

$$C_R \int_{\tau}^{T} d(t)\,dt + C_S \int_{\tau}^{T} (r(t) - d(t))dt + C_T \int_{\tau}^{T} r(t)dt\,.$$

Note that, depending on the demand profile, returns may exceed demand at the end of the product life cycle ($\tau = T$). This is a special case that will be discussed further in section 6.3.1.

For $t > T$ (i.e. R4), there is no demand in the market and therefore all the returns have to be scrapped.

$$C_S \int_{T}^{T+L} r(t)\,dt\,.$$

Finally, the quality-based incentive is given to acquire a higher quality of returns for the remanufacturing operation. Let $P(\alpha)$ denote the acquisition cost function. The corresponding cost of the quality-based acquisition of returns for $t \in [0, T]$ can be defined by:

$$P(\alpha)\rho \int_{0}^{T} d(t)dt\,.$$

The total cost of the market-driven strategy can be defined by the summation of the corresponding costs of manufacturing, remanufacturing, acquisition, testing and scrapping in regions R1-R4:

$$TC_Q(\alpha,t) = C_N\int_0^L d(t)\,dt + C_N\int_L^\tau d(t)\,dt - C_N\int_L^\tau \alpha r(t)\,dt + C_R\int_L^\tau \alpha r(t)\,dt$$
$$+ C_S\int_L^\tau r(t)\,dt - C_S\int_L^\tau \alpha r(t)\,dt + C_R\int_\tau^T d(t)\,dt + C_S\int_\tau^T r(t)dt$$
$$- C_S\int_\tau^T d(t)dt + C_S\int_T^{T+L} r(t)\,dt + P(\alpha)\rho\int_0^T d(t)dt$$
$$+ C_T\int_L^T r(t)dt\,.$$

Simplifying the above gives:

$$TC_Q(\alpha,t) = C_N\int_0^\tau d(t)\,dt - (C_N - C_R + C_S)\alpha\int_L^\tau r(t)\,dt$$
$$+ (C_R - C_S)\int_\tau^T d(t)dt + C_S\int_L^{T+L} r(t)dt + C_T\int_L^T r(t)dt \qquad \text{(6-2)}$$
$$+ P(\alpha)\,\rho\int_0^T d(t)dt.$$

The objective here is to find the optimal quality rate that minimises the total cost of market-driven strategy over the planning horizon, i.e.:

$$\min_{\alpha_{min}\le\alpha\le\alpha_{max}} TC_Q(\alpha,t), \qquad 0 \le t \le T + L\,.$$

It follows from assumption A.4 that at a time point τ, demand and remanufacturable returns intersect, i.e. $d(\tau) = \alpha r(\tau)$ where $\tau \in [t_i, T]$, therefore for the quality parameter we have:

$$\alpha = \frac{d(\tau)}{r(\tau)}, \qquad \forall\tau \in [t_i, T]. \qquad \text{(6-3)}$$

From the above equation, it is clear that at $\tau = t_i$ we obtain $d(t_i) = r(t_i)$, which corresponds to the upper boundary of the quality level, i.e. $\alpha = 1$, and for $\tau = T$ we obtain $d(T) = 0$, which corresponds to the lower limit of the quality parameter, i.e. $\alpha = 0$. As the quality parameter α increases, therefore, the intersection point occurs earlier in the life cycle, i.e. τ decreases. This implies that incentivising the market to obtain a higher quality of returns leads to an increase in the amount of remanufacturing so less new products need to be manufactured to satisfy the remaining demand (R2 decreases and R3 increases).

Let $f(\tau)$ denote $d(\tau)/r(\tau)$, i.e. $\alpha = f(\tau)$, where $\frac{d\tau}{d\alpha} < 0$. We can express the intersection point τ as an inverse function of α:

$$\tau = f^{-1}(\alpha)\,. \tag{6-4}$$

Replacing the above equation into (6-2) we obtain:

$$\begin{aligned} TC_Q(\alpha,t) = {} & C_N \int_0^{f^{-1}(\alpha)} d(t)\,dt - (C_N - C_R + C_S)\alpha \int_L^{f^{-1}(\alpha)} r(t)\,dt \\ & + (C_R - C_S) \int_{f^{-1}(\alpha)}^{T} d(t)dt + C_S \int_L^{T+L} r(t)dt + C_T \int_L^{T} r(t)dt \\ & + P(\alpha)\,\rho \int_0^{T} d(t)dt\,. \end{aligned} \tag{6-5}$$

The market-driven strategy is economically attractive when $TC_Q(\alpha,t) \le TC_O(t)$:

$$C_N \int_{0}^{f^{-1}(\alpha)} d(t)\,dt - (\,C_N - C_R + C_S)\alpha \int_{L}^{f^{-1}(\alpha)} r(t)\,dt + (C_R - C_S) \int_{f^{-1}(\alpha)}^{T} d(t)dt$$

$$+ C_S \int_{L}^{T+L} r(t)dt + C_T \int_{L}^{T} r(t)dt + P(\alpha)\,\rho \int_{0}^{T} d(t)dt$$

$$\leq\; C_N \int_{0}^{T} d(t)\,dt + C_S \int_{L}^{T+L} r(t)dt.$$

Simplifying the above gives:

$$C_N \int_{0}^{f^{-1}(\alpha)} d(t)\,dt - (\,C_N - C_R + C_S)\alpha \int_{L}^{f^{-1}(\alpha)} r(t)\,dt + (C_R - C_S) \int_{f^{-1}(\alpha)}^{T} d(t)dt$$

$$+ C_T \int_{L}^{T} r(t)dt + P(\alpha)\,\rho \int_{0}^{T} d(t)dt \leq\; C_N \int_{0}^{T} d(t)\,dt\,.$$

Switching the boundaries of $C_N \int_0^{f^{-1}(\alpha)} d(t)\,dt$ to $-\,C_N \int_{f^{-1}(\alpha)}^{0} d(t)\,dt$ and substituting it into the above, gives:

$$-(\,C_N - C_R + C_S) \int_{L}^{f^{-1}(\alpha)} \alpha r(t)\,dt + (C_R - C_S) \int_{f^{-1}(\alpha)}^{T} d(t)dt - \;C_N \int_{f^{-1}(\alpha)}^{T} d(t)\,dt$$

$$+ C_T \int_{L}^{T} r(t)dt + P(\alpha)\rho \int_{0}^{T} d(t)dt \leq 0\,,$$

which reduces to:

$$C_T \int_{L}^{T} r(t)dt + P(\alpha) \int_{L}^{T+L} r(t)dt$$
$$\leq (\,C_N - C_R + C_S)\left(\alpha \int_{L}^{f^{-1}(\alpha)} r(t)\,dt + \int_{f^{-1}(\alpha)}^{T} d(t)dt\right). \tag{6-6}$$

The market-driven strategy is therefore economically attractive when the cost advantage from remanufacturing returns $(\mathrm{C_N} - \mathrm{C_R} + \mathrm{C_S})$ $\left(\alpha \int_{L}^{f^{-1}(\alpha)} r(t)\, dt + \int_{f^{-1}(\alpha)}^{T} d(t) dt\right)$ is higher than the sum of the acquisition and testing costs.

Since $TC_O(t)$ is not affected by the quality condition, the maximum cost improvement can be achieved by minimising $TC_Q(\alpha, t)$, i.e.

$$\underset{\alpha_{min} \le \alpha \le \alpha_{max}}{Min} TC_Q(\alpha, t)\ .$$

To prove that $TC_Q(\alpha, t)$ is convex and it is minimised at α^*, the Leibniz theorem can be applied to differentiate $TC_Q(\alpha, t)$ with respect to α:

Recall that according to Leibniz's theorem, differentiation under the integral sign is as follows:

$$\frac{d}{dx}\left(\int_{a(x)}^{b(x)} f(x,t) dt\right)$$
$$= f\big(x, b(x)\big).\frac{\partial b(x)}{\partial x} - f\big(x, a(x)\big).\frac{\partial a(x)}{\partial x} + \int_{a(x)}^{b(x)} \frac{\partial f(x,t)}{\partial x} dt.$$

Therefore for $\frac{\partial TC_Q(\alpha,t)}{\partial \alpha}$ we have

$$\frac{\partial TC_Q(\alpha)}{\partial \alpha} = C_N \frac{\partial f^{-1}(\alpha)}{\partial \alpha} d\big(f^{-1}(\alpha)\big)$$

$$- \left((C_N - C_R + C_S) \int_L^{f^{-1}(\alpha)} r(t)\, dt \right. \tag{6-7}$$

$$\left. + \frac{\partial f^{-1}(\alpha)}{\partial \alpha} \alpha r\big(f^{-1}(\alpha)\big)(C_N - C_R + C_S) \right)$$

$$- (C_R - C_S) \frac{\partial f^{-1}(\alpha)}{\partial \alpha} d\big(f^{-1}(\alpha)\big) + P'(\alpha)\, \rho \int_0^T d(t)dt\,.$$

From (6-3) and (6-4), it is easy to see that:

$$\alpha r\big(f^{-1}(\alpha)\big) = d\big(f^{-1}(\alpha)\big)\,.$$

Substituting the above into (6-7) and factoring $\frac{\partial f^{-1}(\alpha)}{\partial \alpha}$, we obtain:

$$\frac{\partial TC_Q(\alpha)}{\partial \alpha} = \frac{\partial f^{-1}(\alpha)}{\partial \alpha} \Big(C_N\, d\big(f^{-1}(\alpha)\big) - d\big(f^{-1}(\alpha)\big)(C_N - C_R + C_S)$$

$$- (C_R - C_S) d\big(f^{-1}(\alpha)\big)\Big) - (C_N - C_R + C_S) \int_L^{f^{-1}(\alpha)} r(t)\, dt$$

$$+ P'(\alpha)\, \rho \int_0^T d(t)dt,$$

which reduces to:

$$\frac{\partial TC_Q(\alpha)}{\partial \alpha} = - \left((C_N - C_R + C_S) \int_L^{f^{-1}(\alpha)} r(t)\, dt \right) + P'(\alpha)\, \rho \int_0^T d(t)dt\,, \tag{6-8}$$

and for the second order condition, we obtain:

$$\frac{\partial^2 TC_Q(\alpha)}{\partial \alpha^2} = -\left((C_N - C_R + C_S) \frac{\partial f^{-1}(\alpha)}{\partial \alpha} r\big(f^{-1}(\alpha)\big) \right) + P''(\alpha)\,\rho \int_0^T d(t)dt\,. \quad (6\text{-}9)$$

where remanufacturing a unit must always be cheaper than scrapping a return and producing a new one, otherwise remanufacturing would never take place, i.e. $(C_N - C_R + C_S) > 0$. Also, $(t) \geq 0\ \forall\ L \leq t \leq T$, hence $r\big(f^{-1}(\alpha)\big) > 0$.

Finally, from (6-4) we know $\tau = f^{-1}(\alpha)$, since $\frac{d\tau}{d\alpha} < 0$, i.e. as α increases τ decreases hence $\frac{\partial f^{-1}(\alpha)}{\partial \alpha} \leq 0$. It is easy to see that the first parentheses in Eq.(6-9) is always positive for $\forall\ \alpha \in [\alpha_{min}, \alpha_{max}]$. Recall from section 5.3.2 that the acquisition cost function for the quality-based incentive is defined as:

$$P(\alpha) = \frac{P_{max}(\alpha - \alpha_{min})}{(\alpha_{max-}\alpha_{min})(\alpha_{max} - \alpha)^b}\,, \quad (6\text{-}10)$$

with the following first derivative:

$$P'(\alpha) = \frac{P_{max}\big((\alpha_{max} - \alpha) + b(\alpha - \alpha_{min})\big)}{\Delta\alpha(\alpha_{max} - \alpha)^{b+1}}\,, \quad (6\text{-}11)$$

and second derivative:

$$P''(\alpha) = \frac{bP_{max}(2(\alpha_{max} - \alpha) + (b+1)(\alpha - \alpha_{min}))}{\Delta\alpha(\alpha_{max} - \alpha)^{(b+1)}}\,. \quad (6\text{-}12)$$

where $P(\alpha)$ is convex on the interval $\alpha \in [\alpha_{min}, \alpha_{max})$ (see section 5.3.2 for the proof of the convexity). Since the second order condition is always positive for all $\alpha \in [\alpha_{min}, \alpha_{max})$ (i.e. $\frac{\partial^2\, TC_Q\,(\alpha,t)}{\partial \alpha^2} > 0$) we can conclude that $TC_Q(\alpha, t)$ is a convex function of α and that a unique optimal solution α^* exists, which can derived by solving the following first-order condition:

$$P'(\alpha) \int_{0}^{T} d(t)dt - \frac{1}{\rho}\left((C_N - C_R + C_S) \int_{L}^{f^{-1}(\alpha)} r(t)\, dt \right) = 0\,. \tag{6-13}$$

Let

$$\int_{0}^{T} d(t)dt = D(T), \tag{6-14}$$

and

$$\int_{L}^{f^{-1}(\alpha)} r(t)\, dt = \rho D(f^{-1}(\alpha) - L)\,. \tag{6-15}$$

Replacing (6-14) and (6-15) into (6-13), we obtain:

$$P'(\alpha)\, D(T) - (C_N - C_R + C_S) D(f^{-1}(\alpha) - L) = 0\,. \tag{6-16}$$

Given the linear acquisition cost, i.e. $b = 0$, the marginal cost of acquiring a used product with a higher quality is:

$$P'_{b=0}(\alpha) = \frac{P_{max}}{\Delta\alpha}\,.$$

Replacing the above into (6-16) gives:

$$\frac{P_{max}}{\Delta\alpha} D(T) - (C_N - C_R + C_S) D(f^{-1}(\alpha) - L) = 0\,. \tag{6-17}$$

When the acquisition cost is convex ($b = 1$), the marginal cost of acquiring a unit of return with a higher quality increases. The marginal cost of obtaining a higher quality of returns can be obtained by replacing $b = 1$ into (6-10), which gives:

$$P'_{b=1}(\alpha) = \frac{P_{max}}{(\alpha_{max} - \alpha)^2}.$$

Replacing the above into (6-16) gives:

$$(\alpha_{max} - \alpha)^2 D(f^{-1}(\alpha) - L) - \frac{P_{max} D(T)}{(C_N - C_R + C_S)} = 0. \tag{6-18}$$

6.3.1 Investigating the special case where $\tau^* = T$

As previously pointed out in (A.4.), based on the demand pattern (e.g. constant demand or an increasing demand pattern) the returns that can be remanufactured may exceed demand after the end of the product life cycle i.e. $\alpha r(t) > d(t), \forall t \geq T$. This section presents the closed-form solution for the optimal quality rate when intersection point τ occurs at the end of the life cycle, i.e. $\tau = f^{-1}(\alpha) = T$. The general optimality condition for this special case can be obtained by replacing $f^{-1}(\alpha) = T$ into (6-16), which implies:

$$P'(\alpha) - (C_N - C_R + C_S) \frac{D(T - L)}{D(T)} = 0. \tag{6-19}$$

6.3.1.1 Optimality condition when the acquisition cost function is linear ($b = 0$)

Given the linear acquisition cost function, i.e. $P'_{b=0}(\alpha) = \frac{P_{max}}{\Delta\alpha}$, for the optimality condition we obtain:

$$\frac{P_{max}}{\Delta\alpha} - (C_N - C_R + C_S) \frac{D(T - L)}{D(T)} = 0. \tag{6-20}$$

In this situation the total cost function is a linear function with respect to the quality parameter, therefore we have two cases:

- *Case 1: when* $\frac{P_{max}}{\Delta\alpha} - \frac{(C_N - C_R + C_S)D(T-L)}{D(T)} \geq 0$:

In this case, the total cost function is an increasing function with respect to α (the cost of the market-driven strategy increases as α increases). Therefore, α_{min} minimises the total cost of the market-driven strategy, i.e. $\alpha^* = \alpha_{min}$. This situation implies that the firm should operate a closed-loop system, i.e. no incentive should be offered and price-independent returns are remanufactured.

- *Case 2: when* $\frac{P_{max}}{\Delta\alpha} - \frac{(C_N - C_R + C_S)D(T-L)}{D(T)} < 0$:

In this case, the total cost of the market driven strategy is a decreasing function in α. This implies that the firm should offer an incentive price in order to obtain used products with the highest quality i.e. $\alpha^* = \alpha_{max}$. The optimality condition when the acquisition cost is linear can therefore be summarised as follows:

$$\alpha^* \to \begin{cases} \alpha_{min} & \dfrac{P_{max}}{\Delta\alpha} \geq (C_N - C_R + C_S)\dfrac{D(T-L)}{D(T)} . \\ \alpha_{max} & \dfrac{P_{max}}{\Delta\alpha} < (C_N - C_R + C_S)\dfrac{D(T-L)}{D(T)} . \end{cases} \tag{6-21}$$

Moreover, the quality threshold in which the proactive strategy yield a cost improvement over the passive strategy can be obtain by replacing $f^{-1}(\alpha) = T$ into (6-6), which gives:

$$\alpha^* \geq \frac{C_T}{(C_N - C_R + C_S)} + \frac{P(\alpha^*)D(T)}{(C_N - C_R + C_S)D(T-L)} . \tag{6-22}$$

When $\alpha^* = \alpha_{min}$ for the quality threshold we have:

$$\alpha_{min} \geq \frac{C_T}{(C_N - C_R + C_S)}.$$

This means that a cost saving can only be achieved from the closed-loop system when the above inequality holds. In this case no incentive should be offered to increase the quality of returns and the firm should remanufacture the price-independent returns.

Similarly, for $\alpha^* = \alpha_{max}$, we obtain:

$$\alpha_{max} \geq \frac{C_T}{(C_N - C_R + C_S)} + \frac{P_{max} D(T)}{(C_N - C_R + C_S) D(T-L)}.$$

Although the same reasoning applies to this case, here, when the above inequality holds the firm has to offer the maximum incentive price in order to obtain the maximum quality of returns. The optimal strategy can therefore be summarised as follows:

When $\frac{P_{max}}{\Delta\alpha} - (C_N - C_R + C_S)\frac{D(T-L)}{D(T)} < 0$ we have:

$$\alpha^* \rightarrow \begin{cases} \alpha_{max}, & if\ \alpha_{max} > \dfrac{C_T}{(C_N - C_R + C_S)} + \dfrac{P_{max} D(T)}{(C_N - C_R + C_S) D(T-L)}. \\ 0, & if\ \alpha_{max} < \dfrac{C_T}{(C_N - C_R + C_S)} + \dfrac{P_{max} D(T)}{(C_N - C_R + C_S) D(T-L)}. \end{cases}$$

When $\frac{P_{max}}{\Delta\alpha} - (C_N - C_R + C_S)\frac{D(T-L)}{D(T)} \geq 0$ we have:

$$\alpha^* \rightarrow \begin{cases} \alpha_{min}, & if\ \alpha_{min} > \dfrac{C_T}{(C_N - C_R + C_S)}. \\ 0, & if\ \alpha_{min} < \dfrac{C_T}{(C_N - C_R + C_S)}. \end{cases}$$

Note that $\alpha^* = 0$ implies that the remanufacturing operation is not economically attractive for the firm, hence the open-loop system should be operated.

6.3.1.2 Optimality condition when the acquisition cost function is non-linear ($b = 1$)

The optimal quality rate when the acquisition cost is non-linear can be obtained by replacing $P'_{b=1}(\alpha) = \frac{P_{max}}{(\alpha_{max}-\alpha)^2}$ into (6-19), which gives:

$$\frac{P_{max}}{(\alpha_{max} - \alpha)^2} - \frac{(C_N - C_R + C_S)D(T - L)}{D(T)} = 0\,. \qquad (6\text{-}23)$$

Let $\overline{\alpha}$ denote the feasible solution to (6-23). For $\overline{\alpha}$ we obtain:

$$\overline{\alpha} = \alpha_{max} - \sqrt{\frac{P_{max}}{(C_N - C_R + C_S)} \cdot \frac{D(T)}{D(T - L)}}\,. \qquad (6\text{-}24)$$

Therefore, when $\overline{\alpha} < \alpha_{min}$, the optimal solution reaches the value of the lower bound, i.e. $\alpha^* = \alpha_{min}$. This implies that offering incentives to obtain a higher quality of returns is not economically attractive and the firm should only operate a closed-loop system without incentivising the market, i.e. $P(\alpha^*) = 0$. The decision regarding the optimal strategy should be based on the quality threshold (6-22).

$$\overline{\alpha} \geq \frac{C_T}{(C_N - C_R + C_S)} + \frac{P(\overline{\alpha})D(T)}{(C_N - C_R + C_S)D(T - L)}\,.$$

- *Open-loop strategy*

If $\overline{\alpha} < \alpha_{min}$ and $\alpha_{min} < \frac{C_T}{(C_N - C_R + C_S)}$ then $\alpha^* = 0$ i.e. no cost improvement can be achieved by remanufacturing returned products. In this situation it is more economical for the firm to satisfy market demand by manufacturing new products and scrapping the returns.

- *Remanufacturing with no incentive (closed-loop system)*

If $\overline{\alpha} < \alpha_{min}$ and $\alpha_{min} > \frac{C_T}{(C_N - C_R + C_S)}$ then $\alpha^* = \alpha_{min}$, i.e., no incentive should be offered to obtain a higher quality of returns ($P(\alpha^*) = 0$). Therefore, the closed-loop strategy with no incentive will yield a higher cost saving compared to the open-loop system.

- *Incentivise market and remanufacturing (market-driven strategy)*

If $\alpha_{min} \leq \overline{\alpha} \leq \alpha_{max}$ and $\overline{\alpha} > \frac{C_T}{(C_N - C_R + C_S)} + \frac{P(\overline{\alpha})D(T)}{(C_N - C_R + C_S)D(T-L)}$ then $\alpha^* = \overline{\alpha}$ i.e. it is economically justified to incentivise the market in order to obtain a higher quality of returns. In this situation, the firm obtains the acquisition cost of $P(\alpha^*)$ to attract higher quality returns, i.e. it increases the (re)manufacturability of returns. This higher acquisition cost will be offset by a reduction in the manufacturing quantity, which leads to a lower overall cost for this strategy.

To illustrate the impact of returns lead time and demand profile the closed-form solution for the optimal quality rate was derived for constant and triangular increasing demand patterns. The calculation for the optimal quality rate for these two demands profile is fairly straightforward; therefore the reader is referred to Appendix III for the details of the calculation. Table 6—2 summarises the optimal solution.

Table 6—2: Solution for the optimal quality rate.

Demand pattern	α^* for linear acquisition cost ($b = 0$)	$\alpha^*$for non-linear acquisition cost ($b = 1$)
Constant demand	$\begin{cases} \alpha_{min}\ if\ \ \Delta\alpha \leq \dfrac{P_{max}}{(\ C_N - C_R + C_S)\left(1-\frac{L}{T}\right)} \\ \alpha_{max}\ if\ \ \Delta\alpha > \dfrac{P_{max}}{(\ C_N - C_R + C_S)\left(1-\frac{L}{T}\right)} \end{cases}$	$\alpha_{max} - \sqrt{\dfrac{P_{max}}{(\ C_N - C_R + C_S)\left(1-\frac{L}{T}\right)}}$
Increasing demand	$\begin{cases} \alpha_{min}\ if\ \Delta\alpha \leq \dfrac{P_{max}}{(\ C_N - C_R + C_S)\left(1-\frac{L}{T}\right)^2} \\ \alpha_{max}\ if\ \ \Delta\alpha > \dfrac{P_{max}}{(\ C_N - C_R + C_S)\left(1-\frac{L}{T}\right)^2} \end{cases}$	$\alpha_{max} - \left(\sqrt{\dfrac{P_{max}}{(\ C_N - C_R + C_S)}}.\dfrac{1}{1-\frac{L}{T}}\right)$

It is clear that the optimal quality rate for remanufacturing depends on the marginal cost of acquiring a better quality of returns $\frac{P_{max}}{\Delta\alpha}$, the remanufacturing cost advantage $(\mathrm{C_N} - \mathrm{C_R} + \mathrm{C_S})$, and the ratio between return lead time and the life cycle length $\left(\frac{\mathrm{L}}{T}\right)$.

For the constant demand profile and linear acquisition cost, if the quality difference is high $\Delta\alpha > \frac{P_{max}}{(\ C_N - C_R + C_S)\left(1-\frac{L}{T}\right)}$, the remanufacturer will be able to offer the maximum incentive price of P_{max} to attract the highest quality of returns, i.e. $\alpha^* = \alpha_{max}$ for the remanufacturing operation. If the quality difference is low, $\Delta\alpha \leq \frac{P_{max}}{(\ C_N - C_R + C_S)\left(1-\frac{L}{T}\right)}$, the total cost function increases with increasing α and therefore the optimal quality level that minimises the total cost of the market-driven strategy is α_{min} ($\alpha^* = \alpha_{min}$). This situation implies that it is economically beneficial for firm to operate remanufacturing with the price-independent returns i.e. remanufacturing without offering any incentive.

When the firm faces diseconomies of scale in the acquisition of returns, i.e. b=1, the remanufacturer can, at most, obtain a quality rate of $\alpha_{max} - \sqrt{\frac{P_{max}}{(C_N - C_R + C_S)\left(1-\frac{L}{T}\right)}}$. When the remanufacturing cost advantage is high, or a lower incentive price is needed, it is easier to attract a higher quality of returns.

A similar argument applies for the triangular increasing demand pattern. In this case, however, the optimal solution is more sensitive to the return lead time. Intuitively, this means that in the case of an increasing demand profile, when the returns lead time increases, more of the used product arrives at the remanufacturing facility after the end of the product life cycle and therefore will be scrapped.

In the analysis of the constant and increasing demand patterns we investigate the special situation where the intersection point occurs at the end of the planning horizon i.e. $\tau = T$. In the remainder of the analysis, however, we investigate the general case where return and demand intersect before the end of the product life cycle.

6.3.2 Triangular decreasing demand profile:

For the purposes of this study a closed-form solution is required for α^* to allow for analytical treatment while still containing the essential features of time-dependent product returns. The results are therefore illustrated using the following demand pattern:

$$d(t) = \begin{cases} \frac{2D}{T}(T-t) & 0 < t \leq T \\ 0 & elesewhere \end{cases} .$$

Similar to Geyer et al. (2007) a constant returns lead time L is assumed and a constant return rate of ρ over time. However, the main difference here is that we assume that the return rate is not exogenous and can be influenced by offering incentives. The product returns over the time therefore equals:

$$r(t) = \begin{cases} \rho\left(\frac{2D}{T}(T-(t-L)\right) & L < t \leq T+L \\ 0 & elesewhere \end{cases}.$$

A complete description of demand and product returns is given by the four parameters D, ρ, T and L. As Figure 6—4 shows, this section is investigating a scenario in which demand is decreasing i.e. the product life cycle is in a decline phase, intersecting returns at time point t_i.

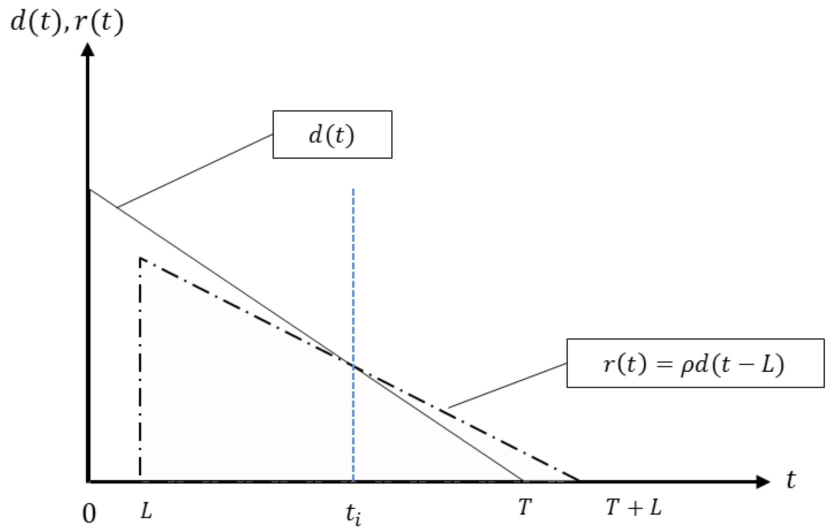

Figure 6—4: Triangular decreasing demand profile.

For the given demand and return profile it is possible to calculate $D(T)$ and $D(\tau - L)$ as follows:

$$D(T) = \frac{2D}{T}\left(T^2 - \frac{T^2}{2}\right) = DT, \tag{6-25}$$

and

$$D(\tau - L) = \frac{2D}{T}\left(T(\tau - L) - \frac{(\tau - L)^2}{2}\right) = -\frac{D}{T}\big((\tau - L)(\tau - L - 2T)\big). \tag{6-26}$$

Replacing the above into (6-17), we obtain:

$$\frac{D}{T}\big((\tau^* - L)(\tau^* - L - 2T)\big) - \frac{P_{max}DT}{\Delta\alpha(\, C_N - C_R + C_S)} = 0,$$

which simplifies to:

$$\tau^{*2} - \tau^*(2T - 2L) + L^2 + 2TL + \frac{P_{max}T^2}{\Delta\alpha(\, C_N - C_R + C_S)} = 0\,.$$

The closed form solution for the intersection point τ^* can be calculated by solving the above equation using the quadratic formula with the numerical coefficients *a=1*, *b=*$-(2T + 2L)$ and *c=* $2TL + L^2 + \frac{P_{max}}{\Delta\alpha(\, C_N - C_R + C_S)}\, T^2$ as:

$$\tau^* = \frac{(2T + 2L) \pm \sqrt{(-2T - 2L)^2 - 4(2TL + L^2 + \frac{P_{max}}{\Delta\alpha(\, C_N - C_R + C_S)}\, T^2)}}{2}.$$

Simplifying the above gives:

$$\tau^* = T\left(1 - \sqrt{1 - \frac{P_{max}}{\Delta\alpha(\, C_N - C_R + C_S)})}\right) + L\,, \qquad \tau \in [t_i, T]. \tag{6-27}$$

It follows from (6-3) that $\alpha^* = \frac{d(\tau^*)}{r(\tau^*)}$, therefore for α^* we obtain:

$$\alpha^* = \frac{T - \tau^*}{\rho(L + T - \tau^*)}. \tag{6-28}$$

Replacing (6-27) into (6-28) gives the closed-from solution for the optimal quality rate:

$$\alpha^* = \frac{1}{\rho} - \frac{L}{\rho\left(T\sqrt{1 - \frac{P_{max}}{\Delta\alpha(\, C_N - C_R + C_S)}}\right)}, \qquad \alpha \in [\alpha_{min}, \alpha_{max}]. \tag{6-29}$$

Let $Z = \left(T\sqrt{1 - \frac{P_{max}}{\Delta\alpha(\,C_N - C_R + C_S)}}\right)$, therefore $\alpha_{min} \leq \frac{Z-L}{\rho Z} \leq \alpha_{max}$ which gives a following threshold for the return lead time:

$$Z(1 - \rho\alpha_{max}) \leq L \leq Z(1 - \rho\alpha_{min}).$$

The above threshold suggests that offering an incentive is economically attractive for the firm when the returns lead time is not high i.e. $L \leq Z(1 - \rho\alpha_{min})$. For a returns lead time within the interval of $[Z(1 - \rho\alpha_{max})\ ,\ Z(1 - \rho\alpha_{min})]$ the optimal quality can be calculated from (6-29). In this situation, the firm has to offer the incentive price that corresponds to the optimal quality level. For a returns lead time of $L \geq Z(1 - \rho\alpha_{max})$ the economic benefit from the market-driven strategy is maximised if the firm offers the maximum price incentive (P_{max}) to obtain the highest quality of used product ($\alpha^* = \alpha_{max}$). For the returns that occur towards the end of the product life cycle, $\forall\, L \geq Z(1 - \rho\alpha_{min})$, offering an incentive is not economically attractive and the firm should accept the price-independent returns for remanufacturing (Figure 6—5).

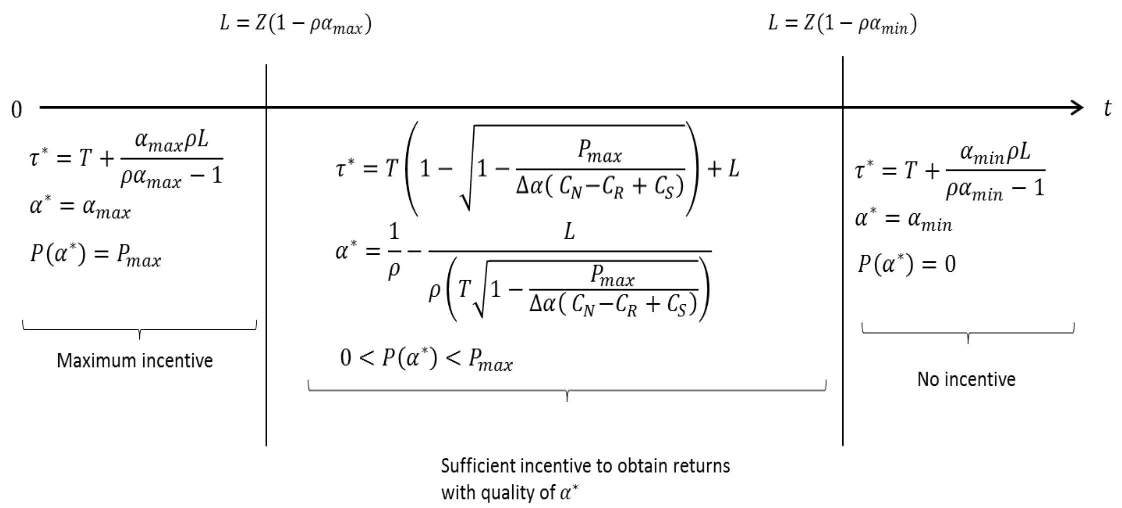

Figure 6—5: The optimality condition with respect to the returns lead time for $b = 0$.

6.3.3 Numerical Examples

Using the triangular decreasing demand profile, the following numerical example investigates the impact of the model's parameters on the optimal acquisition decision. The base set parameters for this example are as follows:

Life cycle length *T=12;* Demand *D=24; L=2;* $\rho = 0.8$*; b=0;* $C_N = 100$; $C_R = 40$; $C_S = 10$; $C_T = 10$; $P_{max} = 10$; $\alpha_{max} = 1$; $\alpha_{min} = 0.2$;

Hence, the corresponding demand and return are:

$$d(t) = 48 - 4t, \qquad t \in [0,12],$$

and

$$r(t) = 0.8.(48 - 4(t - 2)), \quad t \in [2, 14].$$

Of course, the market-driven strategy is financially attractive for firms when a cost improvement can be achieved over the passive strategy ($TC_M(\alpha^*, t) \leq TC_O(t)$). The percentage-cost improvement of the market-driven strategy over the passive strategy is denoted by the Value Recovery (VR) function and can be expressed as:

$$VR^*\% = \frac{TC_O(t) - TC_Q(\alpha^*, t)}{TC_O(t)} * 100\% \,.$$

Figure 6—6 illustrates that the maximum cost improvement from the market-driven strategy can be achieved when returns occur early in the life cycle ($L = 2$). In this situation, financial incentives should be offered to attract the highest quality of returns ($\alpha = \alpha_{max}$). The cost improvement, however, decreases when the returns lead time increases. For delayed returns ($L = 9.5$), offering incentives is not financially attractive ($\alpha^* = \alpha_{min}$). In this situation, the firm has the option to either remanufacture used products with the minimum quality (if $VR\% \geq 0$) or scrap them (if $VR\% < 0$). In this example since there is no cost advantage in remanufacturing ($VR\% < 0$), therefore the open-loop system should be operated.

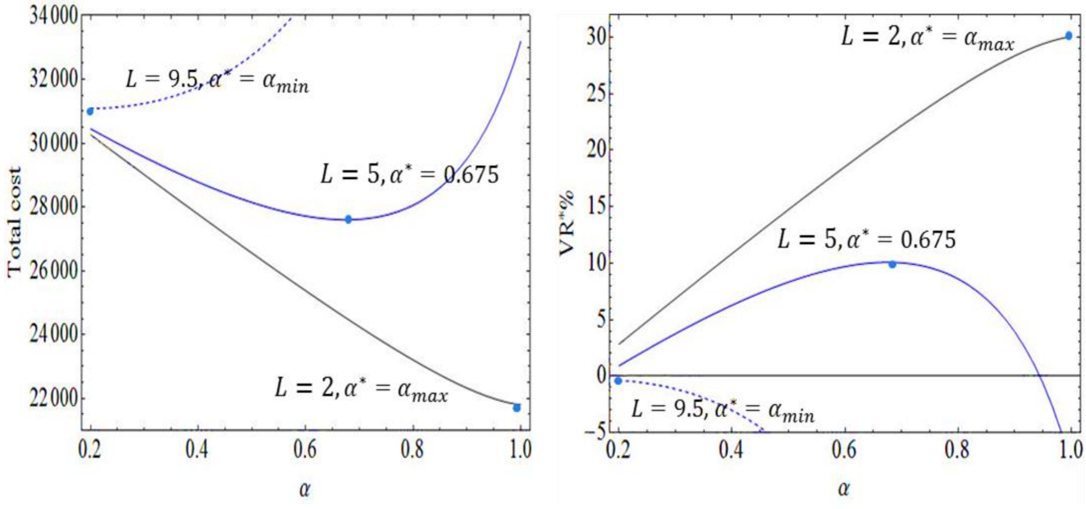

Figure 6—6: Impact of lead time on the optimal acquisition strategy and $VR\%$ when $b = 0$.

The impact of the incentive price on the optimal strategy is illustrated in Figure 6—7. Similar to the previous example, the maximum cost improvement can be achieved from the market-driven strategy when $P_{max} = 10$. When the incentive price increases ($P_{max} = 40$), however, the marginal cost of acquiring a higher quality of returns increases and hence α^* decreases ($\alpha^* = 0.86$), which implies that less of the demand can be satisfied by remanufacturing operations. In this case, operating the market-driven strategy can yield a cost saving of around 10%. Finally, the incentive price of $P_{max} = 50$ yields the optimal quality level of $\alpha^* = \alpha_{min}$. This suggests that offering incentives is no longer financially justified. In this situation, firms should remanufacture the returns with the minimum quality and satisfy the rest of the demand by producing new products; this option yields around a 3% cost saving compared to the open-loop system.

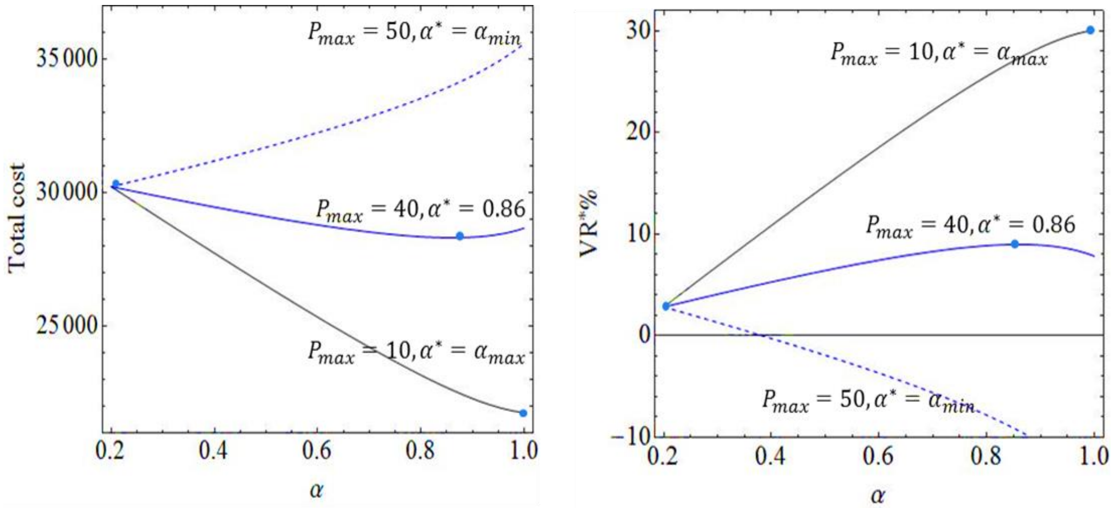

Figure 6—7: Impact of P_{max} on the optimal acquisition strategy and $VR\%$ when $b = 0$.

When the acquisition cost is convex $(b = 1)$, the marginal cost of acquiring a unit of return with a higher quality increases. The optimal quality rate when $b = 1$ for triangular decreasing demand and return can be obtained by replacing (6-25) and (6-26) into (6-18) to give:

$$\left(\alpha_{max} - \frac{T - \tau^*}{\rho(L + T - \tau^*)}\right)^2 - \frac{T^2}{(\tau^* - L)(\tau^* - L - 2T)} * \frac{P_{max}}{(C_N - C_R + C_S)} = 0. \qquad (6\text{-}30)$$

Since (6-30) is a cubic polynomial equation in τ^* it is difficult to obtain a closed-form solution for the optimal quality level α^*. Therefore we first numerically solve the optimal intersection point τ^* and then the corresponding quality rate α^* can be obtained by replacing τ^* into (6-28).

All the parameters in the example remain the same as section 6.3.3., here, however, b=1. Substituting the corresponding values in (6-30), we obtain the following equation with respect to the intersection point τ^*:

$$\left(1 - \frac{(12 - \tau^*)}{0.8(14 - \tau^*)}\right)^2 + \frac{144}{7(\tau^* - 2)(\tau^* - 26)} = 0, \qquad \tau^* \in (4{,}12).$$

Solving the above equation gives $\tau^* = 10.14$. Substituting τ^* into (6-28) yields the following optimal quality rate:

$$\alpha^* = \frac{12 - 10.14}{0.8(2 + 12 - 10.14\,)} = 0.602\,.$$

Therefore, we can distinguish the R1-R4 intervals as [0, 2], [2, 10.14], [10.14, 12] and [12, 14]. During the time interval [0, 2] there are no returns so all the demand has to be satisfied by manufacturing new products. During the interval [2, 10.14] the firm should offer incentives to obtain as many used products for remanufacturing as possible (60.2%). Since in this period demand is always higher than the returns, however, joint manufacturing–remanufacturing is required to satisfy all the demand. During the time interval [10.14, 12] demand is declining and there are sufficient returns in the system. In this period, demand should be satisfied only by remanufacturing and the surplus returns should be scrapped. Finally, during [12, 14] there is no demand in the market and all the returns should be scrapped.

The marginal cost of obtaining a unit of returns with higher quality arises when $b = 1$ and it becomes very expensive to obtain a better quality of returns. As Figure 6—8 illustrates, the maximum cost improvement when $b = 1$ can be obtained when used products are returned early in the life cycle ($L = 2$ and $\alpha^* = 0.602$). When the returns lead time increases, offering financial incentives becomes less economically attractive i.e. the cost improvement offered by the market-driven strategy decreases. Eventually, if the used products return towards the end of the life cycle, the optimal quality reaches its lower limit $\alpha^* = \alpha_{min}$. In this situation the firm should operate the open-loop system since the remanufacturing operation will yield a negative cost improvement ($VR\% < 0$ for $L = 9.5$).

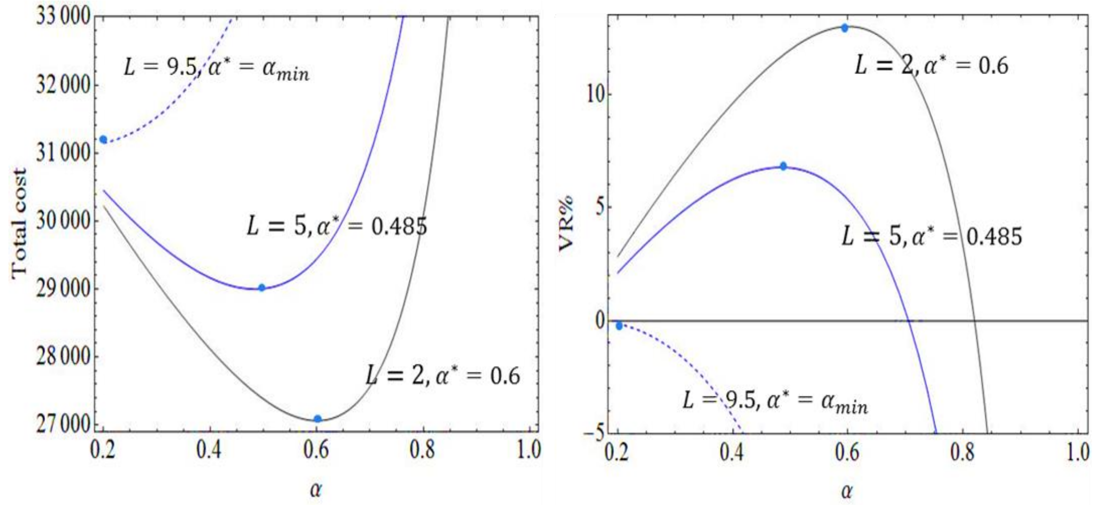

Figure 6—8: Impact of returns lead time on the optimal acquisition strategy and $VR\%$ when $b = 1$.

Figure 6—9 shows that the optimal quality level decreases monotonically with increasing incentive price. When $P_{max} = 50$ the optimal quality is α_{min}, which implies that offering an incentive is no longer economically attractive. For $P_{max} \geq 50$, however, operating a closed-loop system (remanufacturing without giving any incentive) yields a cost advantage over the open-loop system.

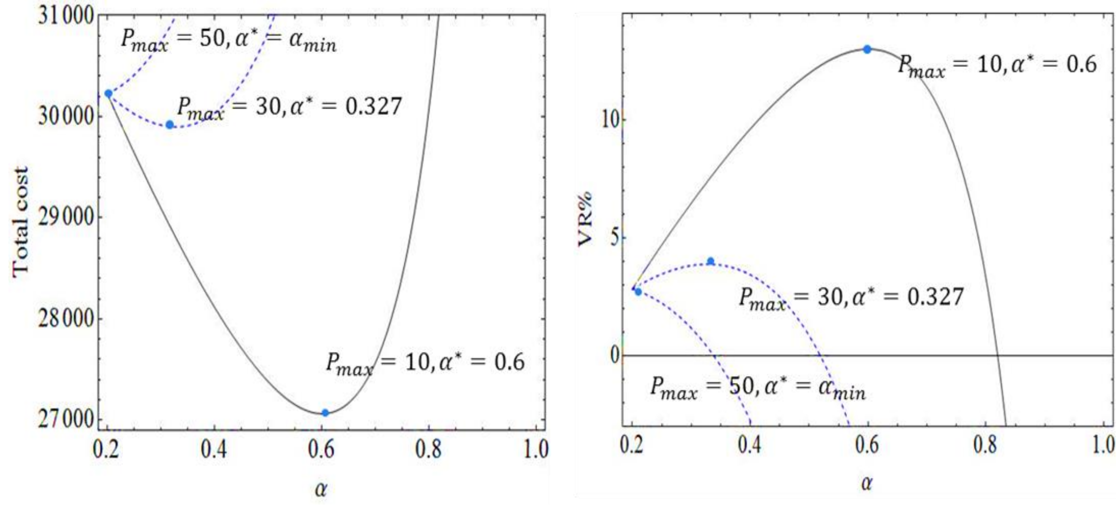

Figure 6—9: Impact of P_{max} on the optimal acquisition strategy and $VR\%$ when b=1.

6.3.4 Sensitivity analysis

In this section, we analyse the effect of changes in model parameters L, P_{max} C_R and b on the optimal quality level and cost saving from the remanufacturing. The ranges for these parameters are as follows: $P_{max} \in [10, 50]$, corresponding to the incentive price of acquiring the highest quality of used product; $C_R \in [30, 90]$, corresponding to a remanufacturing cost between 30% and 90% of the manufacturing cost; $L \in [1, 5]$, corresponding to a returns lead time from the beginning of the product life cycle; and $b \in [0, 3]$, corresponding to the price sensitivity of the acquisition cost, i.e. for $b = 0$ the acquisition cost is linear and for $b = 3$ it is monotonically increasing with respect to α .

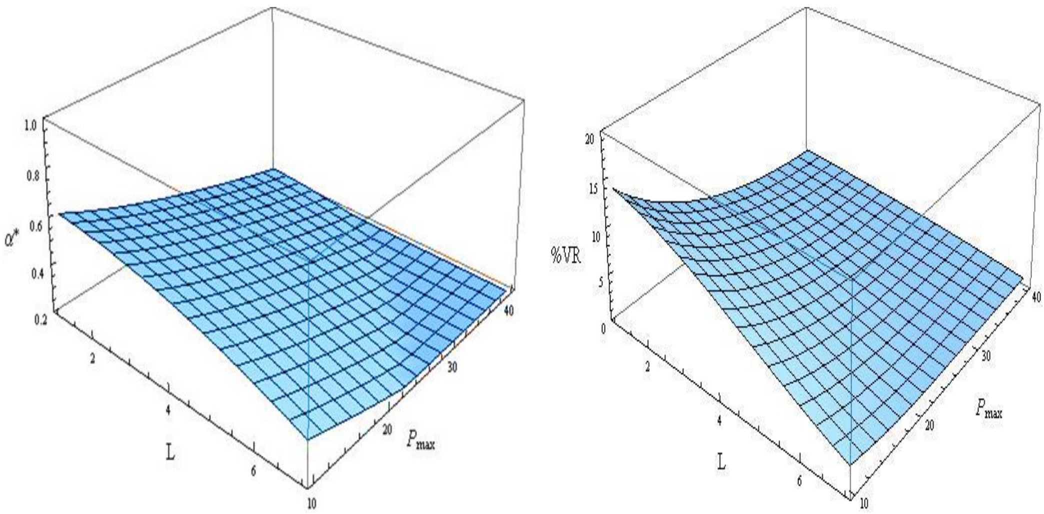

Figure 6—10: Impact of P_{max} and L on the optimal quality level (left) and the value recovery (right) when $0.2 \leq \alpha \leq 1;\ b = 1$.

Figure 6—10 illustrates the impact of changes in the returns lead time L and the incentive price P_{max} on the optimal quality level (left), and the cost saving from remanufacturing (right).

The impact of the incentive price on the cost saving becomes important when the returns lead time increases. When the returns lead time increases the market-driven strategy is economically attractive provided the incentive price is not expensive ($P_{max} < 20$). When both L and P_{max} are high we have $\alpha^* = \alpha_{min} = 0.2$, this suggest that the firm should operate remanufacturing without offering any incentive if it is to sustain a marginal saving over the open-loop system.

Figure 6—11 shows that when C_R increases, the difference between the cost of manufacturing a new product and the remanufacturing cost decreases; therefore the cost advantage of the market-driven strategy decreases. The impact of C_R becomes important when the returns are delayed in the system. For $L = 7$ and $C_R \geq 60$ the value recovery is negative ($\%VR \leq 0$), which implies that scrapping returns and satisfying the market demand by manufacturing new products is the optimal decision.

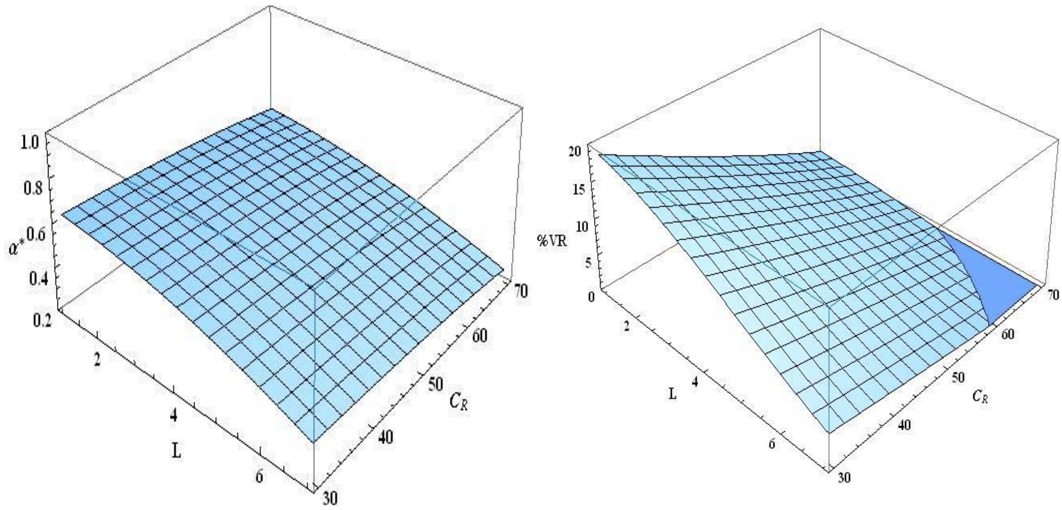

Figure 6—11: Impact of remanufacturing cost and the lead time on the optimal quality (left) and value recovery (right) when $0.2 \leq \alpha \leq 1$; $b = 1$.

Figure 6—12 shows that the maximum cost-saving is achieved when the acquisition cost is linear ($b = 0$). In this situation, acquiring returns with the highest quality level is beneficial, however as returns are delayed in the system, the cost advantage from remanufacturing decreases. On the other hand, the cost advantage of the market-driven strategy decreases when the marginal cost of acquiring a better quality of returns increases, i.e. remanufacturing without offering any incentive sustains a marginal cost saving for the firm.

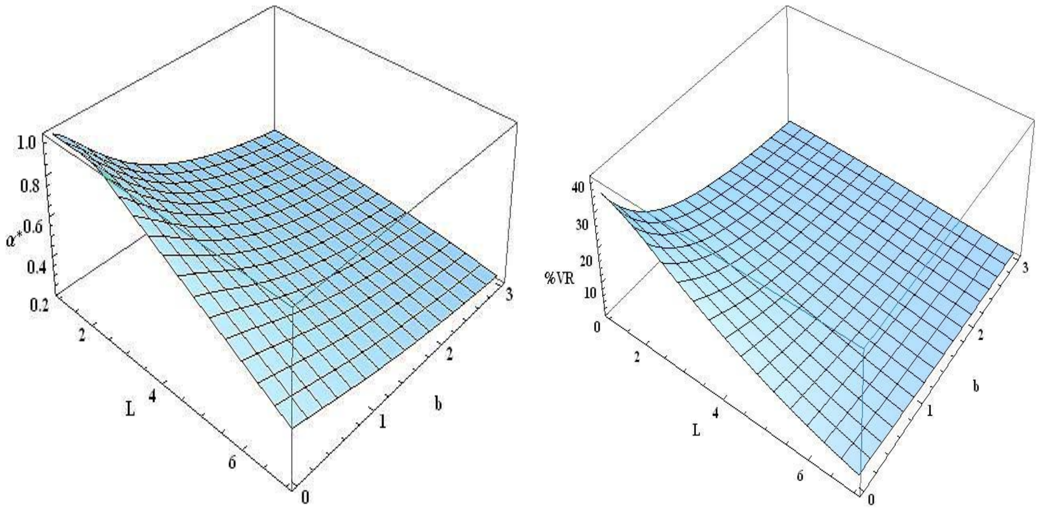

Figure 6—12: Impact of the price sensitivity of the acquisition cost (b) on the optimal quality level (left) and value recovery (right) when $0.2 \leq \alpha \leq 1$.

Finally, the returns rate is one of the key factors in the product acquisition decision. The returns rate can vary depending on product return policies and technological progress. Figure 6—13 shows that the highest cost saving from the market-driven strategy can be achieved when the return rate is high and used products arrive to the system earlier in the life cycle. It is clear that the potential cost saving from the market-driven strategy will be offset if returns are delayed in the system.

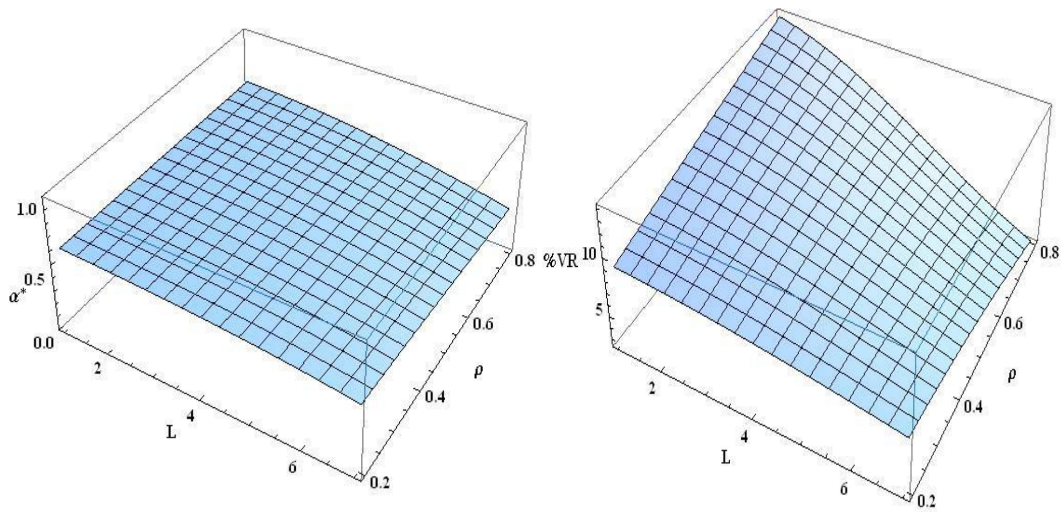

Figure 6—13: Impact of the return rate on the optimal quality level (left) and value recovery (right) when $0.2 \leq \alpha \leq 1$; $b = 1$.

6.4 Dynamic quality level for the remanufacturing operation

Section 6.3 investigated a situation where the firm applies a static acquisition policy for the planning horizon $t \in [0, T + L]$. This section investigates a dynamic policy where the firm can adjust the incentive price according to the product life cycle. Figure 6—14 shows the different regions of the planning horizon with unimodal demand and return patterns. It is easily seen that for $t \in [0, L]$ there are no returns in the system and all the demand has to be satisfied by manufacturing new products. Also, after the time T there is no demand in the market and hence all the returns need to be scrapped. Please see Table 6—1 for the summary of notations.

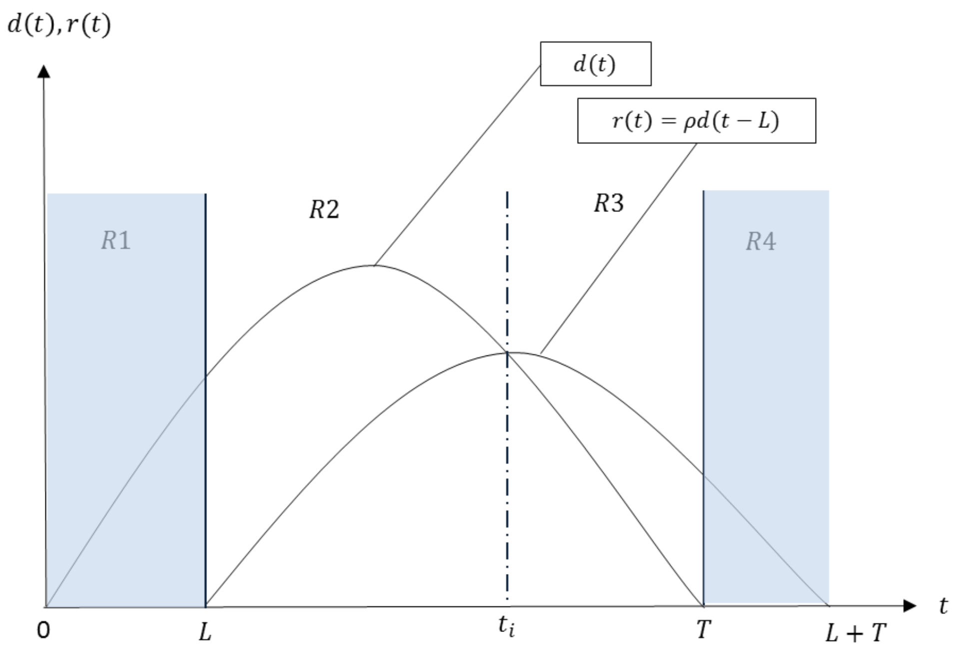

Figure 6—14: The product life cycle with unimodal demand and return pattern.

The objective, therefore, is to minimise the total cost of the market-driven strategy for the planning horizon $t \in [L, T]$. The problem is formulated as a constrained non-linear minimisation problem, as follows:

$$min\, TC_Q = \min_{X_N, X_R, X_S} \int_L^T (X_N(t)C_N) + (X_R(t)C_R) + ((X_S(t)C_S) + (r(t).\, C_T) + (r(t).\, P(\alpha))\ dt, \tag{6-31}$$

s.t.

$$X_N(t) + X_R(t) = d(t), t \in [L, T], \tag{6-32}$$
$$X_R(t) + X_S(t) = r(t), t \in [L, T], \tag{6-33}$$
$$X_R(t) - \alpha(t) r(t) = 0, t \in [L, T], \tag{6-34}$$
$$X_N(t) \geq 0, \tag{6-35}$$
$$X_R(t) \geq 0, \tag{6-36}$$
$$X_S(t) \geq 0, \tag{6-37}$$
$$\alpha(t) \in [\alpha_{min}, \alpha_{max}]. \tag{6-38}$$

The first constraint (6-32) ensures that demand can be satisfied both by manufacturing new products and remanufacturing returns, while the second constraint (6-33) reflects that all returns are either remanufactured or scrapped. Note that due to the unimodality of the demand and the returned products, and constant cost, it can be assumed that no inventory is kept in the system. Constraint (6-34) expresses that a fraction of the returns, $\alpha(t)$, that passes the quality test is remanufactured. It will, therefore, not be optimal for the firm to pay for returns that will not be remanufactured. The remaining constraints are non-negativity constraints for each of the variables.

The size of the problem can be reduced by using $X_N(t) = d(t) - X_R(t)$, $X_S(t) = r(t) - X_R(t)$ and $X_R(t) = \alpha(t)r(t)$. The equivalent optimisation problem will be:

$$\min TC_Q = \min_{\alpha} \int_{L}^{T} C_N\big(d(t) - \alpha(t)r(t)\big) + C_R\big(\alpha(t)r(t)\big) + C_S\Big(\big(1-\alpha(t)\big)r(t)\Big) + (r(t).C_T) + (r(t).P(\alpha))\ dt, \tag{6-39}$$

s.t.

$$-d(t) + \alpha(t)r(t) \leq 0, t \in [L, T], \tag{6-40}$$

$$-\big(1-\alpha(t)\big)r(t) \leq 0, t \in [L, T], \tag{6-41}$$

$$\alpha(t) \in [\alpha_{min}, \alpha_{max}]. \tag{6-42}$$

Due to the boundary condition we have $\big(1-\alpha(t)\big) \in [\alpha_{min}, \alpha_{max}]\ \forall t \in [L\ , T]$, therefore, $-r(t) < 0\ \forall\ t \in [L, T]$. It is easy to see that the constraint (6-41) is always satisfied and can be ignored. In order to solve the optimisation problem (6-39) we have to minimise a non-linear, convex function subject to linear constraints. Using the Lagrangian approach, the Lagrangian function can be defined as:

$$\mathcal{L}(\alpha(t),\lambda(t)) = \int_{L}^{T} \Big[C_N\big(d(t)-\alpha(t)r(t)\big) + C_R\big(\alpha(t)r(t)\big)$$

$$+ C_S\left(\big(1-\alpha(t)\big)r(t)\right) + (r(t).C_T) + (r(t).P\big(\alpha(t)\big)dt\Big]$$

$$+ \lambda(t)\big(-d(t)+\alpha(t)r(t)\big).$$

The objective function (6-39) is convex in α if the acquisition cost $P(\alpha)$ is convex[26] (the proof of the convexity of $P(\alpha)$ is shown in section 5.3.2). Due to the convexity of the objective function, the necessary and sufficient condition for optimality can be written as follows:

We first write the Lagrangians:

$$\frac{\partial\mathcal{L}}{\partial\alpha} = \int_{L}^{T} \big(-C_N + C_R - C_S + P'(\alpha)\big)r(t)\,dt + \lambda(t)r(t) = 0, \tag{6-43}$$

along with:

$$\lambda(t)\big(-d(t)+\alpha(t)r(t)\big) = 0\,, \tag{6-44}$$

$$-d(t)+\alpha(t)r(t) \le 0, \tag{6-45}$$

$$\alpha(t),\lambda(t) \ge 0. \tag{6-46}$$

Let $\bar{\alpha}(t) = \frac{d(t)}{r(t)}$, we can re-write (6-45) as:

$$\alpha(t) \le \bar{\alpha}(t). \tag{6-47}$$

---

[26] $\frac{\partial TC_Q}{\partial\alpha} = \big(-C_N + C_R - C_S + P'(\alpha)\big)r(t)$ and $\frac{\partial^2 TC_Q}{\partial\alpha} = P''(\alpha)r(t)$.

Now looking at (6-44) we first consider the case where $\lambda(t) = 0$ and $-d(t) + \alpha(t)r(t) \leq 0$, this yields:

$$\int_{L}^{T} \left(-C_N + C_R - C_S + P'\big(\alpha(t)\big)\right) r(t)\, dt = 0\,.$$

Since $(t) \geq 0 \;\forall\; t \in [L, T]$, the following equation should be solved for the optimal quality rate:

$$\left(-\, C_N + C_R - C_S + P'\big(\alpha(t)\big)\right) = 0. \tag{6-48}$$

Let $\hat{\alpha}(t)$ denote the solution of (6-48). Then $\hat{\alpha}(t)$ will be an optimal solution $\forall\, r(t)$ when $\hat{\alpha}(t) \leq \bar{\alpha}(t)$. Note that the optimal quality rate in this stage is based on the marginal cost of acquiring a higher quality of returns and thus a remanufacturing cost advantage. This is similar to what was observed in the infinite planning horizon model (section 5.3.4).

In the second case, $\lambda(t) > 0$, we must have $-d(t) + \alpha(t)r(t) = 0$, this implies $\alpha(t) = \bar{\alpha}(t)$.

$\bar{\alpha}(t)$ will then be an optimal solution if it also satisfies $\lambda(t) > 0$, where $\lambda(t)$ is computed using $\frac{\partial \mathcal{L}}{\partial \alpha} = 0$. From (6-43), we obtain:

$$\lambda(t) = -\frac{1}{r(t)}[\int_{L}^{T} \left[-C_N + C_R - C_S + P'\big(\bar{\alpha}(t)\big)\right] r(t)\, dt\,. \tag{6-49}$$

For $\lambda(t) > 0$ when $\alpha(t) = \bar{\alpha}(t)$, we must have:

$$P'\big(\bar{\alpha}(t)\big) \leq (C_N - C_R + C_S). \tag{6-50}$$

Note that $\hat{\alpha}(t)$ (as computed previously) solves $P'(\hat{\alpha}(t)) = C_N - C_R + C_S$. Thus we want $P'\big(\bar{\alpha}(t)\big) \leq P'(\hat{\alpha}(t))$ and $P''\big(\alpha(t)\big) > 0$ i.e. $P'\big(\bar{\alpha}(t)\big)$ is increasing in α, therefore (6-50) is satisfied when we have $\bar{\alpha}(t) < \hat{\alpha}(t)$.

Note that when $\frac{d(t)}{r(t)} \leq \alpha_{min}$, due to the boundary constraint (6-42), we have $\bar{\alpha}(t) = \alpha_{min}$ i.e. $\bar{\alpha}(t) = max\left[\frac{d(t)}{r(t)}, \alpha_{min}\right]$.

Looking at both cases above, we can summarise the optimal solution $\alpha^*(t)$ as follows:

$$\alpha^*(t) = Min\big[\hat{\alpha}(t),\ \bar{\alpha}(t)\big], \forall\ t[L\ ,T].$$

The optimal manufacturing-remanufacturing policy and acquisition cost are summarised in Table 6—3.

Table 6—3: The summary of the optimal manufacturing-remanufacturing policies.

	$0 \leq t \leq L$	$L \leq t \leq t_e$	$t_e \leq t \leq T$	$t_e \leq t \leq t_{min}$	$T \leq t \leq T + L$
X_N^*	$d(t)$	$d(t) - \hat{\alpha}(t)r(t)$	0	0	0
X_R^*	0	$\hat{\alpha}(t)r(t)$	$d(t)$	$d(t)$	0
X_S^*	0	$(1 - \hat{\alpha}(t))r(t)$	$r(t) - d(t)$	$r(t) - d(t)$	$r(t)$
$\alpha^*(t)$	0	$\hat{\alpha}(t)$	$\bar{\alpha}(t) = \dfrac{d(t)}{r(t)}$	$\bar{\alpha}(t) = \alpha_{min}$	0
$P(\alpha^*(t))$	0	$P(\hat{\alpha}(t))$	$P(\bar{\alpha}(t))$	0	0

The intersection point t_e represents the point of time where the returns that can be remanufactured are less than the demand, $(\hat{\alpha}(t)r(t) \leq d(t))$. This means that the firm has to pay the economic incentive $P\big(\hat{\alpha}(t)\big)$ to attract returns with the acceptable rate of $\hat{\alpha}(t)$ and the remaining demands should be satisfied by producing new products. Towards the end of the life cycle $\forall t \in [t_e, t_{min}]$, the number of products that are returned to the firm exceed the market demand. In this situation all the demand can be satisfied by the remanufacturing operation, i.e. firm should modify the incentive price to adjust the returns that can be remanufactured to the demand. Finally, for $t \in [t_{min}, T]$ it can be observed that $\frac{d(t)}{r(t)} \leq \alpha_{min}$, therefore $\alpha^* = \bar{\alpha}(t) = \alpha_{min}$. This implies that the remaining demand at the end of the product life cycle can be satisfied only by remanufacturing returns and it is not optimal to offer any incentive price to attract a better quality of returns. The optimal solution is presented in Figure 6—15.

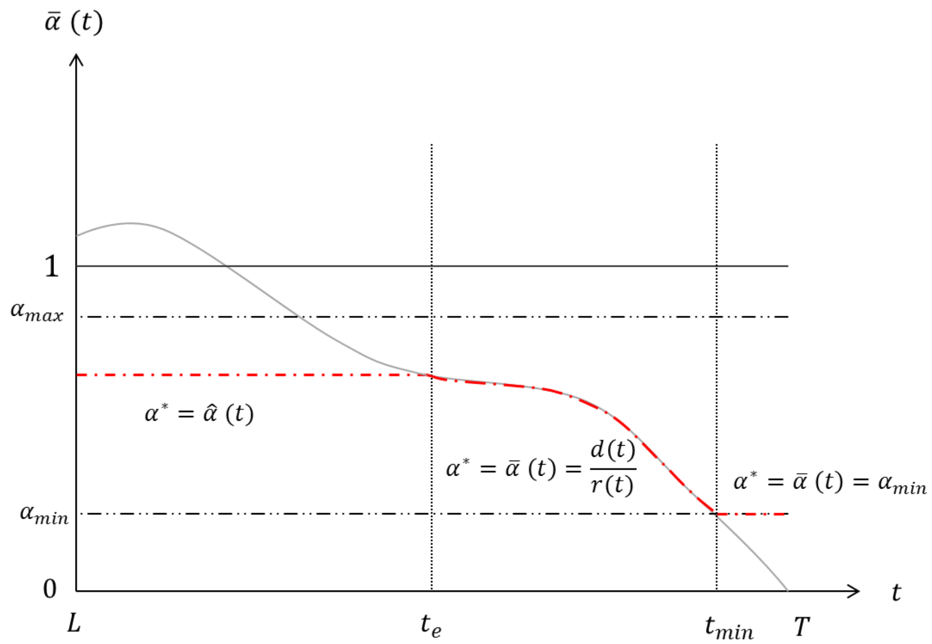

Figure 6—15: Illustration of the optimal solution for $t_e \in [L, T]$.

6.4.1 Numerical Examples

In this section these results are illustrated using two demand patterns.

Example 1. Using the previous example of a triangular decreasing demand and return profile and a base set of parameters similar to those in section 6.3.3

(*T=12; D=24; L=2;* $\rho = 0.8$*; b=1;* $C_N = 100$; $C_R = 40; C_S = 10; C_T = 10; P_{max} = 10; \alpha_{max} = 1; \alpha_{min} = 0.2$), for the demand and returns we get:

$$d(t) = 48 - 4t, \qquad t \in [0,12],$$

and

$$r(t) = 0.8.(48 - 4(t - 2)), \quad t \in [2, 14].$$

The marginal cost of acquiring a unit when $b = 1$ is $P'_{b=1}(\alpha) = \frac{P_{max}}{(\alpha_{max} - \alpha)^2}$. Replacing the corresponding values into (6-48) gives:

$$\left(-100 + 40 - 10 + \frac{10}{(1-\alpha)^2}\right) = 0.$$

Solving the above for α we obtain the value of the economic incentive, i.e. $\hat{\alpha}(t) = 0.622$. The corresponding intersection point t_e when $\hat{\alpha}(t) = 0.622$ can be calculated from $\hat{\alpha}(t_e) = \frac{d(t_e)}{r(t_e)}$. Therefore we have $0.622 = \frac{48 - 4t_e}{0.8.(48 - (t_e - 2))}$, which gives $t_e = 10.019$.

Now the intersection point t_{min}, when the minimum number of returns that can be remanufactured exceed demand, is calculated: i.e. $\alpha_{min} = \frac{d(t_{min})}{r(t_{min})}$. Hence $0.2 = \frac{48 - 4t_{min}}{0.8.(48 - (t_{min} - 2))}$, which yields $t_{min} = 11.619$. Using t_e and t_{min} it is possible to distinguish the following intervals:

For $t \in [2, 10.02]$ the firm has to pay the economic incentive to acquire the quality rate of $\alpha^* = \hat{\alpha}(t) = 0.622$. In this interval, the aim is to obtain the most economical quality of returns to satisfy more of the demand from the remanufacturing. The economic decision regarding the optimal quality rate in this stage is based on the marginal cost of acquiring a higher quality of returns and the remanufacturing cost advantage. In the interval $t \in [\, 10.02, 11.62]$, the firm gradually adjusts the incentive price to match those returns that can be remanufactured to the market demand, i.e. $\alpha^* = \bar{\alpha}(t) = \frac{d(t)}{r(t)}$. Finally, for $t \in [11.62, 12]$, we have $\alpha^* = \bar{\alpha}(t) = 0.2$. This implies that since the minimum number of returns that can be remanufactured returns exceeds demand, no incentive should be offered to obtain a higher quality of returns. The optimal policy in this interval is to operate remanufacturing without incentivising the market. A graphical illustration of the optimal quality rate and the corresponding acquisition cost for $t \in [2, 12]$ is presented in Figure 6—16 and Figure 6—17.

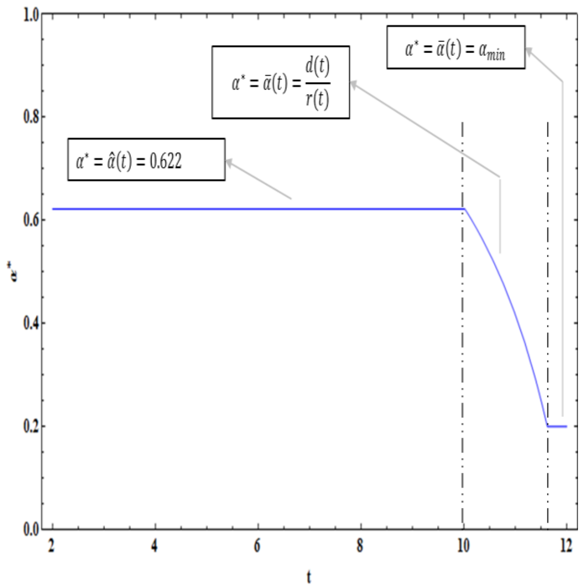

Figure 6—16: The optimal dynamic quality rate for triangular decreasing demand.

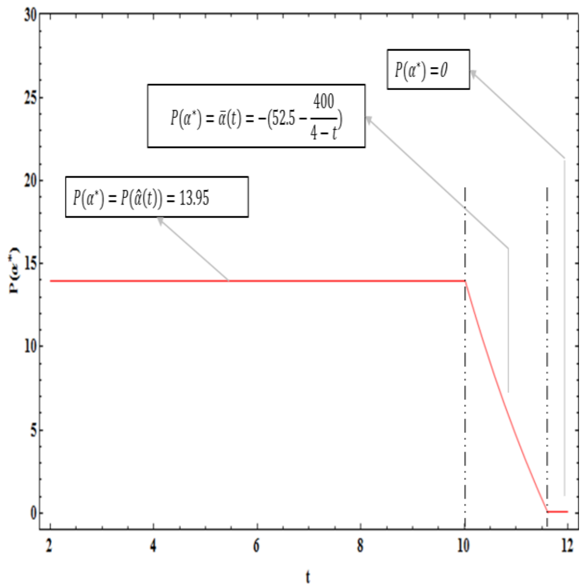

Figure 6—17: The dynamic optimal acquisition price for triangular decreasing demand

A comparison between the dynamic and static policy for manufacturing, remanufacturing and scrapping is shown in Figure 6—18. As was discussed in section 6.3.3, under the static policy, the minimum cost of the market-driven strategy is achieved by obtaining the optimal quality rate of $\alpha_{static} = 0.602, \forall t \in [L, T]$. In the dynamic policy, however, the firm offers different incentives in the planning horizon. As can be seen, the manufacturing and scrapping rate in the static policy is higher compared to the dynamic policy, while, the remanufacturing is higher when the firm applies the dynamic policy.

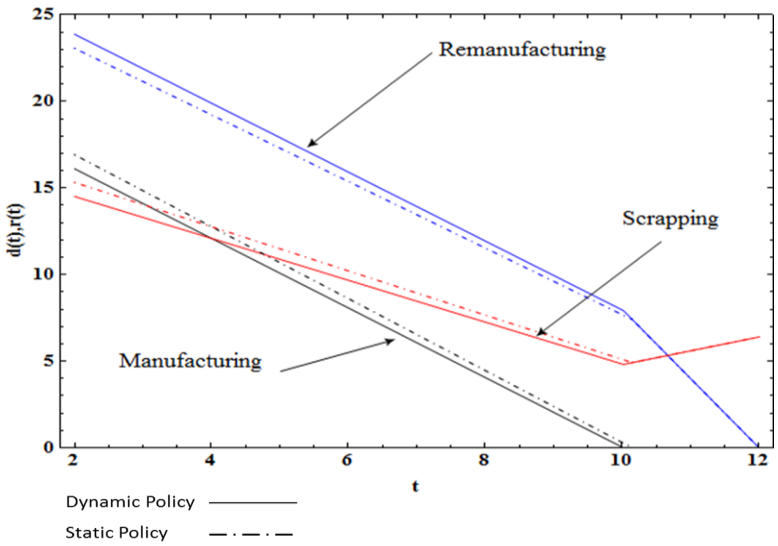

Figure 6—18: Comparison of manufacturing, remanufacturing and scrapping of dynamic policy with the static policy for the triangular decreasing demand for $b = 1$.

The optimal costs of the dynamic policy vs. static policy are shown in Table 6—4. The result clearly shows that the dynamic policy yields a lower cost compared to the static policy. It can also be seen that, although the acquisition cost of the dynamic policy is higher than the static, operating the dynamic policy nonetheless yields a lower cost. This is due to the fact that, in the dynamic policy, the remanufacture rate is higher than in static policy. This higher rate of remanufacturing necessitates a lower rate of manufacturing and scrapping, saving costs overall.

Table 6—4: Comparison between the operational costs of dynamic vs static policy for the planning horizon $t \in [0, T + L]$.

	Manufacturing cost	Remanufacturing cost	Scrapping cost	Testing cost	Acquisition cost	**Total cost**
Dynamic policy	15262	5414	950	2240	2976	26843
Static policy	15694	5242	994	2240	2893	27064

$D(t) = 288, t \in [0, 12]$ and $R(t) = 230.4, t \in [2, 14]$

Example 2. The following further investigates the dynamic policy using a bell shape demand and return profile, described as follows:

$$d(t) = \begin{cases} \frac{DT}{8} - \left(t - \frac{T}{2}\right)^2 & 0 < t \leq T \\ 0 & elsewhere \end{cases},$$

$$r(t) = \begin{cases} 0.8.\left(\frac{DT}{8} - \left(t - \frac{T}{2} - L\right)^2\right) & L < t \leq T + L \\ 0 & elsewhere \end{cases},$$

where *T=12; D=24; L=2;* $\rho = 0.8$.

The corresponding demand and returns are:

$$d(t) = 36 - (t - 6)^2 \qquad 0 < t \leq 12,$$

and

$$r(t) = 0.8(36 - (t - 8)^2) \qquad 2 < t \leq 14.$$

The demand and returns pattern are shown in Figure 6—19, below:

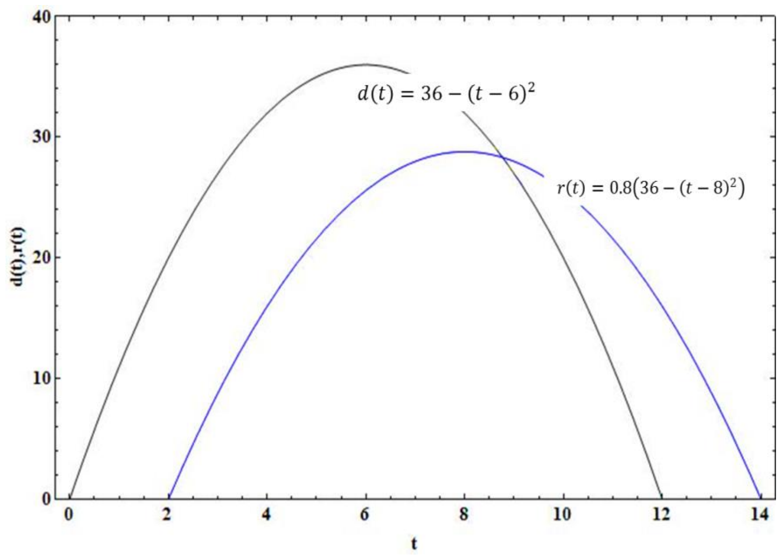

Figure 6—19: The unimodal bell shape demand and returns patterns

First, the optimal policy when the acquisition cost function is linear (i.e. b=0) is investigated, with the same base set of parameters as in the previous example ($C_N = 100$; $C_R = 40$; $C_S = 10$; $C_T = 10$; $P_{max} = 10$; $\alpha_{min} = 0.2$.) except for α_{max}, which is 0.9.

$\hat{\alpha}(t)$ is first calculated from (6-48). Since the acquisition cost function is linear and $\frac{P_{max}}{\Delta\alpha} - (C_N - C_R + C_S) < 0$, the total cost function is decreasing in α. This implies that the minimum cost of the market-driven $\forall t \in [L, t_e]$ is obtained when $\alpha^* = \hat{\alpha}(t) = \alpha_{max} = 0.9$. This in turn suggests that, for the interval of $[L, t_e]$, the firm should offer the maximum incentive price to increase the returns that can be remanufactured, where t_e can be obtained from $\alpha_{max} = \frac{d(t_e)}{r(t_e)} \rightarrow t_e = 9.38$. After the intersection point t_e returns exceed demand $\forall t \in [\, t_e, t_{min}]$, hence the incentive price should be adjusted to match the returns that can be remanufactured with demand. The optimal quality rate for this interval is $\bar{\alpha}(t) = \frac{d(t)}{r(t)}$, $t_e \leq t \leq t_{min}$, where t_{min} can be obtained from $\alpha_{min} = \frac{d(t_{min})}{r(t_{min})} \rightarrow t_{min} = 11.69$. This result is illustrated in Figure 6—20.

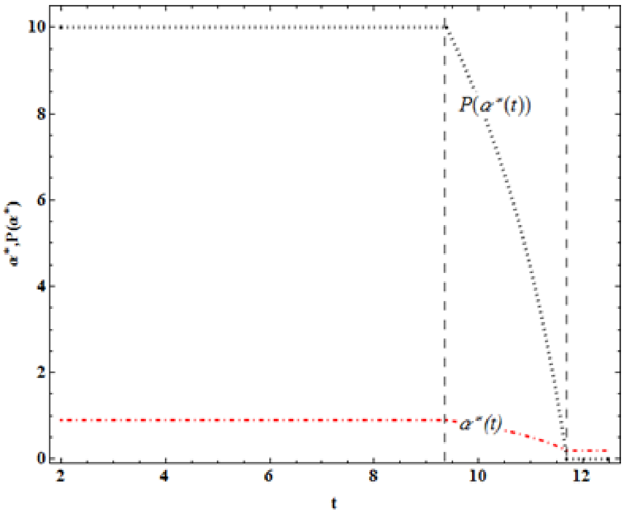

Figure 6—20: The optimal dynamic quality and the corresponding acquisition cost.

Giving the above optimal quality rate and intervals, it is possible to calculate the optimal manufacturing, remanufacturing and scrapping amount (according to Table 6—3). The results are shown in Table 6—5. As can be seen, for $t \in [0, 2]$ demand can only be satisfied by manufacturing new products, also for $t \in [12, 14]$ only those returns that arrive after the end of the product life cycle are scrapped. For $t \in [2, 9.38]$, more of the demand is satisfied by remanufacturing at a lower cost and fewer new products need to be produced. In the interval of $t \in [\, 9.38, 12]$ the remanufacturing rate is adjusted to the demand rate, but since the return rate is higher than demand scrapping increases.

Table 6—5: Optimal manufacturing, remanufacturing and scrapping policy.

	$0 \leq t \leq 2$	$2 < t \leq 9.3$	$9.3 < t \leq 11.7$	$11.7 < t \leq 12$	$12 \leq t \leq 14$	Total
$D(t)$	21.4	231.475	34.62	0.56	0	288
$R(t)$	0	154.24	53.8	5.25	17.06	230.4
X_N^*	21.4	92.65	0	0	0	114
X_R^*	0	138.82	34.62	0.56	0	174
X_S^*	0	15.42	19.2	4.69	17.06	56.4

Note that Total number of testing is equal to the total number of returns $(R(t))$ at each period of time.

The effect of delay in the acquisition of returns is shown in Figure 6—21. When $L = 2$ increases to $L = 2.5$ it can be observed that the amount of manufacturing and scrapping increases, while remanufacturing decreases. This effect is due to the decrease in t_e. For $L = 2.5$ the optimal quality rate is the same ($\hat{\alpha}(t) = 0.9$) but the intersection point t_e decreases to 9.23. This implies that the incentive price has to be adjusted earlier in the life cycle, i.e. the period during which the economic incentive $\hat{\alpha}(t)$ is offered is shortened. Furthermore, the delay will increase scrapping towards the end of the life cycle.

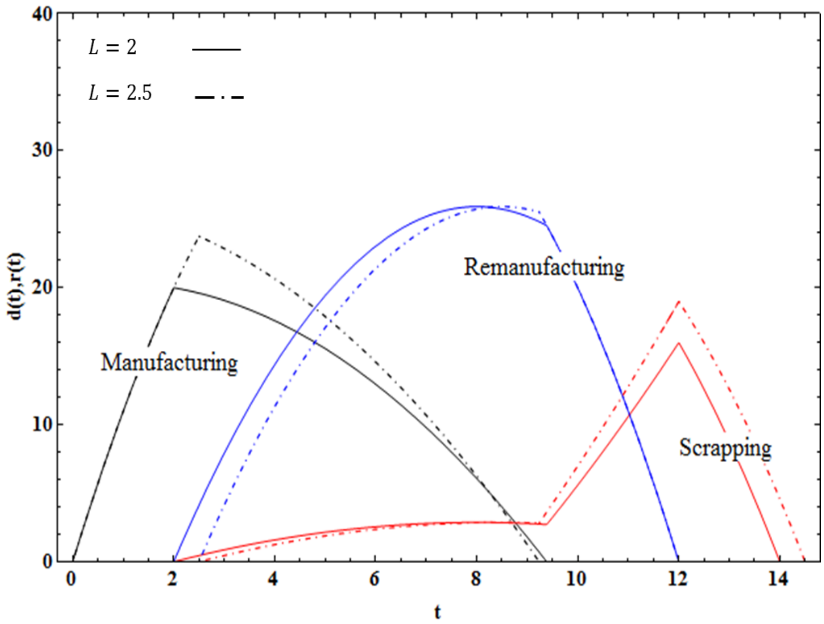

Figure 6—21: Optimal manufacturing, remanufacturing and scrapping for L=2 and L=2.5 when b= 0.

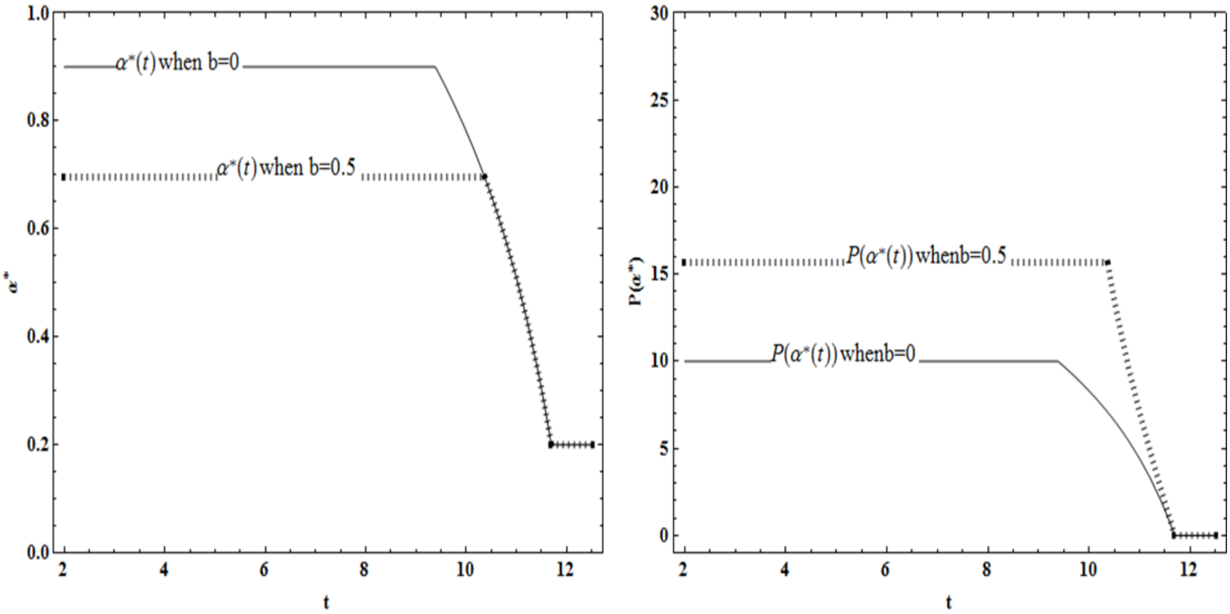

Figure 6—22: Impact of b on the optimal acquisition price.

Finally, the effect of the price sensitivity of the acquisition cost function is investigated when the value of b increases to 0.5. An increase in b implies that the marginal cost of acquiring a unit of return with a higher quality increases and hence it becomes more expensive to influence the returns quality. When $b = 0.5$ the economic quality rate is $\hat{\alpha}(t) = 0.69$, and the corresponding intersection point will be $t_e = 10.36$ (Figure 6—22). An increase in b leads to an increase in the acquisition cost, which leads to a decrease in the remanufacturing rate. This implies that the firm cannot afford to obtain the same amount of returns that can be remanufactured compared to the case when $b = 0$. In order to compensate for this decrease in remanufacturing, the firm has to increase the manufacturing of new products to satisfy the market demand. The impact of b on the optimal manufacturing-remanufacturing policy is illustrated in Figure 6—23.

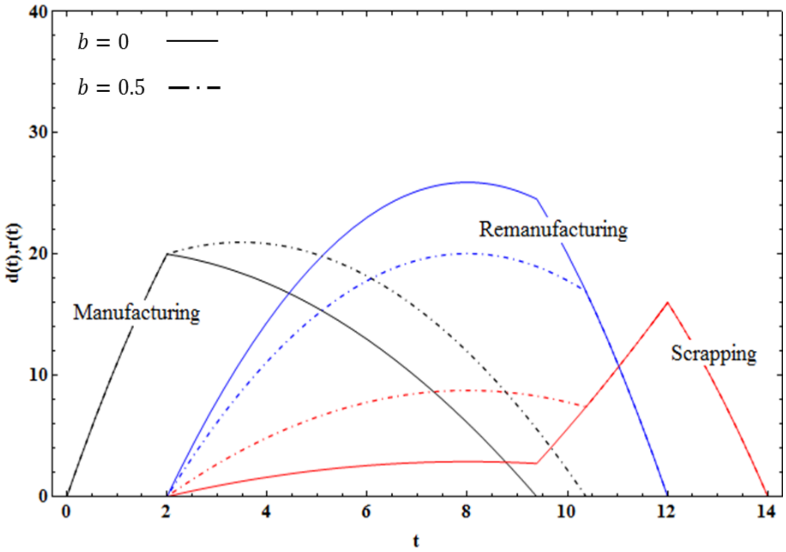

Figure 6—23: Impact of price sensitivity of the acquisition cost function on optimal manufacturing, remanufacturing and scrapping.

6.5 Conclusion

The manufacturing-remanufacturing decision clearly depends on used product quality and market demand. Hence, it is important to consider both factors when making a product acquisition decision. In this chapter the product life cycle has been used as a basis for balancing supply and demand, and the effect of used product quality and returns lead time on the firm's product acquisition decisions has been explored. Initially, a scenario was investigated in which the firm set a static acquisition policy over the planning horizon. This model was then extended to a dynamic case in which the firm adjusted the incentive price and acquisition strategy according to the different stages of the product life cycle. A number of insights have been presented that can be used in the different phases of the life cycle.

In general it was found that there is a breakpoint in the product life cycle where the supply of returns becomes greater than the demand for remanufactured products, as shown in Figure 6—2. This intersection point has a significant impact on the economic advantage enjoyed by remanufacturing operations. Before the intersection point, the ability to acquire the most suitable returns for remanufacturing is based on the marginal cost of acquiring a higher quality of returns and the remanufacturing cost advantage. After the intersection point, this becomes less important since the supply of used products increases, meaning that an important issue is to adjust the incentive price to acquire a sufficient quality of returns to satisfy demand.

According to the results of the dynamic strategy, at the beginning, the firm should offer the highest economic incentive in order to collect as many used products as possible; at this stage, prior to the intersection point t_e, not all demand can be satisfied by remanufacturing. Later in the product life cycle (after the intersection point t_e), however, the economic incentive should be stopped and the incentive price has to be adjusted to synchronise returns that can be remanufactured with demand. The point at which to stop the economic incentive can be greatly affected by different remanufacturing costs, returns lead times and life cycle characteristics (demand profile and life cycle length). Managers should try to synchronise return rates with demand rates, since doing so will lead to lower overall operating costs

Some additional conclusions can also be made based on this sensitivity analysis. The model highlights that the decision regarding the optimal acquisition strategy is mainly based on the relationship between the marginal cost of acquiring a better quality of used product, the remanufacturing cost advantage and the returns lead time. Operating the open-loop system (the passive strategy) is in general not optimal and firms can achieve cost savings through offering incentives and remanufacturing. It is also shown that the economic benefits of the market-driven strategy decrease when returns are delayed in the life cycle. This becomes a crucial factor, especially when the acquisition cost is high (e.g. products with high value that require a higher incentive price to obtain them). In this case, companies might need to reconsider the structure of their returns network in order to be able to act more responsively in processing the returns (see Guide et al., 2006; Mutha and Pokharel, 2009 on centralised and decentralised designs of a collection network). Furthermore, when the return rate is high (e.g. when firms have a liberal return policy) any postponement in processing returns will reduce the cost advantages of the proactive strategy.

Chapter7

Dynamic Remanufacturing Decisions with Multiple Quality Classes and Consideration of Quality Decay

7.1 Introduction

As discussed in Chapter 2, balancing demand and returns is one of the major drivers of economic viability for a remanufacturing system. In Chapter 6, the impact of balancing demand and returns on the product acquisition strategy has been explored in the presence of product life cycle and returns lead time. This chapter is concerned with dynamic manufacturing-remanufacturing and product acquisition decisions in a product recovery context. A different approach is used here to model a hybrid manufacturing-remanufacturing system and the quality of used products. Quality is modelled as a set of multiple predefined quality classes. This way the acquisition and remanufacturing cost needed to recover a particular returned product can be differentiated.

Dynamic models of pricing are extensively used in other research areas such as revenue management and marketing (Bitran and Caldentey, 2003; Yano and Gilbert, 2004; Elmaghraby and Keskinocak, 2003). In the reverse logistics literature, dynamic models are commonly used to address product recovery inventory control problems (Kleber et al., 2002; Minner and Kleber, 2001).

Market demand and supply of used products may be determined upon time dependent elements such as the product life cycle and seasonal effects (Kiesmüller et al., 2004; Minner and Kiesmüller, 2012). The economic advantage of remanufacturing operations is conditioned upon the quality of returns and end-users' returns behaviour that can be controlled by appropriate time-varying buy-back pricing. Therefore, a hybrid manufacturing-remanufacturing system may be defined as a dynamic control system upon predication of said elements. However, incorporating such dynamic elements in modelling requires a complicated analysis that may need to be carried out numerically (Simon, 1989; Kiesmüller et al., 2004).

Despite the advantages of dynamic models in capturing seasonal behaviour and life cycle patterns in product demand and returns, there are very few studies that apply dynamic models to investigate the product acquisition strategy (Xiong et al., 2014). This chapter is concerned with dynamic acquisition pricing assuming that demand cannot be influenced by pricing i.e. prices of new and remanufactured products are exogenously determined. This assumption is widely used in previous product acquisition studies (e.g. Minner and Kiesmüller, 2012; Cai et al., 2014; Xiong et al., 2014).

The integration of dynamic buy-back in a hybrid manufacturing-remanufacturing system has been studied by Minner and Kiesmüller (2012) under a single quality level and by Cai et al. (2014) with two quality levels. Different from these studies, the present model takes into account a rate of decay in the quality of products in the market. The inclusion of this dynamic aspect enables us to investigate the responsive acquisition policies for each quality class. Applying optimal control theory, this chapter develops a dynamic, continuous-time model that provides insights into the optimal acquisition price and quantity for a hybrid manufacturing-remanufacturing system.

The rest of the chapter is structured as follows. Section (7-2) describes the model and relevant assumptions. Section (7-3) states the necessary and sufficient conditions for an optimal solution based on the Pontryagin Maximum Principle. Section (7-4) illustrates the results through numerical examples. Finally, in Section (7-5) the summary of the main findings is presented.

7.2 Model description and assumptions

We consider a firm with a hybrid manufacturing-remanufacturing system (shown in Figure 7—1). The firm offers new and remanufactured products to satisfy the market demand $d(t)$. In our model the remanufactured products are referred to those products that are composed of both remanufactured parts and new parts (when it is necessary), while new products are manufactured using only all-new parts. The quality and performance of remanufactured products are equivalent to new products, and therefore both products can be served in the primary market to satisfy demand, i.e., we assume that the quality of remanufactured products is indistinguishable from their new counterparts.

Blending new and remanufactured parts is a common practise in many industries. For instance Xerox offers “new” and “newly manufactured” versions of their office equipment where newly manufactured products consist of a mixture of new and remanufactured parts (Xerox, 2010a). As reported by Atasu et al. (2010)

managers at Xerox believe that the newly manufactured products have the same quality as those equipment that are comprised of all-new parts. Hence, they are not differentiated in the market i.e. both can be sold in the primary market.

We consider three quality classes in market; 1) brand new products that consist of new and remanufactured products, 2) used product in good quality condition, and 3) used product in a bad quality condition. For the ease of notation, we ranked each quality classes as type 3, type 2, and type 1, respectively, in the remainder of this chapter. The acquisition of used product can only be done from quality type 2 and type 1, i.e., we assume that the customers do not return brand new products and it is not reasonable to buy-back brand new product from the market for the remanufacturing operation.

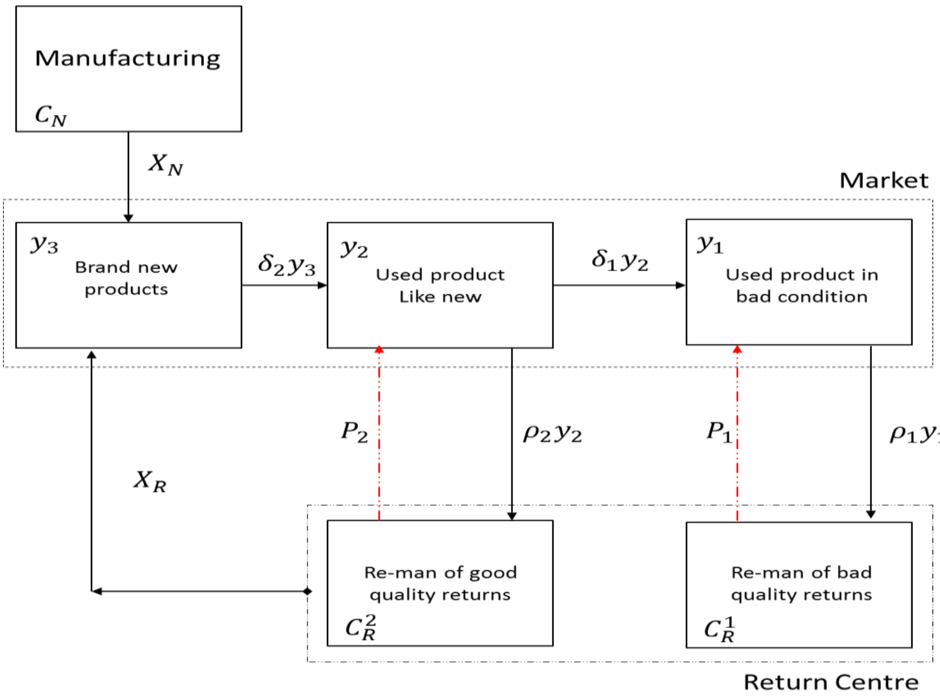

Figure 7—1: A hybrid manufacturing-remanufacturing system with different quality classes.

The states of the system are respectively denoted by $y_3(t)$, $y_2(t)$ and $y_1(t)$ which describe the amount of products of each quality type in the market. The constant values of δ_2 and δ_1 denote the transition rate in which the quality of each type decays.

Inclusion of the decay parameters δ_2 and δ_1 also enable us to capture the delay in the system. This type of delay is known as first-order continuous material delay (i.e. $Outflow = Material\ in\ transit/Average\ delay\ time$) which in our case average delay time is $\frac{1}{\delta_2}$ and $\frac{1}{\delta_1}$. Therefore, the decay parameters δ_2 and δ_1 can be interpreted as the inverse of average time that each product type spent in the states $y_2(t)$ and $y_1(t)$ respectively. Please note that in our model since products may spend different times in each state, a deterministic discrete delay that we introduced in Chapter 6 i.e., $Outflow\ (t) = inflow\ (t - Delay\ Time)$ is not appropriate. We refer the reader to (Sterman, 2000) for further explanation on delays.

The value of ρ_i denotes the fraction of customers of the total potential y_i that return their products. Thus total return of type i can be defined as $\rho_i y_i$.

To attract returns, firms offer financial incentives. The incentive price for a return of type $i, i = 1,2$ is denoted by P_i, and $f(P_i)$ denotes the corresponding return rate function as follows

$$\rho_i = f(P_i) = k_i^{-1} P_i + a_i \ , \qquad i = 1\,,2\,.$$

Where k_i denotes the price sensitivity of purchasing a used product of quality type i, and a_i represent the price-independent returns. Without loss of generality, in order to make a simpler description of the model we assume that $a_i = 0, i = 1, 2$. It is intuitively clear that purchasing a unit of return with high quality is more expensive than the purchasing a unit with lower quality condition i.e. $P_i < P_{i+1}, i =$

1. The assumption of a linear return response function is widely used in the remanufacturing literature (e.g. Galbreth and Blackburn (2006); Bakal and Akcali (2006); Minner and Kiesmüller (2012)). Also, the remanufacturing cost of high quality returns is less expensive than the remanufacturing a unit with lower quality i.e. $C_R^{i+1} < C_R^i, i = 1$. The notation used in this chapter is presented in Table 7—1.

Table 7—1: Notation summary.

$\mathrm{C_N}$	Unit manufacturing cost of a new product
C_R^i	Unit remanufacturing cost of returns of quality grade i, $i = 1,2$
$\overline{C_\iota}$	Remanufacturing cost advantage of returns of type i, $i = 1,2$
$y_i(t)$	Amount of products in the market of quality grade i, $i = 1,2$
$\delta_i(t)$	Quality decay for a return of type $i+1$, $i = 1,2$
$\mathrm{d(t)}$	Demand for product at time t
P_i	Acquisition price of the used product of quality grade i, $i = 1,2$
k_i	Price sensitivity of purchasing a used product of quality grade i, $i = 1,2$
$\rho_i(t)$	Returns rate of used product of quality grade $i, i = 1,2$
$X_N(t)$	Number of manufacturing new product
$X_R(t)$	Number of remanufacturing returns

The firm has to determine the optimal incentive price as well as the optimal manufacturing-remanufacturing quantity in order to minimise the total discounted[27] cost of operation over a finite planning horizon of length T.

$$\min_{X_N, X_R, P} \int_0^T e^{-\beta t}(C_N X_N(t) + C_{R2}\rho_2 y_2 + C_{R1}\rho_1 y_1 + P_2\,\rho_2 y_2 + P_1\rho_1 y_1)dt$$

It is obvious that it will not be optimal for the firm to buy-back used products that will not be remanufactured. Thus we have $X_R(t) = \rho_2(t)y_2(t) + \rho_1(t)\, y_1(t)$.

[27] In continuous-time models, a convenient way of calculating present values is by using the exponential discounting formula ($e^{-\beta t}$). This type of discounting is one of the most well-known discounting function that has been used in economics literatures (Samuelson, 1937)

Under the assumption that demand always has to be satisfied and cannot be backordered we can replace $X_N(t) = d(t) - X_R(t)$.

Using $P_1 = \rho_1 k_1,\ P_2 = \rho_2 k_2,$ and $X_N(t) = d(t) - X_R(t)$ the minimisation problem can be rewritten as

$$\min_{\rho_1,\rho_2} \int_0^T e^{-\beta t}\big(C_N d(t) + \rho_2 y_2 (C_{R2} + \rho_2 k_2 - C_N) + \rho_1 y_1 (C_{R1} + \rho_1 k_1 - C_N)\big) dt. \tag{7-1}$$

Where $\rho_1$and ρ_2 are the decision variables.

Let $\overline{C_2}$ and $\overline{C_1}$ denote the remanufacturing cost advantage of returns of type 2 and type 1, i.e., $\overline{C_2} = C_N - C_R^2 \geq 0$ and $\overline{C_1} = C_N - C_R^1 \geq 0$. Hence, we have $\overline{C_2} > \overline{C_1}$.

The minimisation problem (7-1) can be formulated as an optimal control problem over time period $t \in [0, T]$ as follows

$$\min_{\rho_1,\rho_2} \int_0^T e^{-\beta t}\big(C_N d(t) + \rho_2 y_2 (\rho_2 k_2 - \overline{C_2}) + \rho_1 y_1 (\rho_1 k_1 - \overline{C_1})\big) dt, \tag{7-2}$$

s.t.

$$\dot{y_3} = d(t) - \delta_2\, y_3\,, \tag{7-3}$$

$$\dot{y_2} = \delta_2\, y_3 - \delta_1\, y_2 - \rho_2 y_2, \tag{7-4}$$

$$\dot{y_1} = \delta_1\, y_2 - \rho_1 y_1\,, \tag{7-5}$$

$$d(t) - \rho_1 y_1 - \rho_2 y_2 \geq 0\,, \tag{7-6}$$

$$\rho_1(t) \geq 0, \rho_2(t) \geq 0. \tag{7-7}$$

The marginal increase in the state variable at time t is given by the first derivative of the state variable with respect to time ($\dot{y_i}(t) = \frac{dy_i(t)}{dt}$). The equations (7-3), (7-4), and (7-5) represent the associated movement of the states in the continuous time. Constraint (7-6) ensures that demand has to be satisfied at each point of time and cannot be backordered.

7.3 Analysis of the optimality condition

According to the Pontryagin's Maximum Principle (for details, see Chiang (2000); Kamien and Schwartz (2012)) the solution (7-2) is equivalent to the maximum of the corresponding current value static Hamiltonian function subject to the non-negativity constraints for each point in time. The Hamiltonian function $H(\rho_1, \rho_2, y_1, y_2, y_3, \lambda_1, \lambda_2, t) = H(.)$ for the maximisation problem is defined as

$$\begin{aligned} H(.) = -[C_N d(t) + \rho_2 y_2(\rho_2 k_2 - \overline{C_2}) + \rho_1 y_1(\rho_1 k_1 - \overline{C_1})] \\ + \lambda_1(\delta_1 y_2 - \rho_1 y_1) + \lambda_2(\delta_2 y_3 - \delta_1 y_2 - \rho_2 y_2) \\ + \lambda_3(d(t) - \delta_2 y_3)\,, \end{aligned} \tag{7-8}$$

where $\lambda_1(t)$ and $\lambda_2(t)$ are the adjoint variables to the movement of the state $y_1(t)$ and $y_2(t)$.

To show that the Hamiltonian is concave, we show that the Hessian is negative-definite. Where the Hessian matrix is computed as follows:

$$\mathcal{H}\ f(x_1, x_2, \dots, x_n) = \begin{bmatrix} \frac{\partial^2 f}{\partial x_1^2} & \frac{\partial^2 f}{\partial x_1 x_2} \cdots & \frac{\partial^2 f}{\partial x_1 x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial^2 f}{\partial x_n x_1} & \frac{\partial^2 f}{\partial x_n x_2} \cdots & \frac{\partial^2 f}{\partial x_n^2} \end{bmatrix}.$$

Therefore for the hessian matrix of Hamiltonian $H(.)$ we obtain

$$\mathcal{H}\ H(\rho_1, \rho_2) = \begin{bmatrix} -2k_1 y_1 & 0 \\ 0 & -2k_2 y_2 \end{bmatrix}.$$

Since the $\frac{\partial^2 f}{\partial \rho_1^2}$ and $\frac{\partial^2 f}{\partial \rho_2^2}$ are both negative and the determinants of $\mathcal{H}$ is positive, we can conclude that the Hessian is negative-definite and the Hamiltonian is concave. Maximizing (7-8) subject to constraint (7-6) can be performed using the Lagrangian approach. The corresponding Lagrangian function $\mathcal{L}(., \mu) = \mathcal{L}(..)$ is given by

$$\mathcal{L}(..) = H(.) + \mu\ (d(t) - \rho_1 y_1 - \rho_2 y_2), \tag{7-9}$$

where μ is the Lagrangian multiplier associated with the non-negativity constraint (7-6).

Maximisation of the Lagrangian (7-9), leads to the following equations:

$$\frac{\partial \mathcal{L}}{\partial \rho_1} = 0\ \rightarrow \rho_1^* = \frac{\overline{C_1} - \lambda_1 - \mu}{2k_1}, \tag{7-10}$$

$$\frac{\partial \mathcal{L}}{\partial \rho_2} = 0 \rightarrow \rho_2^* = \frac{\overline{C_2} - \lambda_2 - \mu}{2k_2}. \tag{7-11}$$

The adjoint variables $\lambda_1(t)$ and $\lambda_2(t)$ can be obtained using adjoint equation. For the overview of using the Pontryagin maximum principle we refer the readers to Seierstad and Sydsaeter (1986).

$$\dot{\lambda_1} = \beta\lambda_1 - \frac{\partial\mathcal{L}}{\partial y_1},$$

$$\dot{\lambda_2} = \beta\lambda_2 - \frac{\partial\mathcal{L}}{\partial y_2}, \tag{7-12}$$

$$\dot{\lambda_3} = \beta\lambda_3 - \frac{\partial\mathcal{L}}{\partial y_3}.$$

Using (7-10) and (7-11), the adjoint equations (7-12) can be rewritten as:

$$\dot{\lambda_1}(t) = -\frac{\overline{C_1}^2 - 4k_1\beta\lambda_1 - 2\overline{C_1}(\lambda_1 + \mu) + (\lambda_1 + \mu)^2}{4k_1}, \tag{7-13}$$

$$\dot{\lambda_2}(t) = -\frac{\overline{C_2}^2 - 4k_2\big(\beta\lambda_2 + \delta_1(\lambda_2 - \lambda_1)\big) - 2\overline{C_2}(\lambda_2 + \mu) + (\lambda_2 + \mu)^2}{4k_2}, \tag{7-14}$$

$$\dot{\lambda_3}(t) = \beta\lambda_3 - \delta_2(\lambda_2 - \lambda_3).$$

Along with the following transversality conditions

$$\lambda_1(T) = \lambda_2(T) = \lambda_3(T) = 0. \tag{7-15}$$

Furthermore, the following complementary slackness condition has to hold

$$\mu(t)\big(d(t) - (\rho_1 y_1 + \rho_2 y_2)\big) = 0\,, \mu(t) \geq 0\,, \tag{7-16}$$

with $d(t) \geq \rho_1 y_1 + \rho_2 y_2$ where (7-16) is the Kuhn-Tucker condition.

Let $(t) = \rho_1 y_1 + \rho_2 y_2$, and describe the total acquired returns from the market. If $d(t) - r(t) > 0$ the Lagrangian multiplier should be equal to zero ($\mu(t) = 0$). Otherwise (i.e. $d(t) - r(t) < 0$) $\mu(t)$ should be obtained by replacing (7-10) and (7-11) into $d(t) - \rho_1 y_1 - \rho_2 y_2 = 0$, that gives

$$\mu(t) = \frac{-2d(t)k_1k_2 + \overline{C_1}k_2y_1 + \overline{C_2}k_1y_2 - k_2y_1\lambda_1 - k_1y_2\lambda_2}{k_2y_1 + k_1y_2}. \qquad (7\text{-}17)$$

Thus, a solution to the equations (7-10), (7-11), (7-12) and (7-16), along with the boundary condition in (7-15) gives the optimal solution to our problem.

The solution to this boundary value problem is obtained by coding the problem in Mathematica 10.0. The optimal return rates (ρ_1 and ρ_2) are solved by iterating several times on $\mu(t)$ inside the 'NDSolve' function. Since $y_3(t)$ is independent of $\mu(t)$ it was moved outside the iteration process and computed exactly using 'DsolveValue' function. In the next section, we illustrate the results of numerical analysis using Mathematica 10.0 to find the optimal manufacturing-remanufacturing strategy.

7.4 Numerical investigation

In this section, we report the key findings of the numerical investigation and the effects of model parameters on the optimal manufacturing-remanufacturing and acquisition policy. The base set parameter settings for the numerical investigation are as follow:

The remanufacturing cost advantage for quality type 1 and type 2 are 0.3 and 0.8 respectively (i.e. $\overline{C_1} = 0.3$, $\overline{C_2}$ =0.8). The rate of quality decay for both type 1 and type 2 returns is 0.1 ($\delta_1 = \delta_2 = 0.1$). The price sensitivity of the returns response function for quality type 1 and type 2 are 20 and 22 respectively ($k_1 = 20$, $k_2 = 22$). Furthermore, the initial value of states of the system is 1000 units ($y_i(0) = 1000$). Finally, The discounted factor is $\beta = 0.01$, i.e. 1% continuous interest per unit of time.

We first illustrate our result using the following demand profile

$$d(t) = 4000 + 1000 \sin\left(\frac{2\pi t}{125}\right), \qquad t \in [0, 100].$$

where demand varies between 3000 and 5000 units, i.e. $3000 \leq d(t) \leq 5000$.

As Figure 7—2 illustrates in the beginning of the planning horizon i.e. $t \in [0, 60]$, there are not enough returns in the system for the remanufacturing operation and the market demand is mainly satisfied by producing new products. Later in the planning horizon i.e. $t \in [60, 100]$ the manufacturing rate decreases and market demand can be met by remanufacturing returns. Finally, for $t \in [95, 100]$ all the demand can be satisfied by remanufacturing operation.

Figure 7—3 shows that at the initial stage in the planning horizon, it is optimal to obtain high quality products for the remanufacturing operation i.e. $\rho_2(t)y_2(t) > \rho_1(t)y_1(t)$ $\forall t \in [0, 50]$). However, later in the planning horizon $\forall t \in [50, 100]$ it is beneficial to supply the remanufacturing operation with quality type 1. This result implies that when there are enough returns in the system, the higher remanufacturing cost of $\rho_1(t)y_1(t)$ is offset by the lower acquisition cost of quality type 1.

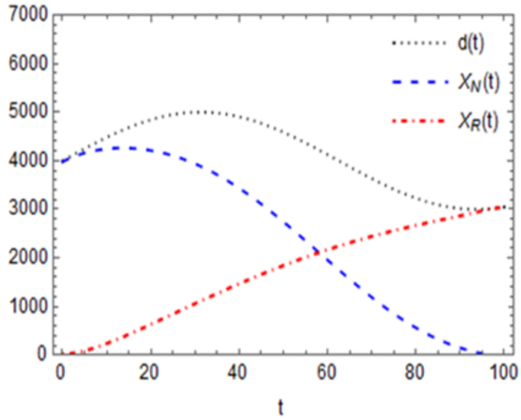

Figure 7—2:Optimal manufacturing-remanufacturing.

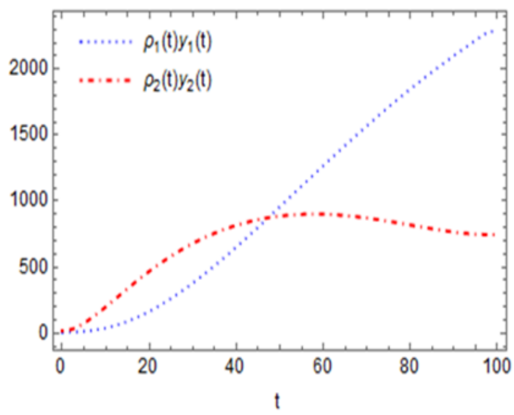

Figure 7—3: Optimal remanufacturing policy from quality type 1 and 2.

Figure 7—4a illustrates the impact of the remanufacturing cost difference between high quality and low quality returns on the optimal recovery policy. When the difference between $\overline{C_1}$ and $\overline{C_2}$ decreases, i.e. $\overline{C_1}$ increases to 0.7, a higher cost saving can be achieved from the remanufacturing operation. It is beneficial to offer a higher price incentive to increase $\rho_1(t)$. In addition, an increase in $\rho_1(t)$ means that the price incentive needs to be adjusted for $t \in [70, 100]$ in order to acquire only sufficient returns to satisfy the market demand (Figure 7—4b).

a. Optimal manufacturing-remanufacturing. b. Optimal acquisition price for quality class 1 and 2.

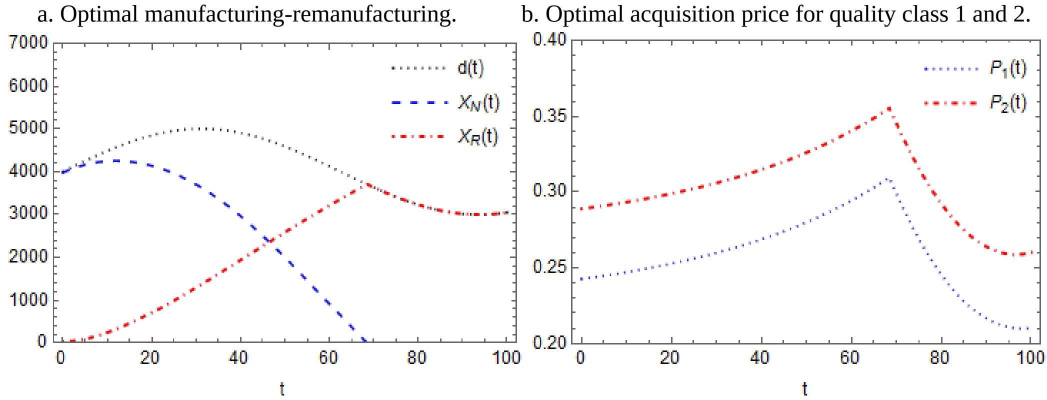

Figure 7—4: Impact of remanufacturing cost advantage on of the optimal manufacturing-remanufacturing and acquisition policy when $\overline{C_1} = 0.7$ and $\overline{C_2} = 0.8$.

Figure 7—5 shows the effect of the price sensitivity of the acquisition cost function when the values of k_1 and k_2 decrease to 17 and 22, respectively. A decrease in k_1 and k_2 implies that the market is less sensitive to the price incentive and therefore it becomes less expensive to influence the returns rate of quality type 1 and type 2. A decrease in k_1 and k_2 leads to a decrease in the acquisition cost, which in turn leads to an increase in the remanufacturing rate.

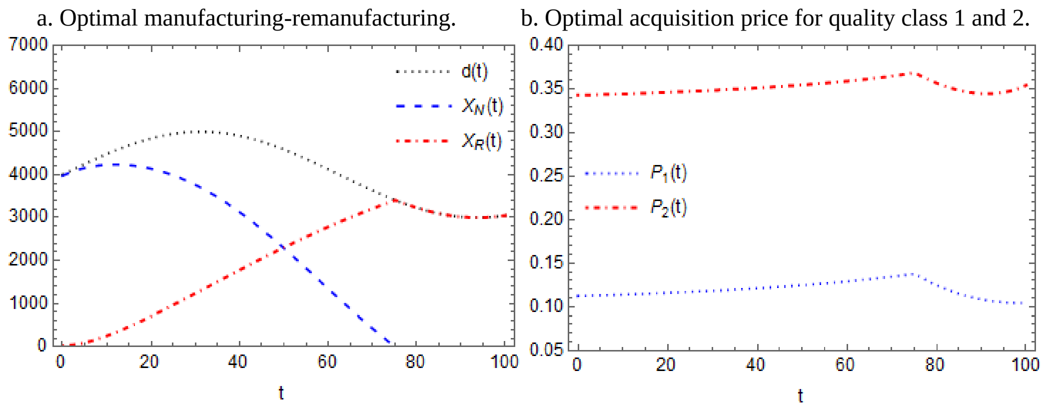

Figure 7—5: Impact of price sensitivity acquisition cost function on of the optimal manufacturing-remanufacturing and acquisition policy when $k_1 = 17$ and $k_2 = 22$.

Figure 7—6 illustrates the impact of the quality decay on the optimal acquisition policy. As we observe from Figure 7—6a when δ_2 and δ_1 are both low ($\delta_2 = \delta_1 = 0.1$), i.e. the rate of quality decay is slow, it is beneficial to buy-back more from quality type 2 and less from quality type 1 (Figure 7-6c). An increase in δ_1 , however leads to a decrease of type 2 acquisition and increase of type 1. This result implies that the lower cost of remanufacturing type 2 returns is offset by the high incentive price that is offered to attract returns, therefore leading to a decrease in the buy-back volume of quality type 2. In order to compensate for this decrease, the firm has to increase the buy-back of type 1 returns. When the δ_1 is fixed and low ($\delta_1 = 0.1$), an increase in δ_2 leads to an increase in the buy-back of both quality type 1and type 2. Figure 7-6c and Figure 7-6d show that the acquisition policy of quality type 1 is less sensitive to the decay parameters δ_1 and δ_2. Additional sensitivity analyses were performed for higher values of δ_1 and δ_2, and the resulting graphs exhibited patterns similar to the ones discussed, and are therefore omitted.

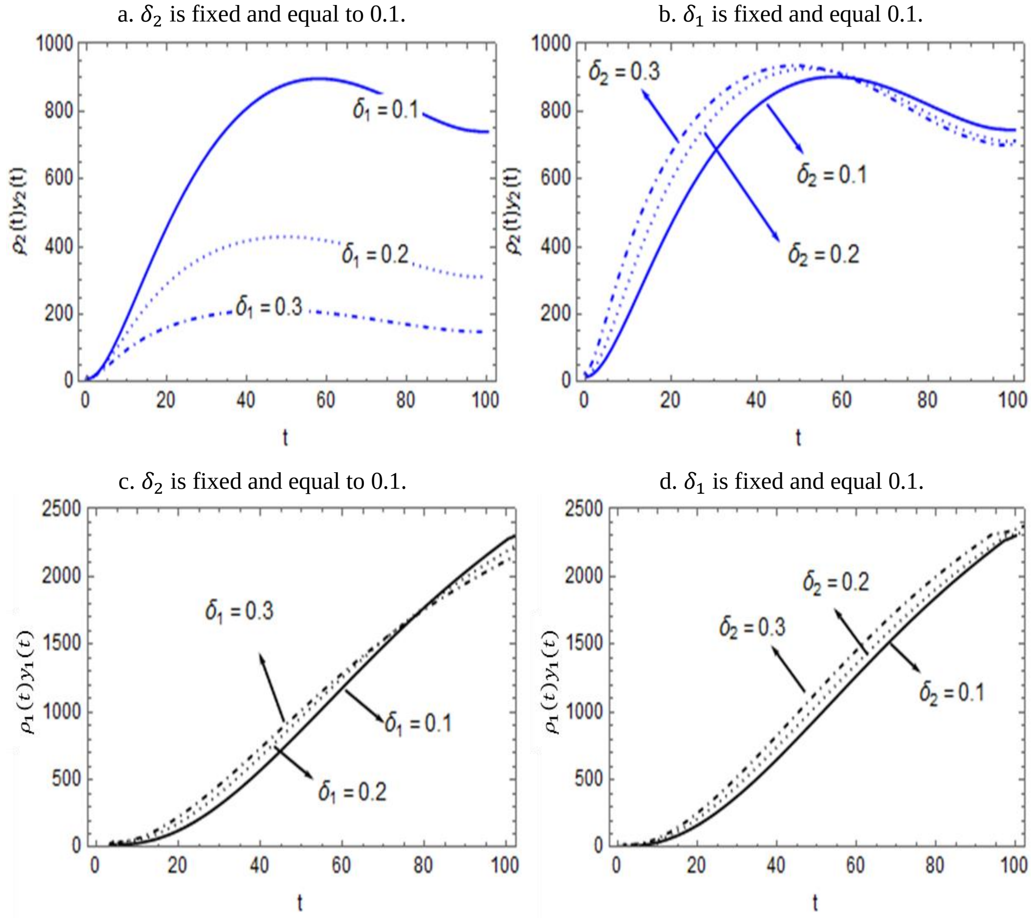

Figure 7—6: Impact of quality decay on the optimal acquisition policy of quality type 1 and 2.

Keeping the same base parameters, we investigate the impact of different demand pattern on the optimal acquisition and manufacturing-remanufacturing policy. Figure 7—7a illustrates that most fluctuations in demand are absorbed by the manufacturing new products, whereas remanufacturing exhibits a relatively stable trend. We also investigate the effect of the demand pattern on the optimal acquisition policy. Figure 7—7b shows that within the acquisition policy, most variations in the demand is absorbed by the acquisition of high quality of returns. It has to be noted that these numerical experiments were conducted for several sets of parameters. The insights obtained were by and large similar to those presented in this section.

a. optimal manufacturing-remanufacturing policy.

b. optimal acquisition policy.

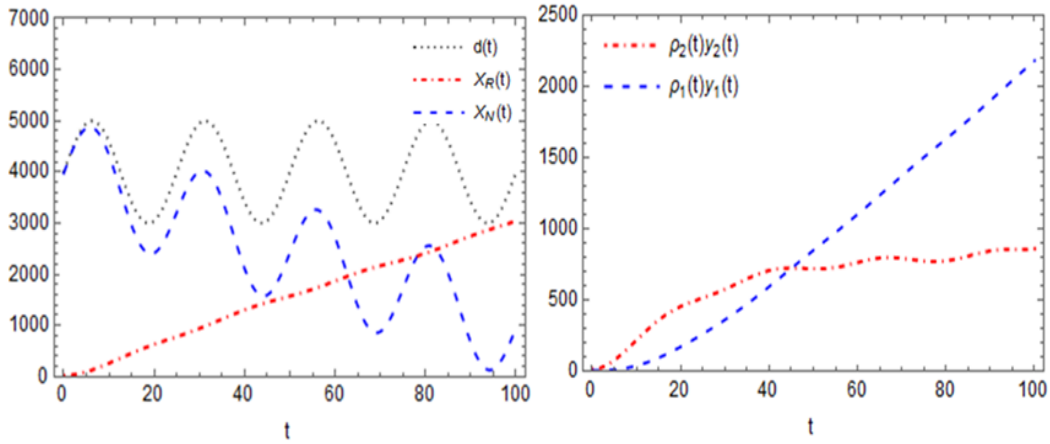

Figure 7—7: The effect of fluctuating demand on the optimal manufacturing-remanufacturing and acquisition policy.

7.5 Conclusions

This chapter have explored the dynamic manufacturing-remanufacturing and buy-back policy in a continuous time framework with a finite planning horizon. The model presented here enables the simultaneous choice of an optimal recovery and acquisition policy of returns in different quality classes. The dynamic model was formulated as an optimal control problem. Applying the Pontryagin's Maximum Principle, a set of necessary conditions for the optimal solution was derived. The analysis of the dynamic system results in a set of non-linear partial differential equations, which in our case are too complicated to obtain an explicit closed-form solution. Therefore, a numerical investigation has been used in order to obtain optimal policies.

The results from the numerical investigation show that the optimal manufacturing-remanufacturing policy depends on the price sensitivity of used product acquisition of both types of quality levels (i.e. low and high), as well as, on the manufacturing-remanufacturing cost difference.

The sensitivity analysis on the quality decay parameters show that in general it is beneficial to obtain a higher rate of high quality returns in the beginning of the planning horizon, and a higher rate of low quality returns towards the end of planning horizon. Furthermore, the intersection point in which the acquisition of low quality of retunes exceeds the acquisition of returns in good condition is postponed in the planning horizon when the overall decay rate is low.

Finally, the impact of demand fluctuation on the optimal manufacturing-remanufacturing and acquisition policy was investigated. The result suggests that most of the fluctuations in demand are absorbed by new product manufacturing and much less by remanufacturing. This implies that firms may require a responsive manufacturing system that is capable of responding rapidly to dynamic changes in market demand. Different from Cai et al. (2014) who reported that the acquisition of both low and high quality of returns have the same trend as the demand pattern, our result indicate that, within remanufacturing, it is the acquisition of the high quality returns that mirrors the variations in demand more than the low quality returns.

Chapter 8

Conclusions and Further Research

8.1 Summary and conclusions

The investigation in this study began in Chapter 1 by calling the attention to a need for a transition from a linear economy to a circular economy in order to maximise resource efficiency and minimise environmental damage. This transition is necessary since intensive industrial activities and material consumption have been causing severe environmental damage and resource crises (Towards The Circular Economy, 2013). In this regard, remanufacturing as one of the main recovery operations in the CLSC can indeed contribute to a circular economy. The aim of remanufacturing is to recover the remaining economic value of used products and bring them to “like new condition”. The variability in timing, quantity, and quality in the return flow of used products, however, imposes several challenges for a remanufacturing firm. Managing these variabilities is a key factor for having an efficient remanufacturing process.

The literature review (Chapter 2), has identified product acquisition management as an essential process in the CLSC, which aims to deal with the heterogeneous characteristics of product returns. The concept of product acquisition management was first formally introduced by Guide and Jayaraman (2000) and it has been attracting more and more attention only recently (Fleischmann et al., 2010; Souza, 2013). Product acquisition management is a key element of a market-driven strategy where financial incentives are given to encourage end users to return their products. From the literature review, it has been observed that there is a lack of research that investigates the economic attractiveness of the market-driven strategy under different costs settings (e.g. economies or diseconomies of scale of the acquisition cost, testing, scrapping, price incentive, etc.). In particular, it has been noted that the majority of assumptions about the relationships between the acquisition cost and return's quality/quantity are rather simplistic (Fleischmann et al., 2010). Since, the structure of the acquisition cost function is essential when investigating product acquisition strategy, it is imperative that research incorporate realistic cost structure (Souza, 2013). Furthermore, incorporating product life cycle aspects and returns lead time are important elements that have received very little attention in the context of product acquisition strategy.

The main objective of this study (as discussed in Chapter 3), was to develop quantitative models to generate meaningful insights in the context of product acquisition management. However, in order to be informed with current status of product acquisition management in practice and their relevant challenges, empirical case studies were conducted (in parallel to the quantitative modelling) at three remanufacturing firms in the U.K. The analysis of the case companies has indicated that economic reasons, environmental obligations and strategic advantages are the common motives among all the case companies to be involved in reverse logistics operations. Beside the challenges in managing the variability in product returns, other issues in closing the loop such as customer perception about remanufactured products and remarketing/reselling the remanufactured products were also identified as serious challenges for the firms in the UK.

The remainder of this section returns to the research objectives formulated in Chapter 1 in order to summarise the findings from the quantitative models (chapter 5-7)

Investigating the economics of market-driven strategies under quantity-based and quality-based incentives

In chapter 5 a novel acquisition cost function (in a form of a rational function) was introduced that can capture a more realistic relationship between acquisition effort and returns quantities/qualities. Utilising this acquisition cost function, chapter 5 has investigated the economic advantage of proactive (market-driven) strategies over the passive strategies (open-loop system). Within the proactive strategy two scenarios were investigated: first, when used products are unsorted and the testing and grading process occurs after the firm has received them, i.e. the quality of returns cannot be influenced by the firm. The second scenario assumes that quality can be influenced via offering quality–based incentives.

The analysis of the passive and proactive strategy have shown that operating the open-loop system (the passive strategy) is in general not optimal and firms can achieve cost savings through offering incentives and remanufacturing operation. However, the economic-oriented decision about operating the proactive or the open-loop strategy is affected to a great extent by the remanufacturing cost advantage and the acquisition cost structure. A diseconomy of scale in the acquisition cost leads to a decrease in the remanufacturing amount, with more new products having to be manufactured to satisfy the market demand. The results have shown that the cost saving from the market-driven strategy is counteracted to a certain extent when a high effort is needed to increase the collection rate. In this case, the attractive option from an economic perspective is the passive strategy i.e. scrapping of returns becomes more cost efficient despite the remanufacturing cost advantage.

The analysis of the quality–based incentive provides interesting insights regarding the relationship between the marginal cost of obtaining a used product with higher quality and the remanufacturing cost advantage. In this model, the decision regarding the optimal acquisition strategy is based on a trade-off between the remanufacturing cost and the acquisition cost. The quality-based model was further investigated with a more realistic remanufacturing cost, i.e. where both remanufacturing and acquisition costs are function of quality. The result of this scenario has indicated that, it is more economically attractive for the firm to offer a higher incentive price to obtain a better quality of returns. This implies that an increase in the acquisition cost for higher quality returns is counteracted by a lower cost of remanufacturing them.

Sensitivity analyses were performed to further explore the effect of the model's parameters on the optimal solution. The results of the sensitivity analysis have shown that when used products are unsorted and the testing and grading process occurs after the firm has received them, an increase in the cost of scrapping leads to a decrease in the optimal return rate and the economic advantage of the market-driven strategy. Interestingly, this effect is reversed when the quality of returns can be influenced by pricing decisions. In the latter case, it is economically attractive to increase the incentive price in order to obtain a higher quality of returns. This, of course, will increase the total cost of the market-driven strategy but still provide a cost saving for the firm since the total cost of the open-loop system also increases.

In addition, the sensitivity analysis of the quality-based model indicated that an increase in the testing cost does not affect the optimal quality rate. However, it leads to an increase in the total cost of the market-driven strategy which then leads to a decrease in the total cost advantage of the market-driven strategy over the passive strategy. This effect is different from what we saw in the quantity-based model. The impact of testing is particularly important in the quality-based model since the process of sorting/grading is effectively transferred to the suppliers of the used products (e.g. the collector). This implies that the uncertainty in the quality of returns should be reduced by the time they arrive at the remanufacturing facility. This result suggests that having a good inspection process prior to purchasing the used product is crucial factor. Failure to do this imposes complexities in testing and grading process and may lead to an increase in the cost of the operation, with a consequent impact on the remanufacturing decisions.

Investigating the optimal product acquisition decisions during the product life cycle

As discussed in Chapter 2, one of the major drivers of economic viability for a remanufacturing firm is balancing the product returns and demand (Östlin et al., 2009). In chapter 6, the product life cycle has been used as a basis for balancing supply and demand. Considering the product life cycle, Chapter 6 has investigated the effect of used product quality and return lead time on the firm's product acquisition decisions. Assuming a unimodal demand profile and constant return lead time, it was shown that there is an intersection point in the product life cycle where the supply of returns becomes greater than the demand. Before the intersection point, the ability to acquire the most suitable returns for remanufacturing is based on the marginal cost of acquiring a higher quality of returns and the remanufacturing cost advantage. After the intersection point, this becomes less important since the supply of used products increases, meaning that an important issue is to adjust the incentive price to acquire a sufficient quality of returns to satisfy demand. The results indicate that besides the impact of the remanufacturing cost advantage and the marginal cost of acquiring a better quality of used product, the decision regarding the optimal acquisition strategy highly depends on the returns lead time. This implies that any postponement in processing returns i.e. when returns are delayed in the life cycle will reduce the cost advantages of the proactive strategy. This becomes a crucial factor, particularly when the return rate is high (e.g. when firms have a liberal return policy) or when the acquisition cost is high (e.g. due to high value of the used products, high cost of transportation and packaging etc.). In this case, firm might need to reconsider the structure of their returns network in order to be able to act in a more agile manner in processing the returns.

In addition to the static acquisition policy, Chapter 6 investigates a scenario in which the firm applies a dynamic acquisition strategy according to the different stage in the product life cycle. The analysis of the dynamic acquisition strategy suggests that, at the beginning, the firm should offer the highest economic incentive in order to collect as many used products as possible; at this stage, prior to the intersection point not all demand can be satisfied by remanufacturing. Later in the product life cycle (after the intersection point), however, the economic incentive should be stopped and the incentive price has to be adjusted in order to synchronise remanufacturable returns with demand. The point at which to stop the economic incentive can be greatly affected by different remanufacturing costs, returns lead times and life cycle characteristics (demand profile and life cycle length). At the very late stage of the product life cycle depending on the firm's sorting policy for remanufacturing (e.g. the minimum quality level for remanufacturing operation), it is also possible that remanufacturing without offering any incentive becomes optimal. The results of the sensitivity analysis have shown that, although the acquisition cost of the dynamic policy is higher than the static policy, operating the dynamic policy provides a higher cost saving. This is due to the fact that, the dynamic policy yields a higher rate of remanufacturing compared to the static policy. This higher rate of remanufacturing necessitates a lower rate of manufacturing and scrapping. Thus, the higher cost of the dynamic acquisition is offset by the remanufacturing cost advantage.

Investigating dynamic remanufacturing systems and buy-back policies in the context of multiple quality levels and quality decay

Different from Chapter 5-6, Chapter 7 has investigated the dynamic manufacturing-remanufacturing system with multiple quality classes where the used product condition decays continuously over time. The dynamic model was formulated as an optimal control problem. Applying the Pontryagin's Maximum Principle, a set of necessary conditions for the optimal solution was derived. Due to the non-linearity in a set of partial differential equations, numerical experiments were used in order to obtain optimal policies.

The analysis from the numerical investigation has shown that the optimal policy is highly affected by manufacturing-remanufacturing cost difference and the price sensitivity of used product acquisition of both low and high quality returns.

The analysis on the quality decay parameters has indicated that in general it is beneficial to obtain a higher rate of high quality returns in the beginning of the planning horizon, and a higher rate of low quality returns towards the end of planning horizon. Furthermore, when the overall decay rate is low the intersection point in which the acquisition of low quality of retunes exceeds the acquisition of returns in good condition is postponed in the planning horizon.

Finally, the impact of demand fluctuations on the optimal policy has shown that the variability in demand is mainly taking care of by manufacturing new products and much less by remanufacturing returns. Furthermore, within the optimal acquisition policy, the result has indicated that it is the acquisition of high quality of returns that mirror the fluctuation in the demand, while the acquisition of low quality of returns illustrated a relatively stable trend.

8.2 Limitations and further research

This study concludes by pointing out the limitation of this present study and some of the important future research directions related to this work. This study has considered a hybrid manufacturing-remanufacturing system in which remanufactured products are perfect substitution for the new products. Although this assumption is widely used in the related literature and it is appropriate for some products such as toner cartridges (e.g. Company C) or office copier machines, relaxing this assumption and analysing market segmentation effects by considering two separate markets for new and remanufactured product with different selling price may be worth the effort for investigation. The inclusion of market segmentation can be insightful for Company B where the remanufactured products are sold at a lower price compared to new products. Extending the models by differentiating products in two partially overlapping markets with both price-conscious and quality-conscious customers can be a direction for future research.

In this study a novel acquisition cost function is proposed to capture the relationships between acquisition price and acquisition quantities/qualities. However, more detailed analysis and empirical work are needed to validate the acquisition cost function under different supply chain relationship. Perhaps a more general case in which both volume and quality are affected by price incentives would be a relevant case for further investigation. However, this arguably will add to the complexity of the model. It is also worthwhile to extend the analysis to cases where acquisition quantities are stochastic. Furthermore, in this study we focused on buy-back strategy as the main PA mechanism. However as mentioned in Chapter 2 a deposit and refund policy is another major type of supply chain relationships in a remanufacturing context. In cases in which the refunded deposit depends on the quality of the returned products (e.g. Company's A policy) the main trade-offs are twofold. The first trade-off concerns the amount of deposit (e.g. higher deposit may improve the return rate but it also reduces the sales volume). The second trade-off concerns the refunding amount based on the quality of returned products (a better quality classification increase the quality of returns but also increase the cost of sorting). These trade-offs are interesting topics for further investigation. Another interesting issue that deserves more attention is pairing the problem of quality classification with the inspection error (e.g. expensive and accurate inspection vs. inexpensive and less accurate inspection). Finally, the dynamic model presented in Chapter 7 can be extended to include leaks by introducing additional parameters for each state equation. The inclusion of leaks in the formulation of the problem will impact on the accumulation of used products in $y_1(t)$, but it may not influence the pricing strategy. Nonetheless, having leaks in the model can lead to interesting insights.

It has to be mentioned that some of the assumptions in this work are restrictive for the purpose of mathematical traceability and analytical treatment, so they may not reflect a real life settings appropriately. For instance, in many cases CLSCs include multiple recovery options to deal with product returns. In this study two recovery options have been considered. This can be extended to cases that include multiple recovery alternatives (e.g. remanufacturing, repair and scrapping) on a product, component, or material level. Accommodating features such as multi products, multi components, multi quality and uncertainty are more likely to be able to represent a realistic model. However, the presence of these features will lead to a complex decision making problem that may provide an isolated insight with a little connection to the larger business issues. It may be the case that the model discussed in this study may not be simply adopted by company to immediately solve its own particular remanufacturing issues. However the analysis in this study provides important insights regarding the product acquisition decision that can be useful in understanding the likely impact of different operational elements on the product acquisition decisions.

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Appendix I

Formulation of Optimal Control Problems

In optimal control problems, variables are divided into two classes, *state variables* and *control variables.* The state variable $x(t)$ changes over time according to the following differential equation:

$$\dot{x}(t) = g(x(t), u(t), t), \qquad x(0) = x_0 \; fixed,$$

where $x(t)$ is the state variable, $\dot{x}(t)$ is the first order derivative of $x(t)$ with respect to time t, and $u(t)$ is the control variable. The state variable can be controlled by changing the control variable $u(t)$, where the control variable $u(t)$ is usually constrained as follows:

$$u(t) \in \Omega(t), \qquad t \in [0, T],$$

with the control trajectory $u(t)$ on the interval $[0, T]$ and the initial state, i.e. $x(0) = x_0$, the state trajectory $x(t)$ over $[0, T]$ can be obtained. The aim is to choose the control $u(t)$ so as to maximise the following objective function:

$$\int_0^T f(x(t), u(t), t)dt,$$

Subject to

$$\dot{x}(t) = g(x(t), u(t), t),$$
$$x(0) = x_0 \; fixed, \qquad x(T) free.$$

where f is a function that measures the system benefit and f and g are assumed to be a continuously differentiable function in the planning horizon $[0, T]$[28].

[28] Sometimes, the following constraints should be considered:

Mixed inequality constraints $g(x(t), u(t), t) \geq 0$, $t \in [0, T]$, or pure constraints involving only state variables $h(x(t), t) \geq 0, t \in [0, T]$. Also the terminal state could be bounded in a set as $x(T) \in X(T)$.

Appendix II

Interview Questions

Overview

- What is the company's perception of reverse logistics and how important are product returns?
- What are the reasons which lead the company's interest and effort in handling the returned products?

Strategic issues

- What are the key strategic objectives of your company's reverse logistics, (can you list them from the most important ones to the least important ones)?
- Is your company affected by any environmental legislation? What are these legislations and how do they affect the company's reverse logistics operations?
- How does your company carry out the reverse logistics activities (e.g. in-house, out sourced)? If both, which one is out-sourced and which one is done in-house?
- Are the reverse logistics activities done centralised, decentralised or a combination of these two?

Product returns and challenges

- Can you please describe the types of returns arriving at the remanufacturing centre (e.g. end-of-use, end-of life, customer returns due to warranty or wrong/damaged deliveries, unsold products, or stock adjustment/over stock)
- Which type of returns creates the greatest flow of the overall return stream?
- Can you share (approximately) the volume of the product returns (and the value in £) per annum?
- How does the company recover the value of returned products? And what is the basis for making the decision?
- Does your company face any uncertainty in managing the returns? If yes which of these uncertainties are more challenging?
- How does the company manage the difficulties caused by these uncertainties?
- Apart from the uncertainties, is there any other major obstacle in managing the returns?
- Managing returns
- Can you please explain the whole process of the value recovery from the product acquisition stage to the stage where the product is ready for remarketing and reselling (i.e. product acquisition, reverse distribution, test/ sort/ disposition, refurbishment/ repair/ recycle, remarketing and reselling)?
- Among the above activities, which is the most difficult to manage and control? Are there any bottlenecks?
- In what stage(s) of the reverse logistics operations does your company carry out the quality inspection?

- Does the company have different quality standards that need to be met prior to the reconditioning?
- What is/are the key factor(s) that have the major impact on cost/profitability of the entire process? Are these factors related to the type of returns or recovery options?
- Can you estimate the time lag between launching a new product and the time when the returns occur?
- Can you estimate the lead time from acquisition of the used product to the time it is delivered back to the market?
- Can you estimate the cost of remanufacturing, testing and scrapping as a fraction of the cost of manufacturing?
- What is the target market for the reconditioned products? Does the company recondition used product to a single set of standards or there are different quality standards for reconditioned products?
- Could you please explain the typical product-life-cycle of your products? Does the return follow the same pattern of the product-life-cycle?
- Product Acquisition
- What is the company return policy? And how does the company acquire the used products from the market?
- Does the company apply different strategies to obtain the used products (e.g. offering financial incentives, trade-in policies, leasing, etc.)?
- What is the main objective of applying the above strategies (e.g. influence return rate, influence timing of return or obtaining better quality of returns)?

- Does the company follow any mechanism, tools or techniques to evaluate the amount of the incentive that is given to the market?
- What are the challenges in managing the product acquisition process?
- Does the company apply any specific model or method to facilitate the above process?
- What is the future for return products in the company? Will this grow in importance or not? And why?

Appendix III

The Calculation of the Optimal Quality Rate for Constant and Increasing Demand Profiles

- **Constant demand profile**

We first examine a simple case where demand and return are both constant over the planning horizon $t \in [0, L+T]$, as shown in Figure A- III-1.

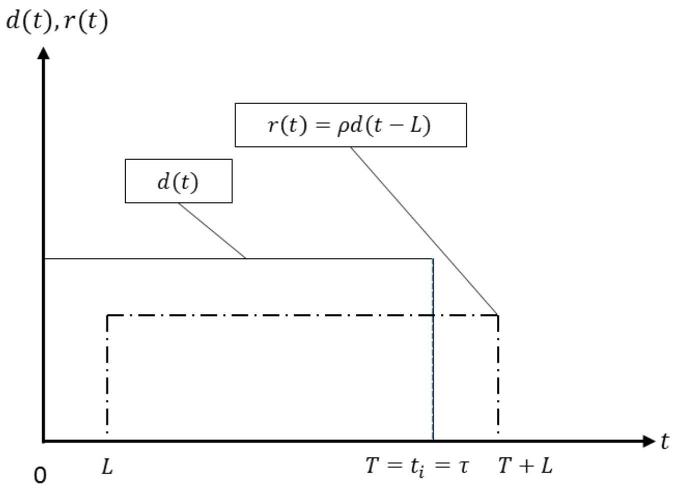

Figure A- III-1 Constant demand profile

In this situation we have:

$$\frac{D(T-L)}{D(T)} = 1 - \frac{L}{T}.$$

Replacing above into (6-21), gives

$$\alpha^* = \begin{cases} \alpha_{min} & \Delta\alpha < \dfrac{P_{max}}{(\,C_N - C_R + C_S)\left(1 - \frac{L}{T}\right)} \\ \alpha_{max} & \Delta\alpha \geq \dfrac{P_{max}}{(\,C_N - C_R + C_S)\left(1 - \frac{L}{T}\right)} \end{cases}.$$

When the firm faces a diseconomy of scale in the acquisition of returns (i.e. b=1) the optimal quality rate can be obtained from (6-24), which gives

$$\alpha^* = \alpha_{max} - \sqrt{\frac{P_{max}}{(\,C_N - C_R + C_S)\left(1 - \frac{L}{T}\right)}}.$$

- **Increasing demand profile**

The increasing demand profile can be completely described by its length *T* and the total demand *D* (Figure A- III-2).

$$d(t) = \begin{cases} \dfrac{2D}{T}t & 0 < t \leq T \\ 0 & elesewhere \end{cases}.$$

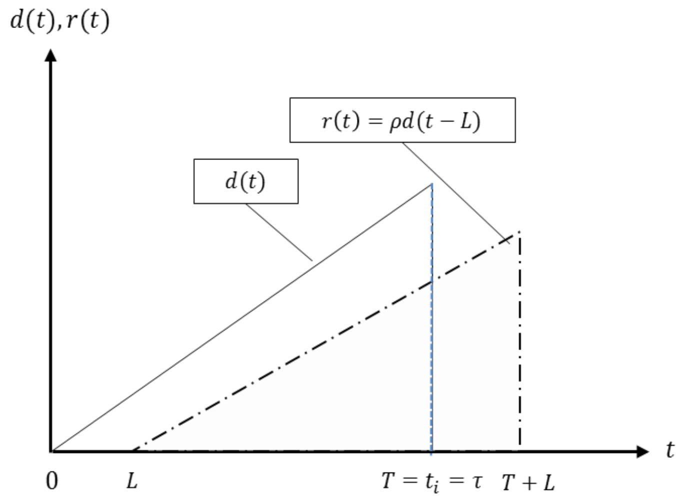

Figure A- III-2 Triangular increasing demand profile

Assuming a constant returns lead time L and a constant return rate ρ over time, the returns over the time is:

$$r(t) = \begin{cases} \rho.\left(\frac{2D}{T}(t-L)\right) & L < t \leq T+L \\ 0 & elesewhere \end{cases}.$$

For the given demand and return profile we have

$$\frac{D(T-L)}{D(T)} = \frac{(T-L)^2}{T^2}.$$

Replacing the above into (6-21) gives

$$\alpha^* = \begin{cases} \alpha_{min} & \Delta\alpha < \dfrac{P_{max}}{(C_N - C_R + C_S)\left(1-\frac{L}{T}\right)^2} \\ \alpha_{max} & \Delta\alpha \geq \dfrac{P_{max}}{(C_N - C_R + C_S)\left(1-\frac{L}{T}\right)^2} \end{cases}.$$

The optimality condition when b=1 can be obtained by replacing $\frac{D(T-L)}{D(T)} = \frac{(T-L)^2}{T^2}$ into (6-24), which gives

$$\alpha^* = \alpha_{max} - \left(\sqrt{\frac{P_{max}}{(C_N - C_R + C_S)}}.\frac{1}{1-\frac{L}{T}}\right).$$