OPTIMAL PRICING AND PRODUCTION STRATEGIES IN CLOSED-LOOP SUPPLY CHAINS WITH CONVEX RECOVERY COSTS, VARIABLE RETURNS QUALITY AND REMANUFACTURING LOSSES

by

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To my parents.

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Abstract

The management of remanufactured products has become an important issue for manufacturers because of the associated economic benefits and the sustainability legislation adopted by governments. Pricing strategy is a key factor in the remanufacturing process as it controls demand cannibalization between new and remanufactured products. This thesis proposes two models to investigate the optimal production and pricing strategies which maximize the total profit of an organization engaging in remanufacturing in a monopolistic environment. Both models are formulated to be more general than current models by incorporating a convex collection and inspection cost, sorting returns into two quality bins and considering remanufacturing losses. Utility theory is used to derive the demand functions according to the customers' tolerance for remanufactured products. The obtained convex programming models are solved to determine the optimal production and pricing strategies. Multiple sets of numerical examples are conducted to investigate the sensitivity of the optimal strategies.

List of Abbreviations Used

BTU	British Thermal Unit
CDC	Collection and Disassembly Center
EOL	End-of-Life
EOU	End-of-Use
KKT	KarushKuhnTucker
OEM	Original Equipment Manufacturer
WEEE	Waste Electrical and Electronic Equipment

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Chapter 1

Introduction

Closed-loop supply chain management is the combined management of both forward and reverse supply chain. According to Mina [35], the closed-loop supply chain can be defined as “the acquisition, distribution, and marketing activities involved in product returns/recoveries, source reduction/conservation, inspection, recycling, salvage, substitution, reuse, disposal, disassembly, refurbishment, repair, and remanufacturing”. From a business view, it can also defined as “the design, control, and operation of a system to maximize value creation over the entire life cycle of a product with dynamic recovery of value from different types and volumes of returns over time” (Guide Jr and Van Wassenhove [30]). Both definitions are consistent with the general structure of the closed-loop supply chain depicted in Figure 1.1 below.

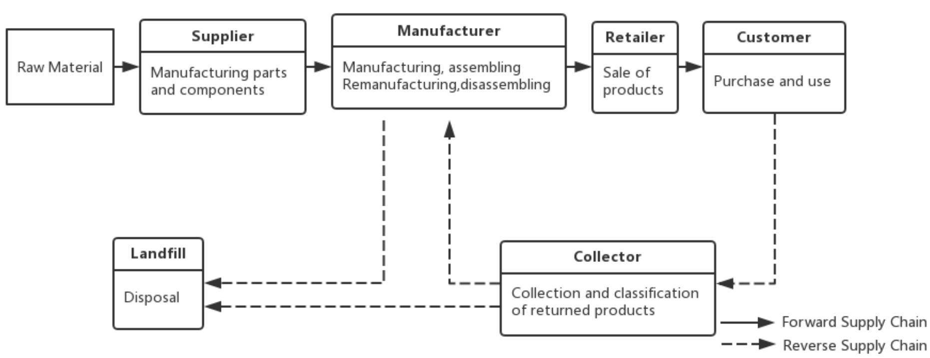

Figure 1.1: The structure of closed-loop supply chain

Over the past decade, closed-loop supply chain management has attracted more attention from both the researchers and companies. Many companies have extended their business into this area in order to maximize their profit and meet the requirement of different kinds of customers. For example, HP Inc., one of the world’s biggest computer manufacturer has offered a service called “HP Renew Program” for selling remanufactured computers with the same quality, warranty as new ones, and lower price (Wu [58]). Lexmark, a well-known printer company, offers a 15% discount on some toner cartridges if the customers agree to return the used ones to the company (Hong et al.[37]). The reasons for these initiatives can be classified into four groups.

Firstly, the increasing environmental awareness of customers leads them to be more willing to buy green products. According to a survey from Bemporad and Baranowski [4], more than two-thirds of consumers surveyed in the United States said that they would buy environment-friendly products and more than half said they would be willing to pay more for it. Moreover, in 2008, over three-fourths of Europeans reported that they bought green products although more expensive (Eurobarometer [17]). Remanufactured products constitute a large and important type of the green products. According to Webster and Mitra [56], the business of remanufactured products has already saved about 120 trillion of energy and 14 millions tonnes of raw materials every year globally. As a result, remanufactured products can attract a large number of customers and bring significant profit to companies involved in these activities.

Secondly, legislation and regulations, such as the Waste Electrical and Electronic Equipment (WEEE) initiative in Europe or the regulation on the administration of the recovery and disposal of waste electrical and electronic products in China, are forcing manufacturers to take responsibility for their end-of-life (EoL) or end-of-use (EoU) products. As a result, under these laws and regulations, some companies have no choice but to invest in the collection and remanufacturing of their products.

Thirdly, the cost of producing remanufactured products is lower than the cost of manufacturing new ones. According to Giutini and Gaudette [26], the cost of producing a remanufactured product is usually 40% to 65% lower than producing a new product. This low cost of remanufactured products allows remanufacturing companies to expand their market share, by setting low prices for their remanufactured products. This can attract customers with low valuations for the low-end market to purchase the remanufactured products and bring substantial gains to the company.

Fourthly, remanufacturing can be seen as a corporate social responsibility program, due to its benefits to the environment. Corporate social responsibility is defined by Khoury et al. [39] as "the overall relationship of the corporation with all of its stakeholders. These include customers, employees, communities, owners/investors, government, suppliers and competitors. Elements of social responsibility include investment in community outreach, employee relations, creation and maintenance of employment, environmental stewardship and financial performance". According to Bhattacharya and Sen [5], customers prefer to purchase products from or invest in a company which has a high corporate social responsibility. As a result, engaging in remanufacturing activities can improve the social responsibility and bring significant benefits to organizations.

Setting the price for new and remanufactured products is a critical issue for remanufacturing companies because of the cannibalization between new and remanufactured products in the same market. The functionality of remanufactured products is usually as good as new ones. So it can attract price sensitive or green customers, who planned to buy new products, and as a result damage the revenue of new products. Our article investigates how to set the prices for new and remanufactured while ensuring that optimal profit is attained. The main goals of this article are:

- To explore the optimal price strategy for new and remanufactured products by building the price model of the remanufacturing process with consideration for the customers' tolerance for remanufactured products, different quality of returned products, the losses in the remanufacturing process and the convex collection and inspection cost.

- To find the optimal production strategy by determining the conditions under which the firm should engage or not in remanufacturing activities.

- To investigate the influence of different parameters on the pricing strategy adopted by the company for new and remanufactured products. Parameters to be analyzed include the customers' tolerance for remanufactured products, the quality of the returned products, the losses in the remanufacturing process, and the collection and remanufacturing costs.

The remainder of this thesis as follows. Chapter 2 presents a comprehensive review of the literature related to the pricing problem in closed-loop supply chains. In chapter 3, we develop two mathematical models for determining the optimal pricing and production strategy for new and remanufactured products. Multiple sensitivity analyses are conducted in chapter 4 as well as extensive discussions of the analytical and numerical results obtained from the model. The general conclusions, limitations of the models and suggested area of future research are mentioned in chapter 5.

Chapter 2

Literature review

In the past decade, the closed-loop supply chain problem has become an important area of academic research. Several comprehensive reviews have already been proposed (see Atasu et al. [1], Guide Jr and Van Wassenhove [30], Souza [52], Steeneck and Sarin [53], Govindan et al. [27], Kumar and Ramachandran [40]).

Atasu et al. [1] provide a critical review of analytic research about the remanufacturing problem from a business economics perspective. Relevant researches are classified into four streams: industrial engineering/operations research, design, strategy, and behavioral. For each stream, the following review briefly lists the assumptions made in each paper and discusses their conclusions.

Guide Jr and Van Wassenhove [30] focus on the evolution of the research on the value recovery of returned products. Five phases are identified: focus on only remanufacturing process, valuing the reserve supply chain, coordinating the reserve supply chain, combining the forward and reserve supply chain and focusing on the price and market of both new and remanufacturing products. Their paper shows a development of the research from a narrow, technically focused area, to a wide subfield of supply chain management.

Souza [52] classifies the research issues into three levels: strategic, tactical, and operational. Strategic issues include the network design, collection issues, supply chain coordination and others. Tactical issues cover the decisions about the acquisition of returned products and how the companies deal with them. Operational issues focus on the production/scheduling plans, priority rules and other factors affecting the actual remanufacturing process.

Steeneck and Sarin [53] review pricing models for new and remanufactured products starting from basic economic ones such as Ferrer [20] to more advanced ones that account for lifecycle, marginal cost of products and other factors. They conclude that there are very few models where the unit remanufacturing cost depends on the quantity processed.

Kumar and Ramachandran [40] discuss papers dealing with revenue management in the remanufacturing industry. It is suggested that the right decisions about quantity, price and market segment of remanufactured products must be made in order to obtain the maximal profit. The authors classified the literature into three groups based on the different issues dealt with: product-related issues, supply chain-related issues, and mathematical formulation-related issues.

In this thesis, we will deal with the pricing problem in the remanufacturing process. The following chapter will present a literature review on pricing models published in the past two decades. We will use a classification similar to the one proposed by Kumar and Ramachandran [40].

- manufacturing process issues,
- market issues and,
- modeling issues.

Table 2.1 outlines secondary issues corresponding to each of these three main issues.

2.1 Manufacturing process issues

In this section, remanufacturing process issues are reviewed. These issues mainly appear in the products acquisition process and the following remanufacturing process.

Main issue	Secondary issue
Manufacturing Process	Product types
	Remanufacturing process
	Lifecycle
	Product design
	Reverse channel
	Quality of returned products
Market	Market type
	Market size
	Customer behavior
	Advertisement
Modeling	Time horizons
	Centralized or decentralized supply chain
	Deterministic or stochastic problem
	Modeling method

Table 2.1: Issues discussed in the literature review

2.1.1 Product types

It is critical for companies engaging in remanufacturing to clearly define their production strategy: produce only remanufactured products or both new and remanufactured products. Decisions made by the company can affect the pricing model and the cannibalization between new and remanufactured products. For example, if a company decides to produce both new and remanufactured products, the cost of obtaining raw materials and manufacturing new products have to be considered in the model. But these cost are not considered when the company produces only remanufactured products. This may affect the demand function of the products in the model.

Liang et al. [42] develop a pricing model for returned products. Their model only considers remanufactured products and the related logistics and remanufacturing cost. Using the geometric Brownian motion approach, the authors analyze the relationship between the price of the returned products and estimated sale price for the remanufactured products.

He [33] extends Liang et al. [42] research to a supply chain setting. The cost of producing remanufactured products and purchasing extra raw materials from the supplier are considered. The paper determines the optimal acquisition price of the returned products and the optimal remanufactured decision in the context of both deterministic or stochastic demands.

Ferrer and Swaminathan [22] study the price of new and remanufactured products in the one-, two-, multi- or infinite-period planning horizon cases. They consider the collection and production cost of the new and remanufactured products. Moreover, they analyze and obtain the optimal price strategy for the firm according to the different remanufacturing savings. They conclude that if the remanufacturing process is highly profitable, the company may sacrifice profit in early periods by offering more new products with a low price in order to obtain more returned products in later periods.

In this thesis, we consider producing new and remanufactured products in either one- or two-period time horizons. The proposed models account for the collection and inspection cost, remanufacturing cost, and manufacturing cost.

2.1.2 Remanufacturing process

The first research question is usually: how is the remanufacturing done? It is often considered that firms want to produce both new and remanufactured products. In some articles, the dismantling and remanufacturing processes are discussed together. For example, the returned products can be used to produce remanufactured products, or can be dismantled/shredded and used as raw material for manufacturing new products. This action can decrease the cost of manufacturing new products. In this situation, the production of remanufactured products may also influence the cost of producing new product, so the company should control the production quantities and sometimes the demands of either new or remanufactured products in order to obtain the maximum profit.

Ferguson et al. [18] present models for finding the best disposition policy for electronic manufacturers. In their model, the returned products can be used for remanufacturing or dismantled. If a returned product is dismantled, it may be used to avoid the penalty cost for buying new parts from the suppliers to make new products.

The demand for new and remanufactured products are stochastic and the price of the remanufactured products is an important decision variable. The optimal remanufacturing and dismantling policy is found in the case of the single period model, when the returned products can be dismantled into several useful parts. For the multi-period model, they consider that dismantling a returned product will yield one single aggregate part. In both models, the study finds that finding the right quantity of returned products to be remanufactured and how many to dismantle for parts can significantly enhance profitability. Furthermore, harvesting spare parts may be beneficial for products with the long lifecycles.

Guo et al. [31] extend Ferguson et al.[18] by proposing a dynamic multi-period remanufacturing model where returned products can be dismantled to obtain more than one useful parts (two parts in the paper). Analysis of the optimal policy shows that when the inventory of parts is high or the number of remanufactured products in the inventory is low, the company should focus on the remanufacturing task and produce more remanufacturing products if they are profitable.

The second question usually considered is how to characterize the parties involved in the remanufacturing activities. It is often about the business environment and competition in particular. Sometimes, only the original equipment manufacturer (OEM) can produce remanufacturing products. In addition, third-party companies may engage in remanufacturing as well when they collect returned products and produce their own remanufactured products. This situation is usually seen with products such as disposable cameras or printer cartridges (Ferrer and Swaminathan [21]). However, compared with third-party companies, the OEM usually takes advantage of their brand recognition, which means that customers prefer products remanufactured by the OEM to the ones from the third-party, when they are at the same price. As a result, pricing of the new and remanufactured products can impact both the OEM and third-party companies in terms of the demand and revenue.

Ferguson and Toktay [19] present a model in the duopoly situation and analyze the competition between the OEM and a third-party remanufacturer. A key result is that, even though producing remanufactured products may not be profitable for the OEM, OEM should not forgo that option in order to prevent third-party remanufacturers from entering this business, which may seriously cannibalize the revenue of the OEM. The authors then present and analyze two optimal policies to prevent third-party companies from entering into the market: one recommends to the OEM to do the remanufacturing job itself and the other is to have the OEM collect the returned products without actually doing the remanufacturing.

Ferrer and Swaminathan [21] study the pricing problem for new and remanufactured products in a competition environment. The OEM only produces new products in the first period and in the second period, it can make either new, or remanufactured, or both products according to the profit. The third-party remanufacturer can collect the remaining returned products and produce only the remanufactured products. Besides obtaining the optimal pricing policy for both the OEM and the third-party, the effects of different parameters in the Nash Equilibrium are also investigated. The authors find that in order to compete with the third-party remanufacturer, the OEM prefers to lower the price of remanufactured products and to utilize all available cores (i.e., starving the third-party).

In our article, we develop our models under the assumption that the process of producing new and remanufactured products are independent. In other words, the collection of returned products does not influence the cost of manufacturing new products. We focus on the pricing problem for a monopolist, who can produce remanufactured products.

2.1.3 Lifecycle

Lifecycle management is a challenging task in the presence of both new and remanufactured products in the market due to the fact that they may impact each other's life cycle. Moreover, the length of the lifecycle, which depends on the diffusion rate and potential repeat purchase rate of the products, controls the number of remanufactured products. If a product is returned at the end of its life cycle, it has little potential for remanufacturing. So products with very short lifecycle (e.g., fashion items) do not usually have many remanufactured ones on the market. Furthermore, the mix new/remanufactured products on the market varies during the lifecycle. In the early period of the products' lifecycle, the company can only produce new products because of the lack of returned products. However at the end of the products' lifecycle, the company may only produce remanufactured products in order to make good use of cores of returned products or used products collected by the company or clear the inventory. In order to sell different kinds of products in the different periods and obtain maximal profit, the prices for new and remanufactured products also vary over the lifecycle.

The work of Debo et al. [14] is one of the first studies to account for lifecycle as an issue in the management of remanufacturing products. In their paper, they extend the Bass diffusion model and get the joint price of the new and remanufactured products in the different periods of their lifecycle. In each period, the demand of new and remanufactured products changes according to the diffusion rate of products, the potential repeat purchases, the price of products and many other factors in different time period. According to the study, products with low diffusion rate are more suitable for remanufacturing and capacity investment should be higher with fast diffusion and a high repeat selling rate.

Robotis et al. [47] extend the work of Debo et al. [14] by investigating the optimal leasing price and leasing duration decisions by a monopolist when the production and servicing capacity are constrained. In their research, except for the factors discussed in the Debo et al. [14], Robotis et al. also consider the periodic preventative maintenance of the leased products, which guarantees that there is no breakdown during the leasing period. Through their analysis, they obtain the conclusion that if the product lifecycle is long and remanufacturing saving is low, the firm should offer a shorter leasing duration. However, if the remanufacturing savings are high, the firm should offer a higher leasing duration.

San Gan et al. [49] study the optimal prices for new and remanufactured products with short lifecycle in a closed supply chain. They divide the lifecycle of the products into four periods. In the first period, the manufacturer only produces new products. In the second and third periods, it produces both new and remanufactured products. The difference is that, in the second period, the new products are in the introduction-growth-maturity phase (the demand increases with time), while in the third phase, the new products are in the decline phase (the demand decreases with time). In the fourth phase, the manufacturer only offers the remanufactured products. The demand of both new and remanufactured products depends both on the period and price. According to their analysis, they find that in the third period of the lifecycle, reducing the price of new products cannot give better profit for the total supply chain and the total profit obtained from optimizing the profit of each member in the system is lower than the joint optimal profit of the whole system.

In this thesis, we do not explicitly consider the lifecycle of either new or remanufactured products. In our two-period model, we assume that the useful life of each product is one period. In other words, after one period, the customer does not need this product but this does not mean that it is broken. It can still to be restored through the remanufacturing process instead of being cleanly disposed of.

2.1.4 Product design

Product design can significantly impact the remanufacturing decisions. Design affects the remanufacturability rate level and the degree of disassemblability of products. The remanufacturability rate level is defined by Debo et al. [14] as the proportion of returned products that can be remanufactured. The degree of disassemblability impacts the ease or difficulty of remanufacturing returned products. It also affects the cost of the remanufacturing process. A high degree of disassemblability often means lower cost for producing remanufactured products which may be good if the OEM does the remanufacturing. However ease of disassembly may entice third-party remanufacturers, causing the OEM more competition. On the other hand, low remanufacturability rate level and the low degree of disassemblability can effectively prevent third-party remanufacturers from entering the market and cannibalizing the revenue of new products, but it also increases the cost of manufacturing new products and decreases the possibility for the OEM to engage in remanufacturing.

Debo et al. [13] study the remanufacturing problem in a competitive environment containing the OEM and several remanufacturers for infinite planning horizons. It is found that it is better for the OEM to enter the remanufacturing business when there are some independent remanufacturers in the market. Moreover, the OEM should opt for lower levels of remanufacturability rate for their products in a competitive environment and the optimal remanufacturability rate level should decrease as the number of competitors in the market increases.

Wu [59] studies a competition game between the OEM and a remanufacturer. The OEM only produces new products and the remanufacturer collects the returned products and produces the remanufactured products. The OEM can decide the degree of disassemblability of the products (high or low), while the remanufacturer can decide the price strategy (high or low) to compete with the OEM. When the market size of the products is very large, the OEM should make products with high degree of disassemblability and thus achieve economies of scale. For the remanufacturer, it prefers to adopt the low price strategy when the production cost and cost saving from the remanufactured products are low and the OEM makes products with low degree of disassemblability.

In this thesis, we consider losses in the remanufacturing process, which means that not all products entering the remanufacturing process will go back to the market. The yield of the remanufacturing process is partially equivalent to the remanufacturability rate level discussed in this chapter 3.

2.1.5 Reverse channel

Reverse channels are often discussed in close-loop supply chain management. There are three main reverse channel structures:

- Collection of products by the manufacturer directly from the customers. For example, Lexmark sends emails to their customers and offers a $30 discount on a $230 Optra-S toner cartridge when customers return their used products to the company directly (Hong et al. [37]).
- Collection by retailers, under contract, for the manufacturer. Sony had a program called GreenFill Program, which allowed its retailers to collect the used electronics on its behalf. (Chuang et al. [11]).
- Collection by a third-party company. This is common in the auto industry (Savaskan et al. [50]).

Savaskan et al. [50] study these three kinds of reverse channel in a closed-loop supply chain containing a manufacturer, a retailer, and a third-party collector. They investigate how the choice of the reverse channel affects the profit of each member and their incentives to invest in the collection program. According to their research, they find that the retailer can perform the collection job more effectively by being the closest to the market. Moreover, they also find that when either the manufacturer or the retailer collects the returned products, the retailer can obtain the most profit.

Hong et al. [36] extend Savaskan et al. [50] to study three hybrid dual-channel collection systems: i) the manufacturer and the retailer collect the used products at the same time; ii) the manufacturer contracts a retailer and a third-party to both concurrently collect the used products; iii) the manufacturer and the third-party collector collect the used products at the same time. The study shows that in the dual channel system, it is most effective when both the manufacturer and the retailer collect the used products. Furthermore, the dual channel is more effective than the single channel system.

In this thesis, we only consider the manufacturer who has the responsibility for collecting the returned products when it is necessary.

2.1.6 Quality of returned products

The quality of returned products is highly variable and depends on how long and intensive their usage was. Quality of returned cores has a directly impact on remanufacturing costs. For example, the quality of some returned products may be functionally as good as new ones, when they are being returned by customers for personal preference (change of mind, wrong color match), error in shipment, etc. Such products do not require remanufacturing and can directly sent back to the market after a quick inspection, testing and repackaging. However, other products that have been returned because of functional faults will require more costly extensive remanufacturing operations. Moreover, due the wide range of quality conditions of the returned products, the quality of the final remanufactured products may also be different and affect their own price.

Mitra [44] studies a one-period revenue management problem for high and low quality remanufactured products. High-quality products are as good as new. Low-quality products are refurbished products which are sold at a lower price. It is found that, depending on the market demand, all refurbished products may not be sold and the rest should be disposed off. The expected profit from remanufacturing can be increased with the increase of the disposal cost or the increase of the availability of remanufactured products. However as the availability of refurbished products rises, the expected profit decreases.

Bulmus et al. [7] study a joint used products acquisition management and pricing problem. The returned products are divided into n bins, according to their quality. The returned products in each bin have different minimal acquisition prices and remanufacturing costs. The return rate of the products is a linear function of their acquisition price. It is found that profit is higher, when the remanufactured products are sold at different prices according to the quality of the returned products, than when they are all sold at the same price.

In this thesis, we assume that there are two lots of returned products: i) like-new products, which do not require remanufacturing, hence their unit remanufacturing cost is set to zero; and ii) the other lot comprised of products that need to be remanufactured to be brought back to a like-new condition at a certain cost before being sent back to the market. Moreover, given that all remanufactured products are like-new, their price in the market is the same regardless of their original lot type.

2.2 Market issues

In this section, we discuss market-related issues considered in the remanufacturing literature. These issues concern the market type, the market size, customer behavior, and other factors.

2.2.1 Market type

This issue deals mainly about the market environment of the manufacturer (monopoly or competition) and whether the new and remanufactured products are sold on the same market or on different markets.

In a monopolistic environment, the manufacturer sets the price and quantities of new and remanufactured products to produce. However, in a competitive environment, these decisions may be affected by the other forces operating in the market. For example, in some situations, even though it is not beneficial for the manufacturer to produce remanufactured products, it should still engage in remanufacturing in order to affect the market share of the other competitors (Ferguson and Toktay [19]).

Seidi and Kimiagari [51] discuss remanufactured process both in the monopoly and competitive environment. Their model is used to describe a supply chain with suppliers, manufacturers, a collection and disassembling center (CDC), a retailer, and customers. The returned products are collected by the CDC and sorted into different quality bins. A mathematical model is developed to study the price and inventory problem in the exclusive market (monopoly) case. However, for the competitive environment, due to the fact that the prices of returned products and remanufactured products are obtained from actual market data, fuzzy if-then rules are used to model the problem.

When new and remanufactured products are sold on the same market, the remanufactured products tend to cannibalize the revenue of the new products. Customers, who are price sensitive, prefer to buy the remanufactured products instead of the new products due to their lower price. Thus, the profit that the manufacturer obtains from the new products may decrease.

It should be noted that a number of older articles have stated that there is no cannibalization of new by remanufactured products. The reader is referred to the discussion in Guide Jr and Li [29]. More recent publications have integrated the idea of cannibalization to their models.

Guide Jr and Li [29] conduct experiments on eBay to test the potential of cannibalization by remanufactured products. Their results show that for commercial products, there is evidence to prove the existence of cannibalization between the new and remanufactured products due to the specific bidding behavior of the customers on eBay.

Heese et al. [34] investigate the consequence of take-back policy for remanufactured products on the firm and customers. In their research, the returned products are sold on a second-hand market and have no connection with the new products. As a result, the demand for new products depends only on the market size, price sensitivity of the customers, and the price of new products. It is also found that the take-back policy benefits the manufacturer with the growth of its market share and profit. The authors also determine that this policy is also valid in the competitive environment when there are high price sensitive customers and highly sustainable products.

Except when new and remanufactured products are sold on separate markets, there is another situation where there is no cannibalization between new and remanufactured products. This occurs when the manufacturer sells the remanufactured products at the same price as new ones and the customers can not tell the difference between new and remanufactured products. For the customers, there is only one kind of products and there is no cannibalization.

Majumder and Groenevelt [43] deal with the pricing of remanufactured products in a competitive environment by developing a two-period model. In the first period, the OEM only sells new products and in the second period, it may produce and sell both new and remanufactured products. A local remanufacturer (competitor) can only sell remanufactured products in the second period. The OEM prices its new and remanufactured products the same and customers can not tell the difference. The authors determine that increasing the OEM's unit remanufacturing cost leads to loss of profit for both the OEM and the local remanufacturer. As a result, the local remanufacturer is encouraged to reduce the unit remanufacturing cost of the OEM by cooperating on the collection process instead of engaging in a price competition on the returned products.

In this thesis, we study the pricing problem for new and remanufactured products in a monopolistic environment where the price of new and remanufactured products are different meaning that they may compete against each other in a single market.

2.2.2 Market size

The demands for new and remanufactured products depend not only on their prices, but also on the size of their potential markets. The market size keeps changing over the different stages of the product lifecycle and it affects the remanufacturing decisions of the firm. For example, the manufacturer will need to choose a suitable time to introduce their remanufacturing products into the market in order to avoid cannibalization by the remanufactured products and to benefit from economies of scale due to the large quantities of returned products.

Atasu et al. [2] study the relationship between the market growth and the remanufacturing decisions. Market size changes according to the products return rate. The returned products come from two sources: end-of-use returns and customer returns (i.e., customers return the products because they do not like them). A customer who returns an end-of-life products is a potential customer, who may buy the products again. But the other kind of returns may decrease the market size of the products. As a result, the return rate has either a positive or a negative influence on the market growth rate. The authors find that there is a threshold on the market size, above which the company should do the remanufacturing business, because it is profitable.

Deng and Yang [15] study the pricing problem for remanufactured products in a competitive environment under uncertain market size.They build a two-period model and the market size in the first and second period has an uncertain change (either an increase or a decrease). Their goal is to find what kind of pricing strategy the OEM and its competitor may choose for the remanufactured products under the uncertain market size. There are two price strategies that the OEM and its competitor may choose. The first one is a high price strategy, in which the remanufactured products will only be bought by green customers who perceive no difference between new and remanufactured products. The other is a low price strategy, which may entice normal customers to buy remanufactured products. Deng and Yang [15] find that under uncertain market size when the remanufacturer chooses the high price strategy, the OEM can monopolize the primary market made of normal customers (excluding the green customers). When the competitor chooses the low price strategy, the OEM will share the market with the competitor.

In our thesis, we assume that change in market size between two selling periods can be ignored, thus the market size in the first and second period stays constant. We conduct sensitivity analysis on how market size affects the optimal production and pricing policy.

2.2.3 Customer behavior

Customer perception/behaviour towards new and remanufacturing products is very important in the pricing problem because it can directly affect the demands of both types of products. In the literature, customer behaviour issues are studied and the demand for new and remanufactured products is derived or modeled using several methods. In the literature reviewed, the most common method used to model demand is the utility theory.

Vorasayan and Ryan [55] study customer demands for new and remanufactured products using customers' valuation and product prices. If the price of a product is higher than the customer's valuation, then this customer will not buy the product. Moreover, customers also choose the product which give them higher utility. For example, for the normal customers, if the prices for new and remanufactured products are same and this price is lower than their valuation of the products (their utility is positive), they will prefer the new products as these will provide them with a higher utility. The paper concludes that remanufacturing may increase the profit of the company or may relieve its manufacturing capacity.

Another basic demand function commonly used is a linear function of the price of the products. Bakal and Akcali [3] investigate the effects of random recovery rate on the pricing of remanufactured products. The fraction of used products, which can be remanufactured is random and the demand for remanufactured products is modeled as a linear function of their price such that the demand increases with the decrease of its price. Majumder and Groenevelt [43] also use this simple linear function to link the prices and demands for new and remanufactured products. They, however, also link the demand for one type of product to the price offered for the other product.

Besides the price, there are many other factors that are considered in modeling the demand function. Gan et al. [25] model the demands for new and remanufactured products as functions of their prices and the current lifecycle stage of the products. Wu [58] model demand as a linear function of both price and service level which includes warranty and advertisement. Debo et al.[14] consider that demand should integrate the market diffusion and the repeated purchase potential of the market.

In most papers, demand is a linear function of price. However, using the results from a survey, Ovchinnikov [45] finds that the customer behaviour is an inverted-U-shaped function of price. The demand may decrease with the decrease of the price because customers become suspicious of the product quality when the price is too low and refrain from buying the product. The inverted-U-shaped function is the blue solid curve in Figure 2.1.

In Figure 2.1, the horizontal axis represents the price discount offered on remanufactured products compared to the price of new products. The vertical axis is the proportion of customers who change their purchase decision and buy remanufactured products. When the discount increases while being moderate, an increasing number of customers switch to remanufactured products. However, after a maximum discount rate (around 20%), customers start having doubts about the quality of the remanufactured products and a decrease is seen in the number of switchers. When the price discount is very large, a small increase is observed again because at that point the products are so cheap that customers no longer care about the quality. Using the inverted-U-shape function, it is found that the company may charge low prices for new and remanufactured products, perform more remanufacturing, and still obtain more profit.

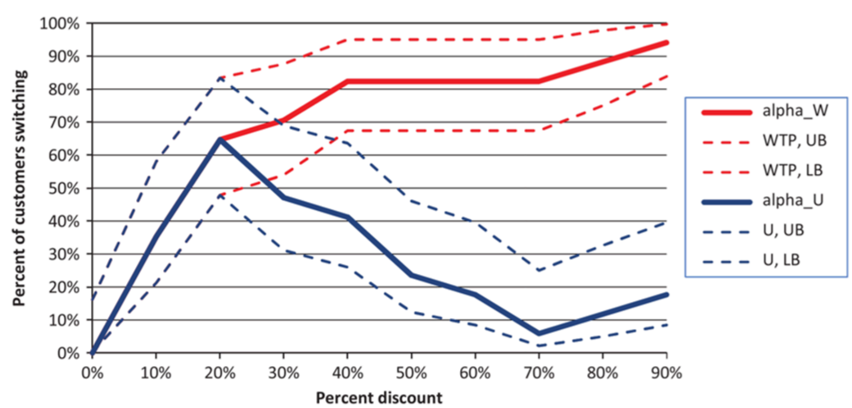

Figure 2.1: Estimates for Functions α^U and α^W (Source: Ovchinnikov [45])

In the models discussed above, the demand partly or completely depends on the price. In other models, demand for new and remanufactured products is a discrete number or a random parameter. Gu and Tagaras [28] model a centralized and a decentralized supply chains with deterministic or stochastic demand. The collector is responsible for collecting the used products, sorting them, and sending a certain number of products to the remanufacturer. There are errors during the sorting process and losses during shipment. It is found that when the demand is deterministic, the remanufacturing decisions of the remanufacturer and collector are the same in the centralized or decentralized supply chain. However, when demand is stochastic, more used products will be collected in the centralized situation than in the decentralized case.

In this thesis, we use utility theory to derive the demand for new and remanufactured products, which is the most common method in the literature. The details are discussed in chapter 3.

2.2.4 Advertisement

Advertisement is an important aspect in the pricing of remanufactured products as it has the potential of directly affecting the demand for remanufactured products by providing better information and educating the customer regarding the advantages of remanufactured products (Sabharwal and Garg [48]). According to a survey conducted by Ovchinnikov [45], when customers have more knowledge about remanufactured products, they are more likely to buy them and advertisement is a good method to reach that goal. However, the investment in advertisement brings extra costs to the remanufacturing process which necessitates to find good trade-offs.

In their study of the remanufacturing problem in the centralized and decentralized supply chains, Hong et al. [37] consider that demand is proportional to the investments in advertisement. The more the retailer or manufacturer invests in advertisement, the more customers want to buy their remanufactured products. Their study finds that local advertisement positively affects the profits of both retailer and remanufacturer. Furthermore, both the manufacturer and the retailer can earn higher profits if they engage in a two-part tariff contract in which the manufacturer agrees to lower the wholesale price of the products and the retailer pays a lump sum fee to the manufacturer in order to cover its losses.

Wu [58] focuses on the remanufacturing problem between two manufacturers and a shared retailer. One of the manufacturers produces new products, while the other produces new and remanufactured products. The manufacturers have to set the price of their products and decide how to invest in the servicing of their products, which includes advertisement and warranty. Their analysis finds that the production cost of products can directly affect the service level decided by the manufacturer: when the production cost is high, the manufacturer will invest less money for servicing in order to lower their total cost.

In this thesis, we do not directly consider the advertisement aspect. But in chapter 3, we discuss the fixed cost incurred by the remanufacturing process, which may influence the remanufacturing decision of the company. This fixed cost contains the advertisement investment, which enables customers to be informed and convinced to buy the remanufactured products.

2.3 Modeling issues

In this section, we discuss the issues specifically related to the pricing model such as the number of periods considered, the type of problem investigated, and the methods used to solve the model.

2.3.1 Time horizons

Time horizon is an important issue to be specified as it corresponds to the structure of the reversed supply chain. For multi-period time horizons, the price, the cost, and the maximum number of returned products may be different in each period. For example, according to San Gan et al. [49], the demand function for new and remanufactured products is different in each period and depends on its position in the lifecycle of the product. In the first period, which is in the beginning of the lifecycle, the demand for remanufactured products is zero, because the products have just been introduced and there is not enough returns to justify remanufacturing. Subsequent periods depend on previous period sales to generate the returns that will be used for remanufacturing.

Zhou et al. [60] discuss the centralized and decentralized remanufacturing problem in a single-period model. In their paper, all the parameters are considered in a steady state phase. For example, the number of returned products depends on the return rate and production quantity of new products in the previous periods. They also assume that the OEM adopts the same policy in every period, so the production quantities of the new products in the different periods are the same. As a result, the maximum number of returned products is related to the number of new products produced in the same period. Zhou et al. [60] find that if remanufacturing is profitable on its own, the OEM should just do it and not consider the cannibalization of new and remanufacturing products.

De Giovanni and Zaccour [12] consider the closed-loop supply chain problem in a two-period model. In the first period, the manufacturer produces and sells new products. In the second period, it chooses a retailer, a third party company, or itself to collect the returned products and obtains a residual value from the returns. The maximum number of returns is a linear function of the number of new products sold in the first period. De Giovanni and Zaccour [12] find that the manufacturer should carry out the collection of the returned products when the unit collection cost is not high or the investment in the collection (advertisement and communications campaigns about recycling) is effective.

In this thesis, we develop a single-period and a two-period model. In both models, the number of remanufactured products depends on quantity of returns. The details of both models are discussed in chapter 3.

2.3.2 Centralized or decentralized supply chain

In practice, the remanufacturing activities involve manufacturers and all other partner organizations in the supply chain. For example, the retailers may play a role in the collecting returned products because they are close to the market and users. Suppliers may provide additional parts or modules needed for remanufacturing to the OEM. So if the supply chain under consideration is decentralized, then the competition among the supply chain members is an important issue which affects the remanufacturing decisions of the OEM. However, if all the members in the supply chain are considered as a single system, then there is no competition.

Kaya [38] studies the remanufacturing problem in a supply chain with a manufacturer and a retailer where the quantity of returned products is decided by their acquisition price (incentive). Both the centralized and decentralized supply chain cases are investigated. In the centralized supply chain, the manufacturer decides the acquisition price of the returned products and runs the collection activity. However, in the decentralized supply chain, a third-party collects the used products and sells them back to the manufacturer. Their study concludes that in the decentralized case, the manufacturer prefers to offer low incentive value, produce less remanufactured products, and earn less profit.

Wei and Zhao [57] investigate the pricing decision in remanufacturing for two competing supply chains each with one manufacturer and one retailer. The manufacturer in the first supply chain does not perform remanufacturing. The manufacturer in the second supply chain integrates remanufacturing into its manufacturing process which allows parts recovered from returned products to be used in manufacturing new products. Two types of supply chain are considered: centralized and decentralized. In the centralized case, the wholesale price between the manufacturer and the retailer is considered as a inner transfer price in the model, which does not affect the total profit. In the decentralized case, four models are formulated according to the different leader-follower relationships between the manufacturer and the retailer in the first and second supply chains. It is found that the total profit of each supply chain is higher in the decentralized case than in the centralized case and the profit for one supply chain can become higher when the leader of the other chain is the retailer. Moreover, for each supply chain, the manufacturer or the retailer can obtain higher profit when they are the leader of this chain.

In this thesis, we only consider the pricing management of new and remanufactured products from the manufacturer's perspective. Thus, the supply chain type is not discussed in this thesis.

2.3.3 Deterministic or stochastic problem

To simplify the analysis of the remanufacturing process, many parameters such as demand and return rate are usually considered as deterministic. However in reality, according to Ferrer and Whybark [23], the remanufacturer may not have full knowledge of all the parameters needed in the remanufacturing process, which may lead to several consequences: high costs, risk of obsolescence, and poor work planning, etc. As a consequence, these parameters are stochastic in nature and may have a great influence on the remanufacturing decisions. For example, the uncertainty of the product demand can effect the production and inventory plan of the company. As a result, deciding whether the problem is deterministic or stochastic is important in each paper.

Ferrer [20] discusses the remanufacturing problem in a monopoly case with all parameters being deterministic. The author finds the reason for success or failure of the remanufactured products in the different industries under consideration. If the remanufacturing savings are not high, the firm cannot obtain enough profit from the remanufactured products according to the utilities of the customers. For example, the automobile industry does not offer remanufactured cars because the cost to recondition a used car to an "as good as a new" state is too high. However in the camera industry, the remanufacturing cost is very low and as a result manufacturers offer remanufactured cameras.

Li et al. [41] study the optimal pricing problem of fashion products in a closed-loop supply chain. In their paper, the demand is not deterministic but contains a uniformly distributed stochastic parameter. The paper focuses on the pricing problem both in a centralized and decentralized supply chain with one manufacturer and one retailer. The optimal price is when the stochastic parameter is within a specific range. Moreover, it is found that the channel profit increases with the width of this range. In the decentralized channel, the retailer needs to order less products than in the centralized channel when the range of stochastic parameter is not too large.

Galbreth and Blackburn [24] study the sorting policies (the rules used to decide which returns can be remanufactured and which ones should be disposed of) for both deterministic and stochastic demand cases. For the deterministic demand, Galbreth and Blackburn [24] obtain the expression of the optimal sorting level of returns with the deterministic demand and give some guidelines and numerical examples to find the optimal sorting level in the stochastic case.

In this thesis, we assume that the manufacturer has full knowledge of the market, which means that all parameters are known and constant (deterministic) except that customers' valuation on the new products follows a uniform distribution.

2.3.4 Modeling method

In this section, we discuss the methods used to model and solve the remanufacturing problems. For simple problems, linear optimization is the most commonly used method. According to Galbreth and Blackburn [24], more than one-fifth of the papers dealing with reverse supply chain from 2007 to 2013 used linear and mixed integer programming models.

However, due to complexities encountered in practice, not all problems can be formulated with linear programming models. Many more problems have to be formulated as nonlinear models. For example, convex programming is used in Ferrer and Swaminathan [21], Vorasayan and Ryan [55], and Sun et al. [54].

The methods used to model and solve remanufacturing problems also depend on wether the parameters are deterministic or stochastic. When parameters are stochastic, dynamic programming or stochastic dynamic programming are often used in the literature. For example, Chen and Chang [10] use dynamic programming to solve their problem. In their paper, the demand function is price sensitive and market demand is uncertain. Fuzzy theory is also used to solve stochastic remanufacturing problem. Seidi and Kimiagari [51] use fuzzy if-then rules to determine the price of remanufactured products in the presence of competition on the market and data uncertainty.

When dealing with competition in the remanufacturing problem, Markov decision process, Game theory, and Nash Equilibrium are often used in the literature. Qiaolun et al. [46] use game theory to describe the competition between the manufacturer, a retailer, and a third-party company for the collection and remanufacturing of returns. They compare the performance of three kinds of reverse channel defined by who carries out the collection (manufacturer or retailer or third-party).

Besides the methods mentioned above, many other nonlinear methods such as queueing theory and dicrete-events simulation are also used. In this thesis, we will formulate convex programming models and use the conditions to derive the optimal solutions.

2.4 Shortcomings of previous research

In this section, we briefly discuss the shortcomings unveiled by the previous literature:

1. The unit collection and inspection cost in reality is dependent on the quantity of collected of returns. The larger the quantity of required returns is, the higher the average collection and inspection cost is. However in most papers, this unit cost is formulated as a constant parameter.

2. The unit remanufacturing cost usually depends on the quantity of the remanufactured products and the number of returns collected by the company. When the company increases the quantity of remanufactured products, the average cost of producing a remanufactured products decreases due to the learning curve. Moreover, when the quantity of remanufactured products is higher than the number of returns collected, the company is more likely to use the returns with relatively high quality first. So the more returns the company collects, the lower the average remanufacturing cost is. Most pricing models in the literature do not account for this decrease of the average unit remanufacturing cost.

3. Due to the different quality of returns, the quality of remanufactured products may also be classified into different quality levels and be sold with different prices. This is not included in any paper to the best of our knowledge.

4. The influence of advertisement on the reverse supply has already be discussed in previous researches. But the question of who should invest on the advertisement in a supply chain, the manufacturer or the retailer, has not been answered.

5. The nonlinear collection and inspection cost, the losses in the remanufacturing process, and the various quality of returns are all individually mentioned in previous studies. However, there is currently no pricing model integrating all these three factors in one single mathematical formulation.

2.5 Problem Description

To address some of shortcomings listed above, we propose a novel mathematical formulation to find the optimal pricing and production strategies in closed-loop supply chains with convex recovery costs, two-quality bins for the returns and remanufacturing losses. We consider a monopolistic company having the opportunity to manufacture both new and remanufactured products. The monopolist can obtain EoL or EoU products from customer markets at a cost that is independent of the quality of the returns. These returns are classified into two groups according to their quality. The high quality returns have no functional errors and only need to be repackaged. Normal quality returns are remanufactured through a process that generates some losses.

2.6 Contribution to the literature

Key contributions of this thesis are:

1. We investigate the optimal production and pricing strategies for a manufacturer engaging in remanufacturing. A one-period model and a two-period model are developed to account for three key parameters that are usually absent in the models currently available in the literature: a proportion of high quality returned products, a remanufacturability rate, and a unit collection and inspection cost rate.

2. Differing from the literature mentioned above, our models consider the relationship between the price for new and remanufactured products in the different

periods. In our study, we constrain that the price for remanufactured products cannot exceed the price of new products in either first or second period. This assumption is reasonable as in (Chari et al. [8] and Gutowski et al. [32]) and leads to new results not yet seen in the literature.

3. After deriving the optimality conditions, we solve our problems and develop exhaustive production and pricing strategy selection charts based on the unit manufacturing and unit remanufacturing costs. These optimal strategies selection charts prove to be more general than any previous study of the same type.

Chapter 3

Pricing and production models

The problem is formulated as an optimization model where the decision variables to be optimized are the prices for new and remanufactured products in the different planning periods. We start by first presenting a single-period deterministic model to make our analysis simple and apparent. Then, we extend our analysis to a two-period model. In the one-period model, the monopolist can manufacture both new and remanufactured products in this single period. In the two-period model, the monopolist can only manufacture new products in the first period and may produce new, remanufactured or both kinds of products in the second period. Utility theory is used to derive the demand functions for each product type. Cost functions considered in the formulation include the manufacturing, remanufacturing, collection, and inspection costs.

The following notation is used in our models:

Indices

i: Index for product type: $i = n$ for new, $i = r$ for remanufactured.
j: Index for the planning period: $j = 1, 2$.
k: Denoting the k^{th} model: $k = I$ and $k = II$ for the one-period and two period models respectively.
e: Index for production strategy type: $e = N$ for only new, $e = R$ for only remanufactured, $e = B$ for both new and remanufactured.

Decision Variables

p_{ij}^k: Price of product type i in period j in model k.

Parameters

c_i^k: Unit manufacturing cost for product type i in model k.
c_c^k: Unit collection and inspection cost rate in model k.
Q^k: Market size in model k.
α^k: Customers' tolerance for remanufactured products in model k.
β^k: Proportion of high quality returns in model k.

γ^k: Remanufacturability rate in model k.
x: Quantity of returns.
d_{ij}^k: Demand of product type i in period j in model k.
TP^k: Total profit in model k.
TP_e^I: Total profit from production strategy e in the one-period model.
π_{ij}^{II}: Profit from product type i in the period j in the two-period model.
s^k: Cost saving defined as the different between the cost of manufacturing. one new product and the cost of producing one remanufactured product in the k model, i.e., $s^k = c_n^k - c_r^k$.
z: Perceived value for new products.
z_i: Lowest perceived value for new products from customers who buy products of type i.

3.1 Assumptions

The following assumptions are made in the formulation of the problem. Each assumption is explained in detail.

Assumption 1. *The collection and inspection cost is a convex function of the quantity collected.*

This assumption is supported by the literature (Ferguson and Toktay[19] and Galbreth and Blackburn[24]). This collection and inspection cost in our thesis includes the purchase, transportation, sorting, handling, and inspection costs for each returned product.

In the large majority of papers, this cost is modeled as a linear function of the quantity of cores collected. In reality, the unit cost for obtaining returns increases with the quantity required because more efforts are needed. The company may need to extend its geographical reach going from densely populated areas to sparsely populated areas, thus losing the economies of scale savings. Moreover, in order to collect more returns, the company may also need to increase their facilities or presence in the sparsely populated areas, which also leads to increased marginal cost. As stated in (Ferguson and Toktay [19]), convex increasing processing costs can occur due to the variance in condition of the returns and the fact that the firms process the cores in the best condition (upon arrival) first.

Without loss of generality, we use a quadratic function for the total collection and inspection cost. Hence, we have: $c_c^k x^2$.

Assumption 2. *Customers prefer new products.*

This assumption implies that customers are usually willing to buy new products instead of remanufactured products, if they have the same price. We use the parameter α^k to represent the customers' tolerance for remanufactured products. If $\alpha^k = 0$, customers will never consider buying remanufactured products. When $\alpha^k = 1$, customers do not differentiate between new and remanufactured products. In other words, customers have the same valuation on the new and remanufactured products. These customers are also known as "green customers", who are environmentally conscious or only care about the functionality of the products (Atasu et al. [2]). In our models, we assume that $0 \leq \alpha^k \leq 1$.

Customers usually prefer new products because they have doubts about the quality of the remanufactured products given that they may have been used before being returned.

In general, customers' willingness-to-pay for products is based on the warranty offered, the price, the brand, and many other factors. However, all studies show that price is the most critical factor. So, we will assume that customers' willingness-to-pay for the products only depends on the price for the new and remanufactured products.

Assumption 3. *Consumers' willingness-to-pay for new products is heterogeneous and uniformly distributed in [0, Q^k].*

It is assumed that the size of the market for both new and remanufactured products is Q^k and each customer will only buy one product in each period. According to the utility theory, for a customer of type z, whose perceived value for the new product is z, the utility of buying one new or remanufactured product is given by Eq. (3.1) and (3.2), respectively:

$$U_N(z) = z - p_n^k \tag{3.1}$$

$$U_R(z) = z\alpha^k - p_r^k \tag{3.2}$$

Moreover, these utility functions are subject to the following constraints:

$$U_N(z_n) \geq 0 \tag{3.3}$$

$$U_R(z_r) \geq 0 \tag{3.4}$$

$$U_N(z_n) \geq U_R(z_n) \tag{3.5}$$

where z_n and z_r are the lowest valuation of new products for people who want to buy new or remanufactured products. Constraints (3.3) and (3.4) imply that a customer will not buy a product if its utility is less than 0. Constraint (3.5) implies that customers who are willing to buy new products have higher utility for new than for remanufactured products. From these constraints, z_n and z_r are obtained as:

$$z_n = \frac{p_n^k - p_r^k}{1 - \alpha} \tag{3.6}$$

$$z_r = \frac{p_r^k}{\alpha} \tag{3.7}$$

We assume that there are Q^k potential customers heterogeneous and uniformly distributed in $[0, Q^k]$, according to their willingness-to-pay. Thus, z_n and z_r divide the whole potential market into three parts:

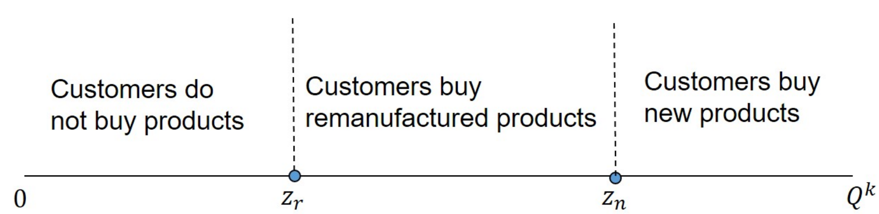

Figure 3.1: Market segments based on valuation

Demand for new and remanufactured products (d_n^k and d_r^k) are then obtained according to their prices and market size:

$$\begin{aligned} d_n^k &= Q^k - z_n \\ &= Q^k - \frac{p_n^k - p_r^k}{1-\alpha^k} \end{aligned} \tag{3.8}$$

$$\begin{aligned} d_r^k &= z_n - z_r \\ &= \frac{\alpha^k p_n^k - p_r^k}{\alpha^k\left(1-\alpha^k\right)} \end{aligned} \tag{3.9}$$

Assumption 4. *The manufacturer is the monopolist and has a complete knowledge and control of the market.*

It is assumed that the manufacturer sets the price for new and remanufactured products, which balances demand and the supply (i.e., supply equals demand). There is no back-order or overproduction. This assumption is reasonable in a monopolistic environment.

Assumption 5. *There are losses during the remanufacturing process.*

Unlike most models in the current literature, we assume that there are losses during the remanufacturing process due to processing issues, unexpected worse quality of returns not detected during the inspection stage or damage occurring during disassembly or reassembly. Not all returns can go back to the market through remanufacturing activities. We introduce a constant remanufacturability rate to account for the losses. This assumption is reasonable over long production periods as is the case in our models.

Assumption 6. *The price of remanufactured products is always lower than the price of new products.*

This assumption implies that the company prices remanufactured products lower than new products to make remanufactured products more attractive to a certain proportion of customers (Chari et al. [9]). Even "green customers" do not want to pay more for remanufactured products, although they see no difference between new and remanufactured products. As explained by Chari et al. [8], the remanufacturing cost of a product is usually a fraction of the manufacturing cost. Therefore, a general consumer perception is that a remanufactured product is seen as inferior to a new product. Gutowski et al. [32] even state that remanufactured products generally sell for about 50-80% of the new product.

3.2 Problem description and preliminary results

All products recovered from customer markets are inspected and sorted into two categories: high quality and normal quality. High quality products have no functional defect but are being returned for other reasons such as aesthetics and cognitive dissonance. For example, a customer may return a laptop because its color is not matching their monitor or desk. The functionality of such return is almost the same as a new one. As a result, this product just needs to be repackaged and directly sent back for sale. Thus, the reconditioning cost for these high quality returns is negligible in comparison with the remanufacturing cost. In both one and two-period models, the parameter β^k is used to represent the proportion of high quality returns.

On the other hand, normal quality returns require further remanufacturing processes. Their unit remanufacturing cost is assumed to be known and constant. During the remanufacturing process, some losses are incurred due to the unexpected worse quality of returns as Assumption 5.

The reverse supply chain considered in this thesis is showed in Figure (3.2). After x products have been collected and inspected, $\beta^k x$ high quality units go back to the market directly. The remaining products are remanufactured. Because of the remanufacturing losses, only $\left(1-\beta^k\right) x\gamma^k$ units are made and sent back to the market based on Assumption 5. So the efficiency rate for the remanufacturing process is given by:

$$\left(1-\beta^k\right)\gamma^k+\beta^k. \tag{3.10}$$

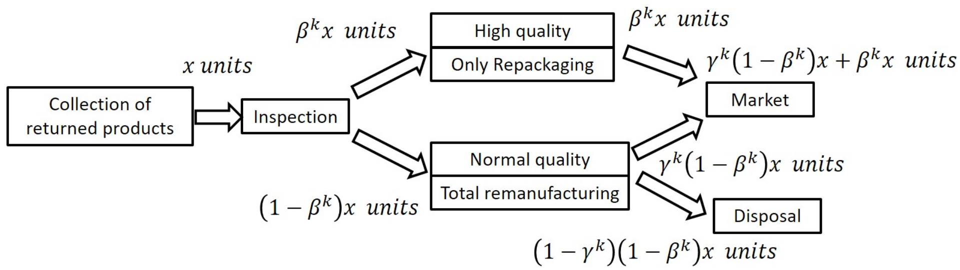

Figure 3.2: Reverse supply chain

According to Assumption 4, supply is equal to the demand. Therefore equating Eq. (3.9) and Eq. (3.10), yields the quantity of returns to be collected:

$$\begin{aligned}\frac{\left(\alpha^k p_{n1}^k - p_{r1}^k\right)}{\alpha^k\left(1-\alpha^k\right)} &= \left(1-\beta^k\right)x\gamma^k + \beta^k x \\ x &= \frac{\left(ap_{n1}^k - p_{r1}^k\right)}{\alpha^k\left(1-\alpha^k\right)\left(-\gamma^k\beta^k+\gamma^k+\beta^k\right)}\end{aligned} \tag{3.11}$$

3.3 One-period model

In the one-period model, the monopolist can produce both new and remanufactured products and set the prices in order to obtain the maximum profit. The quantity of returns that the company can collected is unlimited. But due to the convex collection and inspecting cost, the company still cannot collect too much returns. Based on Eq. (3.11), the one-period model is:

$$\begin{aligned}Max: \quad TP^I =& \frac{p_{n1}^I\left(\left(1-\alpha^I\right)Q^I - p_{n1}^I + p_{r1}^I\right)}{1-\alpha^I} + \frac{p_{r1}^I\left(\alpha^I p_{n1}^I - p_{r1}^I\right)}{\alpha^I\left(1-\alpha^I\right)} \\ &- \frac{c_n^I\left(\left(1-\alpha^I\right)Q^I - p_{n1}^I + p_{r1}^I\right)}{1-\alpha^I} \\ &- \frac{c_c^I\left(\alpha^{II}p_{n1}^I - p_{r1}^I\right)^2}{\alpha^{I^2}\left(1-\alpha^I\right)^2\left(-\gamma^I\beta^I+\gamma^I+\beta^I\right)^2} \\ &- \frac{c_r^I\left(1-\beta^I\right)\left(\alpha^I p_{n1}^I - p_{r1}^I\right)}{\alpha^I\left(1-\alpha^I\right)\left(-\gamma^I\beta^I+\gamma^I+\beta^I\right)}\end{aligned} \tag{3.12}$$

s.t.:

$$Q^I - \frac{p^I_{n1} - p^I_{r1}}{1-\alpha^I} \geq 0 \tag{3.13}$$

$$\frac{\alpha^I p^I_{n1} - p^I_{r1}}{\alpha^I\left(1-\alpha^I\right)} \geq 0 \tag{3.14}$$

$$p^I_{n1}, p^I_{r1} \geq 0 \tag{3.15}$$

The objective function (Eq. 3.12) has five terms. $\frac{p^I_{n1}\left(\left(1-\alpha^I\right)Q^I - p^I_{n1} + p^I_{r1}\right)}{1-\alpha^I}$ and $\frac{p^I_{r1}\left(\alpha^I p^I_{n1} - p^I_{r1}\right)}{\alpha^I(1-\alpha^I)}$ are the revenues from new and remanufactured products. $\frac{c^I_n\left(\left(1-\alpha^I\right)Q^I - p^I_{n1} + p^I_{r1}\right)}{1-\alpha^I}$, $\frac{c^I_r\left(1-\beta^I\right)\left(\alpha^I p^I_{n1} - p^I_{r1}\right)}{\alpha^I(1-\alpha^I)(-\gamma^I\beta^I+\gamma^I+\beta^I)}$ and $\frac{c^I_c\left(\alpha^I p^I_{n1} - p^I_{r1}\right)^2}{{\alpha^I}^2(1-\alpha^I)^2(-\gamma^I\beta^I+\gamma^I+\beta^I)^2}$ are the total manufacturing cost, total remanufacturing cost, and total collection and inspection cost, respectively. Constraints (3.13) and (3.14) ensure that the demands for new and remanufactured products are non-negative.

In the reminder of this section, we use $m^I = \beta^I\gamma^I - \beta^I - \gamma^I$ to simplify the writing.

Lemma 1. *The objective function is concave and the constraints are convex, therefore the optimization problem is convex.*

Proof. To show that the objective is concave, we need to prove that its Hessian is negative semi-definite (See Eiselt et al. [16] and, Boyd and Vandenberghe [6]). The Hessian matrix of the objective function is:

$$A_1 = \begin{vmatrix} -\frac{2}{1-\alpha^I} - \frac{2c^I_c}{(1-\alpha^I)^2 {m^I}^2} & \frac{2}{1-\alpha^I} + \frac{2c^I_c}{\alpha^I(1-\alpha^I)^2 {m^I}^2} \\ \frac{2}{1-\alpha^I} + \frac{2c^I_c}{\alpha^I(1-\alpha^I)^2 {m^I}^2} & -\frac{2}{\alpha^I(1-\alpha^I)} - \frac{2c^I_c}{{\alpha^I}^2(1-\alpha^I)^2 {m^I}^2} \end{vmatrix} \tag{3.16}$$

Matrix A_1 is negative semi-definite if and only if the following two conditions are satisfied:

$$\frac{4{m^I}^2\alpha^I\left(1-\alpha^I\right) + 4c^I_c}{{\alpha^I}^2\left(1-\alpha^I\right)^2 {m^I}^2} \geq 0 \tag{3.17}$$

$$\frac{2{m^I}^2\alpha^I\left(1-{\alpha^I}^2\right) + 2{\alpha^I}^2 c^I_c + 2c^I_c}{{\alpha^I}^2\left(1-\alpha^I\right)^2 {m^I}^2} \geq 0 \tag{3.18}$$

Given that $0 \leq \alpha^I \leq 1$, $-1 \leq m^I \leq 0$, and $c_c^I \geq 0$, it is easy to see that Eq. (3.17) and (3.18) are always satisfied. Thus, A_1 is negative semi-definite and the objective function is concave.

Since constraints (3.13) and (3.14) are linear, they are also convex. □

Theorem 1 and Figure 3.3 summarize the optimal production and pricing strategies in the one-period model. c_{rl}^I represents the l^{th} thresholds of unit remanufacturing cost in one-period model.

Theorem 1. *The optimal production and pricing strategies for the monopolist depend on the unit remanufacturing cost (c_r^I):*

1. *If $c_r^I \leq c_{r1}^I$, then only produce remanufactured products and set $p_{r1}^I = p_1^I$.*
2. *If $c_{r1}^I < c_r^I < c_{r2}^I$, then produce both new and remanufactured products and set $p_{n1}^I = p_2^I$, and $p_{r1}^I = p_3^I$.*
3. *If $c_r^I \geq c_{r2}^I$, then only produce new products and set $p_{n1}^I = p_4^I$.*

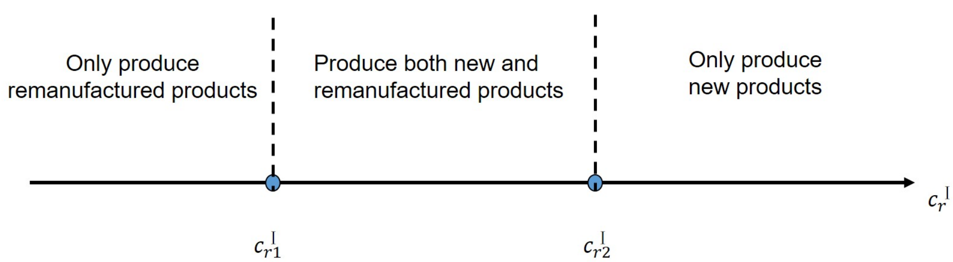

Figure 3.3: Results of one-period model

Critical values	Expression
c_{r1}^I	$\frac{Q^I {\alpha^I}^2 {m^I}^2 - {m^I}^2 \left(Q^I - c_n^I\right)\alpha^I - c_c^I \left(Q^I - c_n^I\right)}{\alpha^I m^I (\beta^I - 1)}$
c_{r2}^I	$\frac{\alpha^I m^I c_n^I}{\beta^I - 1}$
p_1^I	$\frac{\alpha^I \left(Q^I \alpha^I {m^I}^2 + c_r^I \left(\beta^I - 1\right) m^I + 2\, c_c^I\, Q^I\right)}{2\, {m^I}^2 \alpha^I + 2\, c_c^I}$
p_2^I	$\frac{Q^I}{2} + \frac{c_n^I}{2}$
p_3^I	$\frac{\left(Q^I \alpha^I \left(\alpha^I - 1\right) {m^I}^2 + c_r^I \left(\beta^I - 1\right)\left(\alpha^I - 1\right) m^I - c_c^I \left(Q^I + c_n^I\right)\right)\alpha^I}{\left(2\, {\alpha^I}^2 - 2\, \alpha^I\right) {m^I}^2 - 2\, c_c^I}$
p_4^I	$\frac{Q^I}{2} + \frac{c_n^I}{2}$

Table 3.1: Critical values in the one-period model

Proof. Given that the optimization problem is convex according to Lemma 1, the optimal solutions are obtained from solving the following conditions:

$$\frac{\partial TP^I}{\partial p^I_{n1}} - u_1 + u_2\alpha^I \leq 0 \tag{3.19}$$

$$p^I_{n1}\left(\frac{\partial TP^I}{\partial p^I_{n1}} - u_1 + u_2\alpha^I\right) = 0 \tag{3.20}$$

$$\frac{\partial TP^I}{\partial p^I_{n1}} + u_1 - u_2 \leq 0 \tag{3.21}$$

$$p^I_{r1}\left(\frac{\partial TP^I}{\partial p^I_{r1}} + u_1 - u_2\right) = 0 \tag{3.22}$$

$$Q^I - \frac{p^I_{n1} - p^I_{r1}}{1-\alpha^I} \geq 0 \tag{3.23}$$

$$u_1\left(Q^I - \frac{p^I_{n1} - p^I_{r1}}{1-\alpha^I}\right) = 0 \tag{3.24}$$

$$\frac{\alpha^I p^I_{n1} - p^I_{r1}}{\alpha^I\left(1-\alpha^I\right)} \geq 0 \tag{3.25}$$

$$u_2\left(\frac{\alpha^I p^I_{n1} - p^I_{r1}}{\alpha^I\left(1-\alpha^I\right)}\right) = 0 \tag{3.26}$$

$$p^I_{n1}, p^I_{r1}, u_1, u_2 \geq 0 \tag{3.27}$$

From Eq. (3.22), either $p^I_{r1} = 0$ or $p^I_{r1} \neq 0$. When $p^I_{r1} = 0$, the demand for new and remanufactured products (d^I_r and d^I_n) is given by:

$$d_r\left(p^I_{n1}, p^I_{r1} = 0\right) = \frac{p^I_{n1}}{1-\alpha^I} \tag{3.28}$$

$$d_n\left(p^I_{n1}, p^I_{r1} = 0\right) = Q^I - \frac{p^I_{n1}}{1-\alpha^I} \tag{3.29}$$

If $p^I_{r1} = \alpha^I p^I_{n1}$, the demand for new and remanufactured products (d^I_r and d^I_n) is given by:

$$d_r\left(p^I_{n1}, p^I_{r1} = \alpha^I p^I_{n1}\right) = 0 \tag{3.30}$$

$$d_n\left(p^I_{n1}, p^I_{r1} = \alpha^I p^I_{n1}\right) = Q^I - p^I_{n1} \tag{3.31}$$

Comparing these two cases, it is easy to see that the company makes more profit in the second case than in the first because there is more demand for new in the second case. As a result, $p_{r1}^{I} = 0$ can never be the optimal choice for the company. Therefore only $p_{r1}^{I} \neq 0$ case needs to be considered.

When $p_{r1}^{I} \neq 0$ then $p_{n1}^{I} \neq 0$, because when $p_{n1}^{I} = 0$, the demand for remanufactured products (d_{r}^{I}) is negative according to Eq. (3.9).

$$d_{r}\left(p_{n1}^{I} = 0, p_{r1}^{I}\right) = \frac{-p_{r1}^{I}}{1-\alpha^{I}} < 0 \tag{3.32}$$

As a result, $p_{n1}^{I} \neq 0$ and $p_{r1}^{I} \neq 0$. So the conditions (3.19) to (3.22) can be simplified into two conditions:

$$\frac{\partial TP^{I}}{\partial p_{n1}^{I}} - u_1 + u_2\alpha^{I} = 0 \tag{3.33}$$

$$\frac{\partial TP^{I}}{\partial p_{n1}^{I}} + u_1 - u_2 = 0 \tag{3.34}$$

By solving conditions (3.23) to (3.27), (3.33), and (3.34), the results in Theorem 1 can be obtained. □

Theorem 1 shows that for high values of c_{r}^{I}, the monopolist should produce only new products. For low values of c_{r}^{I}, the monopolist should produce only remanufactured products. When the value of c_{r}^{I} is intermediate, the monopolist should produce both.

A variant of the one-period model is obtained by introducing a fixed cost for the remanufacturing process. This fixed cost would cover the investments to be made to set up the infrastructure required to support the remanufacturing processes. The monopolist incurs this cost only when remanufacturing is selected.

For small values of the fixed cost ($F < F_1$), the selection sequence of the optimal production and pricing strategies does not change (see Figure 3.4). But the value of the new threshold $\bar{c_{r2}^{I}}$ is smaller than the original c_{r2}^{I} (no fixed cost).

For large values of the fixed cost ($F \geq F_1$), producing both new and remanufactured products never becomes the optimal production strategy. The value of the new threshold c_{r3}^{I} (see Figure 3.5) is smaller than c_{r1}^{I}.

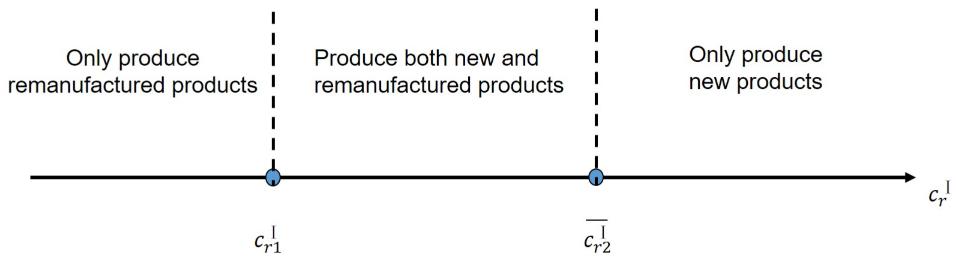

Figure 3.4: Results for one-period model with fixed cost ($F < F_1$)

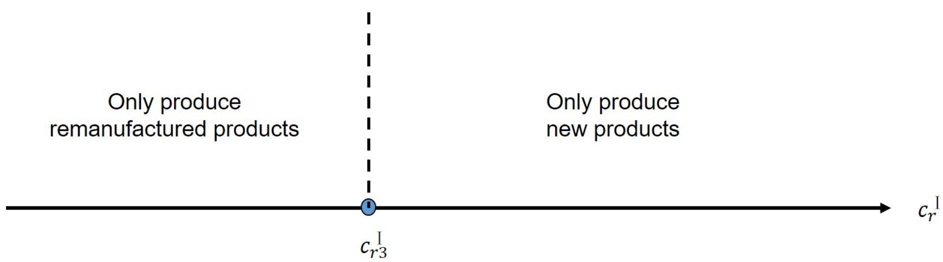

Figure 3.5: Results for one-period model with fixed cost ($F \geq F_1$)

Critical values	Expression
F_1	$-\frac{1}{4}\frac{\left(Q^I-c_n^I\right)^2\left(\left({\alpha^I}^2-\alpha^I\right){m^I}^2-c_c^I\right)}{{m^I}^2{\alpha^I}^2}$
$\overline{c_{r2}^{I}}$	$\frac{\alpha^I c_n^I m^I+2\sqrt{F}\sqrt{\left(-{\alpha^I}^2+\alpha^I\right){m^I}^2+c_c^I}}{\beta^I-1}$
c_{r3}^{I}	$\frac{Q^I\alpha^I m^I+\sqrt{\left({Q^I}^2-2Q^I c_n^I+{c_n^I}^2+4F\right)\left({m^I}^2\alpha^I+c_c^I\right)}}{\beta^I-1}$

Table 3.2: Critical values when considering the fixed cost for collection and inspection

3.4 Two-period model

In the two-period model, the monopolist can produce only new products in the first period and decides whether to produce new and/or remanufactured products in the second period in order to obtain the maximum profit. We assume that the quantity of returns in the end of first period is limited by the quantity of products sold in the first period. For both periods, the size of the market does not change. The remanufacturing process is the same as we discussed in the one-period model. Hence, the mathematical formulation of the problem is:

$$\begin{aligned} Max: \quad TP^{II} = & \left(p_{n1}^{II} - c_n^{II}\right)\left(Q^{II} - p_{n1}^{II}\right) + \frac{p_{n2}^{II}\left(\left(1-\alpha^{II}\right)Q^{II} - p_{n2}^{II} + p_{r2}^{II}\right)}{1-\alpha^{II}} \\ & + \frac{p_{r2}^{II}\left(\alpha^{II}p_{n2}^{II} - p_{r2}^{II}\right)}{\alpha^{II}\left(1-\alpha^{II}\right)} - \frac{c_n^{II}\left(\left(1-\alpha^{II}\right)Q^{II} - p_{n2}^{II} + p_{r2}^{II}\right)}{1-\alpha^{II}} \\ & - \frac{c_c^{II}\left(\alpha^{II}p_{n2}^{II} - p_{r2}^{II}\right)^2}{\alpha^{II^2}\left(1-\alpha^{II}\right)^2\left(-\gamma^{II}\beta^{II} + \gamma^{II} + \beta^{II}\right)^2} \\ & - \frac{c_r^{II}\left(1-\beta^{II}\right)\left(\alpha^{II}p_{n2}^{II} - p_{r2}^{II}\right)}{\alpha^{II}\left(1-\alpha^{II}\right)\left(-\gamma^{II}\beta^{II} + \gamma^{II} + \beta^{II}\right)} \end{aligned} \tag{3.35}$$

s.t.:

$$Q^{II} - \frac{p_{n2}^{II} - p_{r2}^{II}}{1-\alpha^{II}} \geq 0 \tag{3.36}$$

$$\frac{\alpha^{II}p_{n2}^{II} - p_{r2}^{II}}{\alpha^{II}\left(1-\alpha^{II}\right)} \geq 0 \tag{3.37}$$

$$\left(Q^{II} - p_{n1}^{II}\right) - \frac{\alpha^{II}p_{n2}^{II} - p_{r2}^{II}}{\alpha^{II}\left(1-\alpha^{II}\right)\left(-\gamma^{II}\beta^{II} + \gamma^{II} + \beta^{II}\right)} \geq 0 \tag{3.38}$$

$$p_{n1}^{II} - p_{r2}^{II} \geq 0 \tag{3.39}$$

$$p_{n1}^{II}, p_{n2}^{II}, p_{r2}^{II} \geq 0 \tag{3.40}$$

The objective function (Eq. 3.35) can be divided into two terms. The first term $\left(p_{n1}^{II} - c_n^{II}\right)\left(Q^{II} - p_{n1}^{II}\right)$ represents the profit that the company obtains in the first period. The rest represents the profit in the second period. This term is the same as in the one-period model.

Constraints (3.36) and (3.37) indicate that the demand for new and remanufactured products in the second period are non-negative. Constraint (3.38) ensures that the quantity of returns cannot be higher than the demand for new products in the first period. Constraint (3.39) implies that the price for remanufactured products in the second period cannot be higher than the price for new products in the first period.

In the reminder of this section, we use $m^{II} = \beta^{II}\gamma^{II} - \beta^{II} - \gamma^{II}$ to simplify the writing.

Lemma 2. *In two-period model, the objective function is concave and the constraints are convex, therefore the optimization problem is convex.*

Proof. The Hessian matrix of the objective function is:

$$A_2 = \begin{vmatrix} -\frac{2}{1-\alpha^{II}} - \frac{2c_c^{II}}{(1-\alpha^{II})^2 m^{II2}} & \frac{2}{1-\alpha^{II}} + \frac{2c_c^{II}}{\alpha^{II}(1-\alpha^{II})^2 m^{II2}} & 0 \\ \frac{2}{1-\alpha^{II}} + \frac{2c_c^{II}}{\alpha^{II}(1-\alpha^{II})^2 m^{II2}} & -\frac{2}{\alpha^{II}(1-\alpha^{II})} - \frac{2c_c^{II}}{\alpha^{II2}(1-\alpha^{II})^2 m^{II2}} & 0 \\ 0 & 0 & -2 \end{vmatrix} \tag{3.41}$$

Matrix A_2 is negative semi-definite if and only if the following three conditions are satisfied:

$$\frac{8m^{II2}\alpha^{II}\left(1-\alpha^{II}\right)+8c_c^{II}}{\alpha^{II2}\left(1-\alpha^{II}\right)^2 m^{II2}} \geq 0 \tag{3.42}$$

$$\frac{2m^{II2}\alpha^{II2}\left(1-\alpha^{II}\right)^2+2m^{II2}\alpha^{II}\left(1-\alpha^{II}\right)+2\alpha^{II2}c_c^{II}+2c_c^{II}}{\alpha^{II2}\left(1-\alpha^{II}\right)^2 m^{II2}} \geq 0 \tag{3.43}$$

$$\frac{4m^{II2}\alpha^{II}\left(1-\alpha^{II}\right)\left(2+\alpha^{II}\right)+4\alpha^{II2}c_c^{II}+8c_c^{II}}{\alpha^{II2}\left(1-\alpha^{II}\right)^2 m^{II2}} \geq 0 \tag{3.44}$$

Given that $0 \leq \alpha^{II} \leq 1$, $-1 \leq m^{II} \leq 0$, and $c_c^{II} \geq 0$, it is easy to see that Eq. (3.42), (3.43), and (3.44) are always satisfied. Thus, A_2 is negative semi-definite and the objective function is concave.

Since all constrains are linear, they are convex. □

Theorem 2 and Figure 3.6 summarize the optimal production and pricing strategies in the two-period model. c_{il}^{II} represents the l^{th} thresholds of unit manufacturing cost of product type i in two-period model.

Theorem 2. *The optimal production and pricing strategies depend on the unit manufacturing cost and the unit remanufacturing cost:*

1. *If $c_r^{II} \geq c_{r1}^{II}$, then produce only new products in the second period and set $p_{n1}^{II} = p_{n2}^{II} = p_1^{II}$.*

2. *If $c_{r2}^{II} \leq c_r^{II} < c_{r1}^{II}$, then produce both new and remanufactured products in the second period, collect part of the new products sold in the first period, and set $p_{n1}^{II} = p_{n2}^{II} = p_2^{II}$, and $p_{r2}^{II} = p_3^{II}$.*

3. *If* $c_{r4}^{II} \leq c_r^{II} < c_{r2}^{II}$ *and* $c_n^{II} > c_{n1}^{II}$*, or if* $c_{r3}^{II} \leq c_r^{II} < c_{r2}^{II}$ *and* $c_n^{II} \leq c_{n1}^{II}$*, then produce both new and remanufactured products in the second period, collect all the new products sold in the first period, and set* $p_{n1}^{II} = p_4^{II}$*,* $p_{n2}^{II} = p_5^{II}$*, and* $p_{r2}^{II} = p_6^{II}$*.*

4. *If* $c_r^{II} \leq c_{r6}^{II}$ *and* $c_n^{II} > c_{n1}^{II}$*, or if* $c_r^{II} \leq c_{r3}^{II}$ *and* $c_n^{II} \leq c_{n1}^{II}$*, then produce both new and remanufactured products in the second period, collect all the new products sold in the first period, and set* $p_{n2}^{II} = p_7^{II}$*, and* $p_{n1}^{II} = p_{r2}^{II} = p_8^{II}$*.*

5. *If* $c_{r5}^{II} \leq c_r^{II} < c_{r4}^{II}$ *and* $c_n^{II} > c_{n1}^{II}$*, then produce only remanufactured products in the second period, collect all the new products sold in the first period and set* $p_{n1}^{II} = p_9^{II}$*, and* $p_{r2}^{II} = p_{10}^{II}$*.*

6. *If* $c_{r6}^{II} \leq c_r^{II} < c_{r5}^{II}$ *and* $c_n^{II} > c_{n1}^{II}$*, then produce only remanufactured products in the second period, collect all the new products sold in the first period, and set* $p_{n1}^{II} = p_{r2}^{II} = p_{11}^{II}$*.*

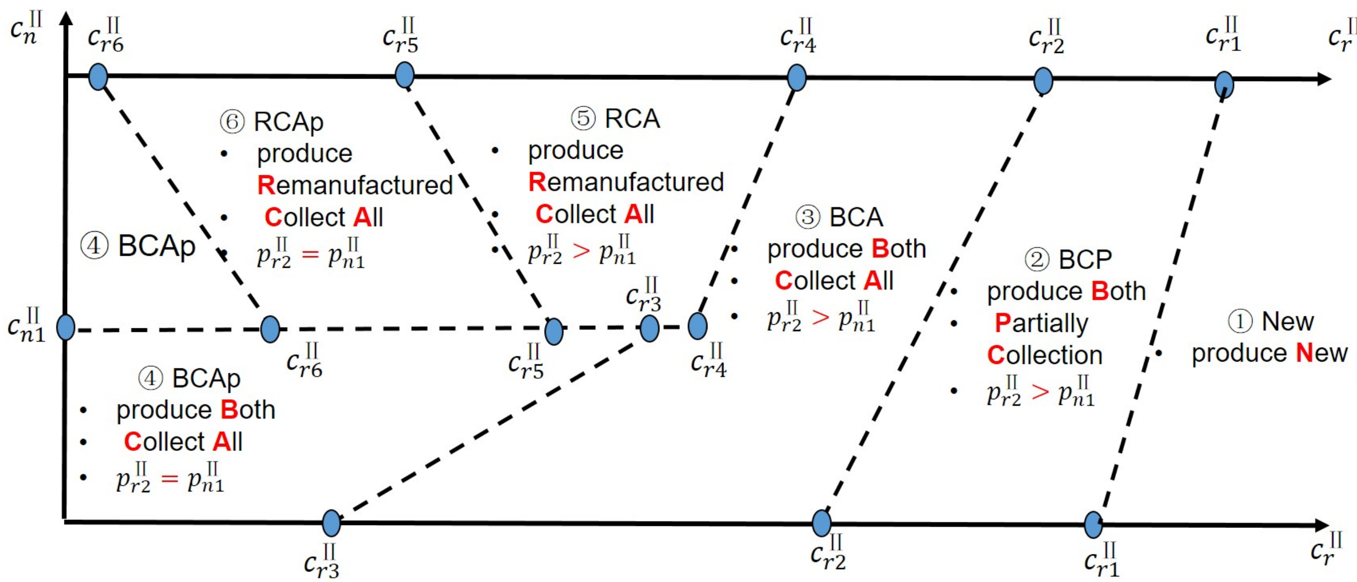

Figure 3.6: The result of two-period of model

The following labeling convention is adopted for the production strategies in Figure 3.6: a numerical counter followed by three or four letters. The first letter represents the type of products being made in the second period: N for New; B for Both new and remanufactured; R for Remanufactured. The second and third letters represent the type of collection of returns: CA is for Collect All, and CP for Partial Collection. In some cases, a fourth letter in small caps is used to show that the price for remanufactured products is equal to the price for new products in the first period. Please note that policy 1-New is the only exception to this convention as there is no collection of returns needed.

Proof. Given that the optimization problem is convex according to Lemma 2, the optimal solutions of Theorem 2 are obtained from solving the following conditions:

$$\frac{\partial TP^{II}}{\partial p_{n2}^{II}} - u_1 + u_2\alpha^{II} - u_3\alpha^{II} \leq 0 \tag{3.45}$$

$$p_{n2}^{II}\left(\frac{\partial TP^{II}}{\partial p_{n2}^{II}} - u_1 + u_2\alpha^{II} - u_3\alpha^{II}\right) = 0 \tag{3.46}$$

$$\frac{\partial TP^{II}}{\partial p_{n2}^{II}} + u_1 - u_2 + u_3 - u_4 \leq 0 \tag{3.47}$$

$$p_{r2}^{II}\left(\frac{\partial TP^{II}}{\partial p_{r2}^{II}} + u_1 - u_2 + u_3 - u_4\right) = 0 \tag{3.48}$$

$$\frac{\partial TP^{II}}{\partial p_{n1}^{II}} + u_3\alpha^{II}\left(1-\alpha^{II}\right)\left(-\gamma^{II}\beta^{II} + \gamma^{II} + \beta^{II}\right) + u_4 \leq 0 \tag{3.49}$$

$$p_{n1}^{II}\left(\frac{\partial TP^{II}}{\partial p_{n1}^{II}} + u_3\alpha^{II}\left(1-\alpha^{II}\right)\left(-\gamma^{II}\beta^{II} + \gamma^{II} + \beta^{II}\right) + u_4\right) = 0 \tag{3.50}$$

$$Q^{II} - \frac{p_{n2}^{II} - p_{r2}^{II}}{1-\alpha^{II}} \geq 0 \tag{3.51}$$

$$u_1\left(Q^{II} - \frac{p_{n2}^{II} - p_{r2}^{II}}{1-\alpha^{II}}\right) = 0 \tag{3.52}$$

$$\frac{\alpha^{II}p_{n2}^{II} - p_{r2}^{II}}{\alpha^{II}\left(1-\alpha^{II}\right)} \geq 0 \tag{3.53}$$

$$u_2\left(\frac{\alpha^{II}p_{n2}^{II} - p_{r2}^{II}}{\alpha^{II}\left(1-\alpha^{II}\right)}\right) = 0 \tag{3.54}$$

$$\left(Q^{II} - p_{n1}^{II}\right) - \frac{\alpha^{II}p_{n2}^{II} - p_{r2}^{II}}{\alpha^{II}\left(1-\alpha^{II}\right)\left(-\gamma^{II}\beta^{II} + \gamma^{II} + \beta^{II}\right)} \geq 0 \tag{3.55}$$

$$u_3\left(\left(Q^{II} - p_{n1}^{II}\right) - \frac{\alpha^{II}p_{n2}^{II} - p_{r2}^{II}}{\alpha^{II}\left(1-\alpha^{II}\right)\left(-\gamma^{II}\beta^{II} + \gamma^{II} + \beta^{II}\right)}\right) \geq 0 \tag{3.56}$$

$$p_{n1}^{II} - p_{r2}^{II} \geq 0 \tag{3.57}$$

$$u_4\left(p_{n1}^{II} - p_{r2}^{II}\right) \geq 0 \tag{3.58}$$

$$p_{n1}^{II}, p_{n2}^{II}, p_{r2}^{II}, u_1, u_2, u_3, u_4 \geq 0 \tag{3.59}$$

Similarly as in the one-period model: $p_{n2}^{II} > 0$ and $p_{r2}^{II} > 0$. Moreover, according to the constraint (3.39), $p_{n1}^{II} \geq p_{r2}^{II}$. As a result, $p_{n1}^{II} > 0$. So, conditions (3.45) to

Critical values	Expression
c_{r1}^{II}	$\frac{\alpha^{II} c_n^{II} m^{II}}{\beta^{II}-1}$
c_{r2}^{II}	$\frac{-{m^{II}}^{2}\left(Q^{II}-c_n^{II}\right){\alpha^{II}}^{2}+m^{II}\left(\left(Q^{II}-c_n^{II}\right)m^{II}+c_n^{II}\right)\alpha^{II}+c_c^{II}\left(Q^{II}-c_n^{II}\right)}{\beta^{II}-1}$
c_{r3}^{II}	$\frac{-{m^{II}}^{2}{\alpha^{II}}^{3}Q^{II}+3\left(Q^{II}m^{II}-Q^{II}/3+c_n^{II}/3\right)m^{II}{\alpha^{II}}^{2}+\left(-2{m^{II}}^{2}Q^{II}\right)\alpha^{II}}{\left({\alpha^{II}}^{2}m^{II}-\alpha^{II}m^{II}-1\right)(\beta^{II}-1)}$ $\frac{+\left(\left(Q^{II}-2c_n^{II}\right)m^{II}+\left(c_c^{II}+1\right)\left(Q^{II}+c_n^{II}\right)\right)\alpha^{II}+\left(-2c_c^{II}-1\right)Q^{II}-c_n^{II}}{\left({\alpha^{II}}^{2}m^{II}-\alpha^{II}m^{II}-1\right)(\beta^{II}-1)}$
c_{r4}^{II}	$\frac{{m^{II}}^{2}Q^{II}{\alpha^{II}}^{2}-m^{II}\left(m^{II}+1\right)\left(Q^{II}-c_n^{II}\right)\alpha^{II}-\left(c_c^{II}+1\right)\left(Q^{II}-c_n^{II}\right)}{m(\beta^{II}-1)\alpha^{II}}$
c_{r5}^{II}	$\frac{\left(-{m^{II}}^{2}{\alpha^{II}}^{2}+\left(2{m^{II}}^{2}-2c_c^{II}-2\right)\alpha^{II}+2c_c^{II}+1\right)Q^{II}+c_n^{II}\left(\alpha^{II}m^{II}+1\right)}{(\beta^{II}-1)(\alpha^{II}m^{II}+1)}$
c_{r6}^{II}	$\frac{{m^{II}}^{2}{\alpha^{II}}^{3}Q^{II}+\left(\left(-{m^{II}}^{2}-2c_c^{II}+2m^{II}-2\right)Q^{II}+m^{II}c_n^{II}\left(m^{II}+1\right)\right){\alpha^{II}}^{2}}{\alpha^{II}(\beta^{II}-1)(\alpha^{II}m^{II}+1)}$ $\frac{+\left(\left(-4m^{II}+2c_c^{II}+1\right)Q^{II}+2m^{II}c_n^{II}+c_n^{II}\right)\alpha^{II}-Q^{II}+c_n^{II}}{\alpha^{II}(\beta^{II}-1)(\alpha^{II}m^{II}+1)}$
c_{n1}^{II}	$-\frac{\left(2{\alpha^{II}}^{2}m^{II}-3\alpha^{II}m^{II}-1\right)Q^{II}}{\alpha^{II}m^{II}+1}$
p_1^{II}	$\frac{Q^{II}}{2}+\frac{c_n^{II}}{2}$
p_2^{II}	$\frac{Q^{II}}{2}+\frac{c_n^{II}}{2}$
p_3^{II}	$\frac{\left(Q^{II}\alpha^{II}\left(\alpha^{II}-1\right){m^{II}}^{2}+c_r^{II}\left(\beta^{II}-1\right)\left(\alpha^{II}-1\right)m^{II}-c_c^{II}\left(Q^{II}+c_n^{II}\right)\right)\alpha^{II}}{\left(2{\alpha^{II}}^{2}-2\alpha^{II}\right){m^{II}}^{2}-2c_c^{II}}$
p_4^{II}	$\frac{2{m^{II}}^{2}Q^{II}{\alpha^{II}}^{2}+\left(-2{m^{II}}^{2}Q^{II}-m^{II}c_n^{II}\right)\alpha^{II}+\left(-2c_c^{II}-1\right)Q^{II}-c_n^{II}+c_r^{II}\left(\beta^{II}-1\right)}{2{m^{II}}^{2}{\alpha^{II}}^{2}-2{m^{II}}^{2}\alpha^{II}-2c_c^{II}-2}$
p_5^{II}	$\frac{Q^{II}}{2}+\frac{c_n^{II}}{2}$
p_6^{II}	$\frac{\alpha^{II}\left(Q^{II}\alpha^{II}\left(\alpha^{II}-1\right){m^{II}}^{2}+\left(Q^{II}-c_n^{II}+c_r^{II}\left(\beta^{II}-1\right)\right)\left(\alpha^{II}-1\right)m^{II}-\left(c_c^{II}+1\right)\left(Q^{II}+c_n^{II}\right)\right)}{\left(2{\alpha^{II}}^{2}-2\alpha^{II}\right){m^{II}}^{2}-2c_c^{II}-2}$
p_7^{II}	$\frac{-Q^{II}{\alpha^{II}}^{4}{m^{II}}^{2}+4\left(\left(Q^{II}+c_n^{II}/4\right)m^{II}-Q^{II}/4+c_n^{II}/4+\left(-\beta^{II}/4+1/4\right)c_r^{II}\right)m^{II}{\alpha^{II}}^{3}}{-2+2{\alpha^{II}}^{3}{m^{II}}^{2}+\left(-2{m^{II}}^{2}-2c_c^{II}+4m^{II}-2\right){\alpha^{II}}^{2}-4\alpha^{II}m^{II}}+$ $\frac{-3\left(\left(Q^{II}+c_n^{II}/3\right)m^{II}-Q^{II}+\left(-\beta^{II}/3+1/3\right)c_r^{II}\right)m^{II}{\alpha^{II}}^{2}+\left(\left(-2Q^{II}-2c_n^{II}\right)m^{II}\right)\alpha^{II}}{-2+2{\alpha^{II}}^{3}{m^{II}}^{2}+\left(-2{m^{II}}^{2}-2c_c^{II}+4m^{II}-2\right){\alpha^{II}}^{2}-4\alpha^{II}m^{II}}$ $\frac{+\left(\left(-2c_c^{II}-1\right)Q^{II}-c_n^{II}+c_r^{II}\left(\beta^{II}-1\right)\right)\alpha^{II}-Q^{II}-c_n^{II}}{-2+2{\alpha^{II}}^{3}{m^{II}}^{2}+\left(-2{m^{II}}^{2}-2c_c^{II}+4m^{II}-2\right){\alpha^{II}}^{2}-4\alpha^{II}m^{II}}$
p_8^{II}	$\frac{Q^{II}m^{II}\left(m^{II}+1/2\right){\alpha^{II}}^{3}+\left(-{m^{II}}^{2}Q^{II}+\left(Q^{II}/2-c_n^{II}/2\right)m^{II}+\left(-c_c^{II}-1/2\right)Q^{II}-c_n^{II}/2\right){\alpha^{II}}^{2}}{-1+{\alpha^{II}}^{3}{m^{II}}^{2}+\left(-{m^{II}}^{2}-c_c^{II}+2m^{II}-1\right){\alpha^{II}}^{2}-2\alpha^{II}m}$ $+\frac{\left(-Q^{II}m-Q^{II}/2-c_n^{II}/2\right)\alpha^{II}\left(\beta^{II}/2-1/2\right)c_r^{II}{\alpha^{II}}^{2}}{-1+{\alpha^{II}}^{3}{m^{II}}^{2}+\left(-{m^{II}}^{2}-c_c^{II}+2m^{II}-1\right){\alpha^{II}}^{2}-2\alpha^{II}m}$
p_9^{II}	$\frac{\left(\left(2{m^{II}}^{2}+m^{II}\right)\alpha^{II}+2c_c^{II}+1\right)Q^{II}+\left(-\beta^{II}+1\right)c_r^{II}+c_n^{II}}{2{m^{II}}^{2}\alpha^{II}+2c_c^{II}+2}$
p_{10}^{II}	$\frac{\alpha^{II}\left(Q^{II}\alpha^{II}{m^{II}}^{2}+\left(Q^{II}-c_n^{II}+c_r^{II}\left(\beta^{II}-1\right)\right)m^{II}+2Q^{II}\left(c_c^{II}+1\right)\right)}{2{m^{II}}^{2}\alpha^{II}+2c_c^{II}+2}$
p_{11}^{II}	$\frac{\alpha^{II}Q^{II}\left(m^{II}+1\right)}{\alpha^{II}m^{II}+1}$

Table 3.3: Critical values for the two-period model

(3.50) can be simplified as follows:

$$\frac{\partial TP^{II}}{\partial p_{n2}^{II}} - u_1 + u_2\alpha^{II} - u_3\alpha^{II} = 0 \tag{3.60}$$

$$\frac{\partial TP^{II}}{\partial p_{n2}^{II}} + u_1 - u_2 + u_3 - u_4 = 0 \tag{3.61}$$

$$\frac{\partial TP^{II}}{\partial p_{n1}^{II}} + u_3\alpha^{II}\left(1-\alpha^{II}\right)\left(-\gamma^{II}\beta^{II} + \gamma^{II} + \beta^{II}\right) + u_4 = 0 \tag{3.62}$$

Solving conditions (3.51) to (3.59), and (3.60) to (3.62) yields the results in Theorem 2. □

The appearance of policy 4-BCAp, when the value of c_r^{II} is extremely low and the value of c_n^{II} is high, is counter-intuitive. The model suggests to produce both new and remanufactured (Policy 4-BCAp) when producing only remanufactured products seems to be the most profitable option given that the unit remanufacturing cost is at its lowest. The following analysis explains this behavior. Figures 3.7 and 3.8 are plotted for the following specific values: $\alpha^{II} = 0.95, \beta^{II} = 0.2, \gamma^{II} = 0.6, c_n^{II} = 1700, c_c^{II} = 0.1$, and $Q^{II} = 2000$, which cover the region where policies 4-BCAp to 6-RCAp are active.

If the company insists on producing only remanufactured products in the second period, when $c_r^{II} < c_{r6}^{II}$, the total profit decreases (i.e., the solid blue line increases faster than the solid thin red line in Figure 3.7). Adopting policy 4-BCAp, although causing profit losses from new products in both periods, yields more profit gains from remanufactured products which is positive overall (i.e., the dashed green line is below the dashed blue dashed line, but the dashed purple line is above the dashed orange line).

Figure 3.8 depicts that as the unit remanufacturing cost decreases, the optimal demand for new products keeps constant in the policies 5-RCA and 6-RCAp, but increases continuously in policy 4-BCAp. The optimal demand for remanufactured products increases in policy 5-RCA and then keeps constant in policy 6-RCAp. When policy 4-BCAp becomes the optimal production strategy, the demand for remanufactured products increases again. The reason for this is when unit remanufacturing cost decreases, producing remanufactured products becomes more profitable and the company is stimulated to engage more in remanufacturing activities. However, increasing demand for remanufactured products not only results in the increase of total remanufacturing cost, but also leads to growth of collection and inspection cost. Due to the losses in the remanufacturing process, producing one unit remanufactured products requires more than one unit returned products in average. Moreover, due to the convex collection and inspection cost, the unit collection and inspection cost margin increases with the increase of the demand. On the other hand, in order to obtain enough returns, the company needs to set the price for new products in the first period at a low level, which results in the huge losses of the profit in the first period. As a result, in order to balance the gains and losses, the company should not increase the demand for remanufactured products, when the unit remanufacturing cost is not sufficiently low ($870 < c_r^{II} < 900$), while increase the demand, when the gains can cover the losses ($c_r^{II} < 870$).

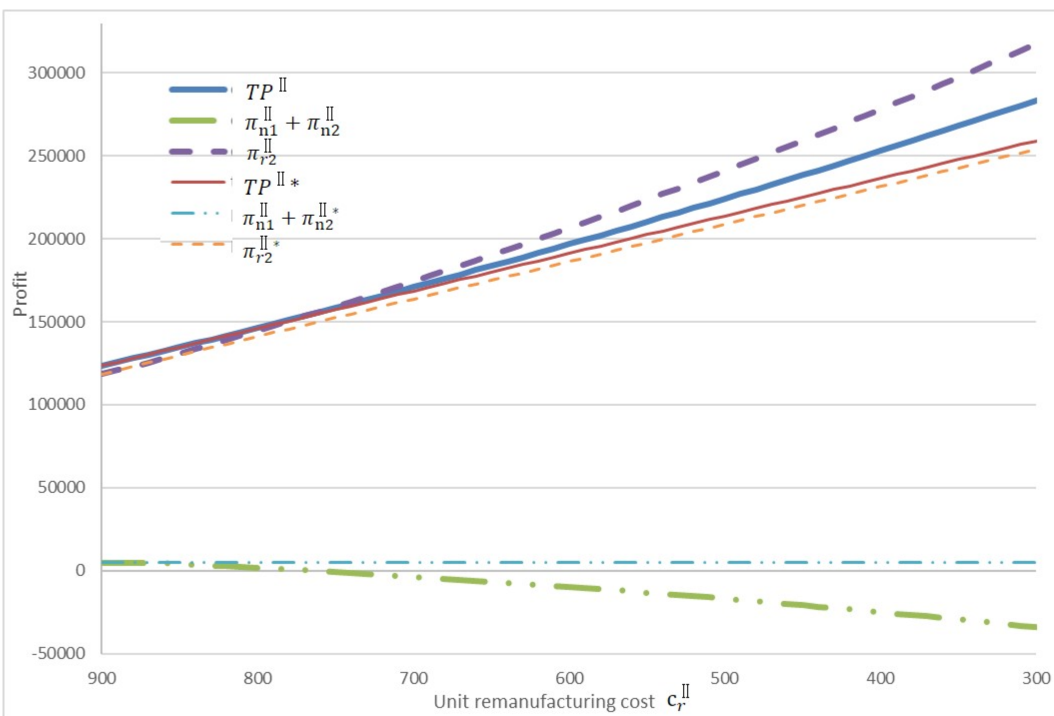

Figure 3.7: Profit functions from policies 4-BCAp and 6-RCAp as c_r^{II} decreases
* denotes profit functions when producing only remanufactured instead of producing both new and remanufactured products in the second period.

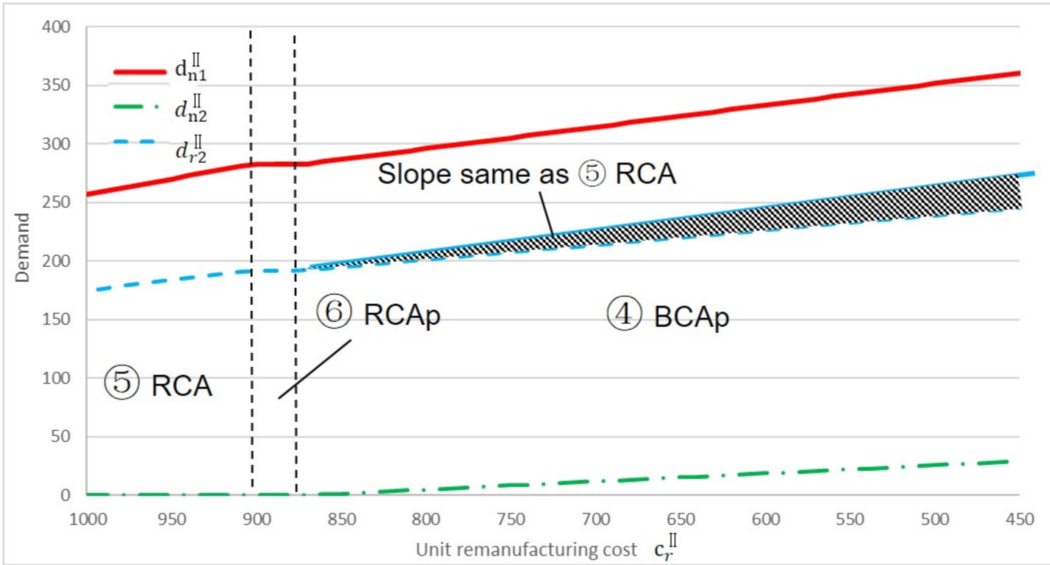

Figure 3.8: Optimal demand functions as the unit remanufacturing cost decreases

But even the company increases the demand for remanufactured products in the second period, due to the losses of profit in the first period and the convex collection and inspection cost, the increase rate of the demand for remanufactured products is slower than before (i.e., the solid blue line, which is parallel to the blue dashed line when policy 5-RCA is the optimal strategy, increase faster than the blue dashed line when policy 4-BCAp is the optimal strategy). As a result, in order to satisfy the total demand, the company needs to produce some additional new products.

From formulation perspective, the main difference in the policies 4-BCAp and 6-RCAp is that the demand for new products in second period is zero in policy 6-RCAp and positive in the policy 4-BCAp. Moreover, it also can be found that in both the policies 4-BCAp and 6-RCAp, the company collects all the products sold in the first period and set the price of the remanufactured products in the second period to be the same as the price of new products in the first period. So we simplified our objective function into a new function with the only decision valuable d_{n2}^{II}:

$$TP^{II} = \frac{\left(m^{II^2} - c_c^{II} - 1\right) Q^{II^2} \alpha^{II^2} + \left(m^{II^2} + 2\, c_c^{II} - 2\, m^{II} + 2\right) d_{n2}^{II} Q^{II} \alpha^{II^2}}{\left(\alpha^{II} m^{II} + 1\right)^2}$$
$$+ \frac{\left(-m^{II^2} + 2\, c_c^{II} + 1\right) Q^{II^2} \alpha^{II} - \left(-c_n^{II} + c_r^{II}\, \left(-1 + \beta^{II}\right)\right) m^{II} Q^{II} \alpha^{II^2}}{\left(\alpha^{II} m^{II} + 1\right)^2}$$
$$+ \frac{d_{n2}^{II}\, \alpha^{II^2} \left(\left(2\, m^{II} - 1\right) d_{n2}^{II} + \left(-m^{II} c_n^{II} - c_n^{II} + c_r^{II}\, \left(-1 + \beta^{II}\right)\right) m^{II}\right)}{\left(\alpha^{II} m^{II} + 1\right)^2}$$
$$+ \frac{\left(\left(4\, m^{II} - 2\, c_c^{II} - 1\right) d_{n2}^{II} + \left(-c_n^{II} + c_r^{II}\, \left(-1 + \beta^{II}\right)\right) \left(m^{II} - 1\right)\right) Q^{II} \alpha^{II}}{\left(\alpha^{II} m^{II} + 1\right)^2}$$
$$+ \frac{\left(-2\, m^{II} c_n^{II} + c_r^{II}\, \left(-1 + \beta^{II}\right)\right) d_{n2}^{II}\, \alpha^{II} - m^{II^2} d_{n2}^{II}\, \left(Q^{II} - d_{n2}^{II}\right) \alpha^{II^3}}{\left(\alpha^{II} m^{II} + 1\right)^2}$$
$$+ \frac{-Q^{II^2} c_c^{II} + \left(d_{n2}^{II} - c_n^{II} + c_r^{II}\, \left(-1 + \beta^{II}\right)\right) Q^{II} - d_{n2}^{II}\, \left(c_n^{II} + d_{n2}^{II}\right)}{\left(\alpha^{II} m^{II} + 1\right)^2}$$
$$+ \frac{d_{n2}^{II^{\,2}}\, \alpha^{II^2} \left(-m^{II^2} - c_c^{II}\right) - \left(2\, m^{II} d_{n2}^{II} + c_n^{II}\right) d_{n2}^{II}\, \alpha^{II}}{\left(\alpha^{II} m^{II} + 1\right)^2} \tag{3.63}$$

The derivative of TP^{II} with respect to d_{n2}^{II} is given by:

$$\frac{\partial TP^{II}}{\partial d_{n2}^{II}} = \frac{\left(\left(Q^{II} - c_n^{II}\right) m^{II^2} + \left(c_r^{II}\, \left(-1 + \beta^{II}\right)\right) m^{II} + 2\, Q^{II} \left(c_c^{II} + 1\right)\right) \alpha^{II^2}}{\left(\alpha^{II} m^{II} + 1\right)^2}$$
$$+ \frac{\left(\left(4\, Q^{II} - 2\, c_n^{II}\right) m^{II} + \left(-2\, c_c^{II} - 1\right) Q^{II} - c_n^{II} + c_r^{II}\, \left(-1 + \beta^{II}\right)\right) \alpha^{II}}{\left(\alpha^{II} m^{II} + 1\right)^2}$$
$$+ \frac{\left(-2\, Q^{II} - c_n^{II}\right) \alpha^{II^2} - m^{II^2} \alpha^{II^3} Q^{II} + Q^{II} - c_n^{II}}{\left(\alpha^{II} m^{II} + 1\right)^2}$$
$$+ \frac{\left(2\, m^{II^2} \alpha^{II^3} + \left(-2\, m^{II^2} - 2\, c_c^{II} + 4\, m^{II} - 2\right) \alpha^{II^2} - 4\, \alpha^{II} m^{II} - 2\right) d_{n2}^{II}}{\left(\alpha^{II} m^{II} 1\right)^2} \tag{3.64}$$

By adopting policy 6-RCAp, $c_r^{II} > c_{r6}^{II}$, the value range of the constant term and the coefficient of decision valuable d_{n2}^{II} in Eq. (3.64) are:

$$\frac{\left(\left(Q^{II}-c_n^{II}\right)m^{II^2}+\left(-2\,Q^{II}-c_n^{II}+c_r^{II}\,\left(-1+\beta^{II}\right)\right)m^{II}+2\,Q^{II}\left(c_c^{II}+1\right)\right)\alpha^{II^2}}{\left(\alpha^{II}m^{II}+1\right)^2}$$
$$+\frac{\left(\left(4\,Q^{II}-2\,c_n^{II}\right)m^{II}+\left(-2\,c_c^{II}-1\right)Q^{II}-c_n^{II}+c_r^{II}\,\left(-1+\beta^{II}\right)\right)\alpha^{II}}{\left(\alpha^{II}m^{II}+1\right)^2}$$
$$\frac{+Q^{II}-c_n^{II}-m^{II^2}\alpha^{II^3}Q^{II}}{\left(\alpha^{II}m^{II}+1\right)^2}<0 \tag{3.65}$$

$$\frac{\left(2\,m^{II^2}\alpha^{II^3}+\left(-2\,m^{II^2}-2\,c_c^{II}+4\,m^{II}-2\right)\alpha^{II^2}-4\,\alpha^{II}m^{II}-2\right)}{\left(\alpha^{II}m^{II}+1\right)^2}<0 \tag{3.66}$$

According to Eq. (3.65) and (3.66), $\frac{\partial TP^{II}}{\partial d_{n2}^{II}}<0$, when $d_{n2}^{II}>0$. As a result, when policy 6-RCAp is the optimal production strategy, $d_{n2}^{II}=0$ and does not increases as unit remanufacturing cost (c_r^{II}) decreases.

Similarly, by adopting policy 6-RCAp, $c_r^{II}<c_{r6}^{II}$, the value range of the constant term and the coefficient of decision valuable d_{n2}^{II} in Eq. (3.64) are::

$$\frac{\left(\left(Q^{II}-c_n^{II}\right)m^{II^2}+\left(-2\,Q^{II}-c_n^{II}+c_r^{II}\,\left(-1+\beta^{II}\right)\right)m^{II}+2\,Q^{II}\left(c_c^{II}+1\right)\right)\alpha^{II^2}}{\left(\alpha^{II}m^{II}+1\right)^2}$$
$$+\frac{\left(\left(4\,Q^{II}-2\,c_n^{II}\right)m^{II}+\left(-2\,c_c^{II}-1\right)Q^{II}-c_n^{II}+c_r^{II}\,\left(-1+\beta^{II}\right)\right)\alpha^{II}}{\left(\alpha^{II}m^{II}+1\right)^2}$$
$$\frac{+Q^{II}-c_n^{II}-m^{II^2}\alpha^{II^3}Q^{II}}{\left(\alpha^{II}m^{II}+1\right)^2}>0 \tag{3.67}$$

$$\frac{\left(2\,m^{II^2}\alpha^{II^3}+\left(-2\,m^{II^2}-2\,c_c^{II}+4\,m^{II}-2\right)\alpha^{II^2}-4\,\alpha^{II}m^{II}-2\right)}{\left(\alpha^{II}m^{II}+1\right)^2}<0 \tag{3.68}$$

The constant term (Eq. 3.67) is positive and the coefficient of decision valuable d_{n2}^{II} (Eq. 3.68) is negative. Thus, when d_{n2}^{II} is not too large, $\frac{\partial TP^{II}}{\partial d_{n2}^{II}}>0$. Moreover, the constant term (Eq. 3.67) increases as unit remanufacturing cost decreases (c_r^{II}). As a result, the increase of d_{n2}^{II} leads to the increase of total profit.

Chapter 4

Numerical examples and sensitivity analysis

This chapter presents detailed sensitivity analyses for both one-period and two-period models previously discussed. Six analyses are conducted to investigate the influence of key parameters on the optimal results. In all analyses, optimal production strategies will be derived based on the values of the unit remanufacturing cost c_r.

4.1 Sensitivity to the customers' tolerance for remanufactured products

In this first test, the sensitivity to the customers' tolerance for remanufactured products is analyzed by varying α^k and c_r^k while keeping all other parameters as: $\beta^k = 0.2, \gamma^k = 0.6, c_n^k = 1700, c_c^k = 0.1$, and $Q^k = 2000$ $(k = I, II)$.

4.1.1 One-period model

In the one-period model, the choice of the optimal production and related pricing policy are affected by the unit remanufacturing cost c_3^I as seen in Figure 4.1. It depicts the production strategy based on the unit remanufacturing cost c_r^I and the customers' tolerance for remanufactured products, when other parameters are fixed.

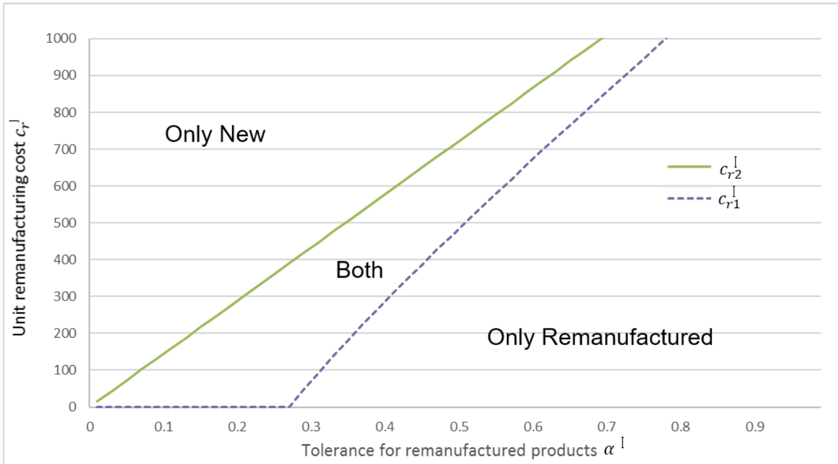

Figure 4.1: Optimal production strategies in one-period model

According to the figure, it can be seen that the possibility of obtaining the maximum profit by producing only new products decreases as the customers' tolerance for remanufactured products increases. The possibility of producing both new and remanufactured increases when $\alpha^I \in [0, 0.27)$ and decreases beyond 0.27. When customers' tolerance for remanufactured products is very high the opportunity to produce only remanufactured products is increased.

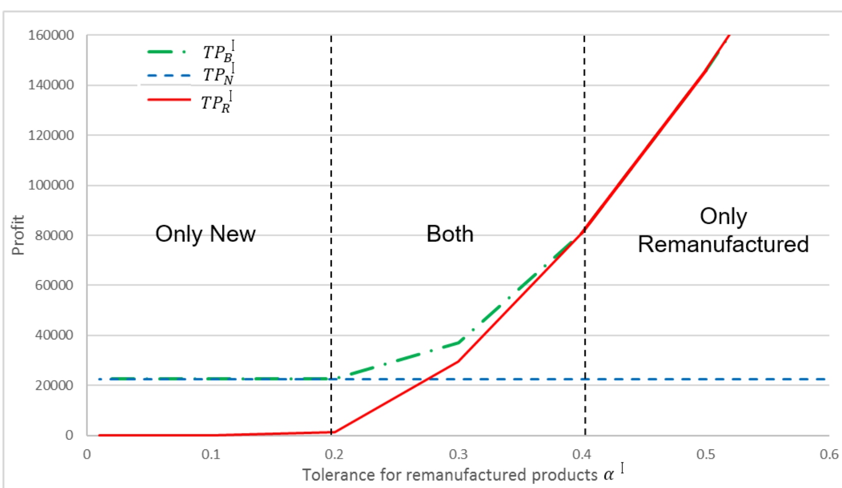

Figure 4.2: Relationship between profits and α^I in one-period model

Figures 4.2, 4.3, and 4.4 are plotted for a specific value $c_r^I = 300$. Figure 4.2 shows how the profit changes as the customers' tolerance for remanufactured products increases. It shows that when customers' tolerance for remanufactured products is sufficient high, remanufacturing becomes beneficial and the total profit increases.

However, when producing only new products is the most profitable choice for the company, the profit is independent of the customers' view on the remanufactured products. The reason is trivial: new products are the only products on the market and therefore, their demand is not affected by α^I.

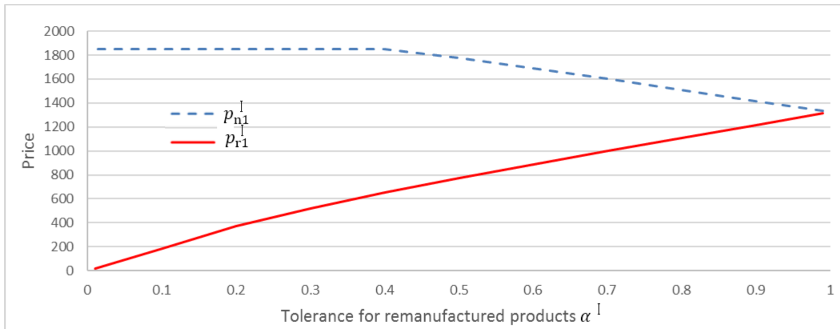

Figure 4.3: Relationship between optimal prices and α^I in one-period model

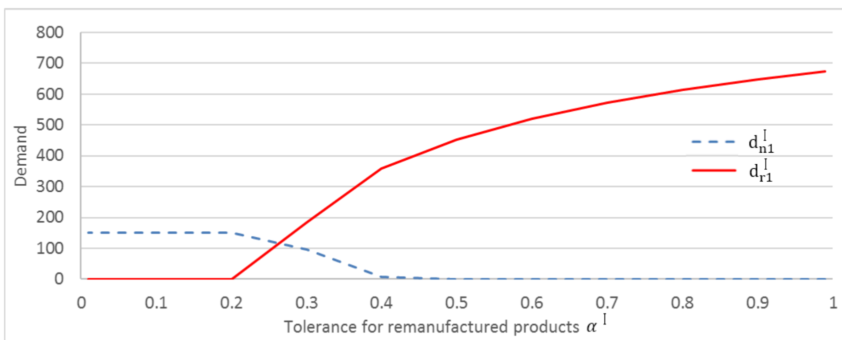

Figure 4.4: Relationship between demands and α^I in one-period model

According to Figure 4.3, in order to get the maximum profit, the price of the remanufactured products increases when α^I increases. At the same time, the price of new products decreases continuously. This causes the demand for remanufactured products to increase while the demand for new products decreases (see Figure 4.4). This can be explained by the fact that when customers have totally opposite views on the new and remanufactured products, most of them will not consider buying remanufactured products even for a low price. As a result, the remanufactured products are not profitable and the company focuses only on the sale of the new products by setting the optimal price. When the average view of customers for the remanufactured products improves, the remanufactured products become acceptable for some customers at a certain price and this price increases with the increase of α^I. So in this situation, both the demand and the price of the remanufactured products both begin to increase. However, because of the cannibalization between the new and remanufactured products in the same market, the demand of new products decreases.

Moreover, when customers' tolerance for remanufactured products keeps increasing, the demand of remanufactured products increases rapidly. Due to the nonlinear marginal cost of remanufactured products (including the collection and remanufacturing cost), the company will lower the price for new products in order to reduce the growth of the total remanufacturing cost.

4.1.2 Two-period model

For the two-period model, the analysis is much more complex. The choice of the optimal production and pricing policies in the two-period model depends on the unit manufacturing cost, the unit remanufacturing cost, and the customers' tolerance for the remanufactured products. Figure 4.5 depicts the optimal production strategies based on the customers' tolerance for remanufactured products and unit remanufacturing cost. The production strategies use the same notation introduced in Figure 3.6.

From Figure 4.5, it can be seen that if customers' tolerance for remanufactured products is too small ($\alpha^{II} \leq 0.12$) or too high ($\alpha^{II} \geq 0.96$), then the unit manufacturing cost c_n^{II} is smaller than its threshold c_{n1}^{II} and the selection of the optimal policy depends on the unit remanufacturing cost c_r^{II} and its thresholds c_{r1}^{II}, c_{r2}^{II}, and c_{r3}^{II}.

However, in the other case ($0.12 \leq \alpha^{II} \leq 0.96$), the selection depends on c_r^{II}, c_{r1}^{II}, c_{r2}^{II}, c_{r4}^{II}, c_{r5}^{II}, and c_{r6}^{II}. For example, if $c_r^{II} \geq 200$ and $\alpha^{II} < 0.1$, then the optimal production strategy is 1-NCP (New with partial collection) in order to obtain the maximal profit.

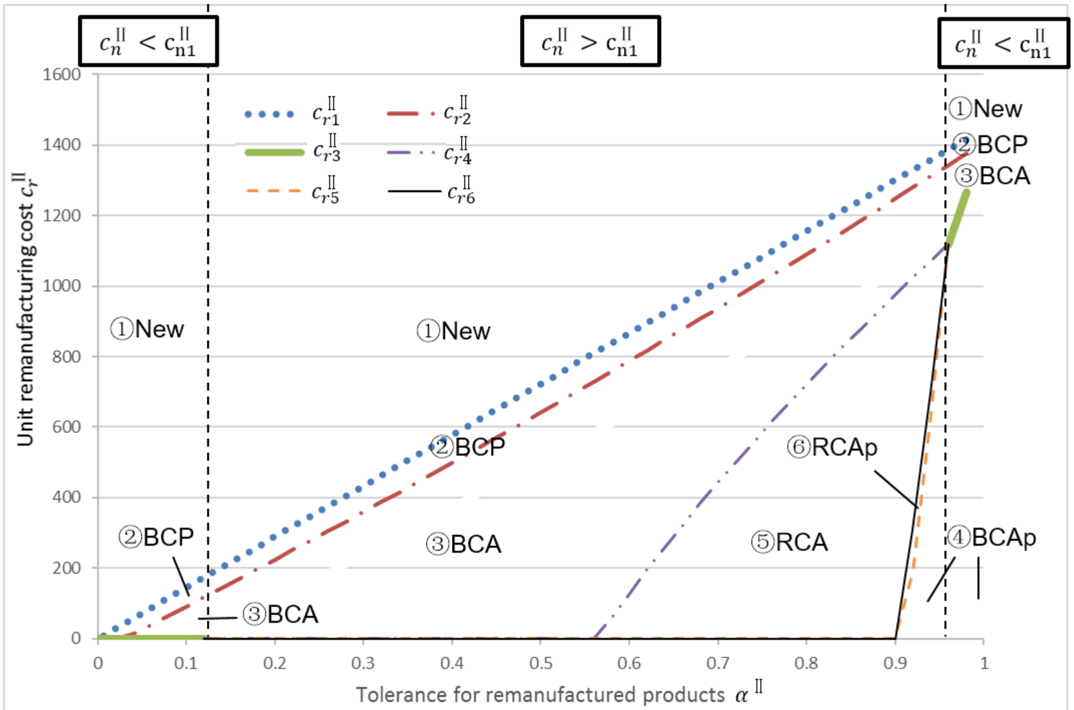

Figure 4.5: Optimal production strategies in two-period model

The left part of Figure 4.5 shows the case $c_n < c_{n1}^{II}$ where only policy 1-New, policy 2-BCP or policy 3-BCA can be chosen depending on the value of the unit remanufacturing cost and customers' tolerance for remanufactured products. When the customers' tolerance for remanufactured products increases, the possibility for the company to produce only new products in the second period (policy 1-New) decreases. The opportunity to produce both new and remanufactured products in the second period (policy 2-BCP and policy 3-BCA) become non-negligible with the probability of adopting policy 3-BCA increasing rapidly.

The middle part of Figure 4.5 shows the case $c_n^{II} > c_{n1}^{II}$. When the customers' tolerance for remanufactured products increases, the company is less likely to only produce new products in the second period (policy 1-New). Policy 2-BCP and 3-BCA (produce both) become significant with the probability of adopting policy 3-BCA increasing the most. The probability of adopting policy 3-BCA increases when $\alpha^{II} < 0.55$ and then decreases due to the appearance of policies 4-BCAp, 5-RCA, and 6-RCAp. The opportunity to produce only remanufactured products in the second period (policies 5-RCA and 6-RCAp) appears around $\alpha^{II} = 0.55$ and increases steadily until $\alpha^{II} = 0.90$ beyond which value it starts to decrease. When $\alpha^{II} > 0.9$, the company is more likely to obtain the maximum profit by adopting policy 4-BCAp.

The right part of Figure 4.5 depicts a variant of case $c_n < c_{n1}^{II}$. It is similar to the left part of Figure 4.5. Here the difference lies in the appearance of policy 4-BCAp which causes policy 3-BCA to diminish.

Another insight that can be drawn from these results concerns the sequence of policy selection. As α^{II} increases, the general selection sequence is: policy 1, policy 2, policy 3, policy 5, policy 6, and policy 4. It should be noted that depending on the actual value of the unit remanufacturing cost, some of the policies may not be adopted regardless of how α^k changes. In other words, in the second period, the sequence goes from producing only new products, to producing both new and remanufactured, to producing only remanufactured products, and finally back to producing both new and remanufactured. This result is slightly different from the result in the one-period model. In some cases, when the customers perceive a very small difference between the new and remanufactured products, the company should produce both products instead of only remanufactured products in the second period. In the two-period model, the number of returned products is limited by the number of new products sold in the first period. So producing more remanufactured products in the second period may require more new products to be sold in the first period at a lower price, which causes profit losses for the company. As a result, in the two-period model, when α^{II} is sufficiently large, the company should barely produce more remanufactured products, but produce enough new products to satisfy demand. This is also seen in Figure 4.6, where for low values of α^{II}, the profit from remanufactured (solid red curve) decreases.

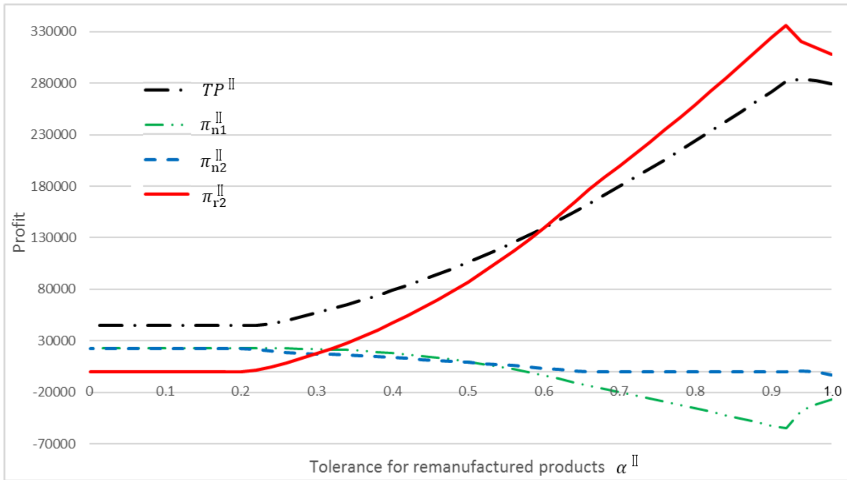

Figure 4.6: Relationship between profits and α^{II} in two-period model

Figures 4.6, 4.8, and 4.9 are plotted for a specific value $c_r^{II} = 300$. One interesting feature from Figure 4.6, shows the profit from remanufactured products to be higher than the total profit (i.e., the solid red curve passes above the long dashed black curve) for high values of α^{II}. This occurs because producing so many remanufactured products in the second-period requires a high volume of sales of new products in the first-period at a low price. Thus, causing profit losses in the first period as shown by the long-dashed green curve dropping into negative values. Therefore, the total profit will be lower than the profit from remanufactured products only.

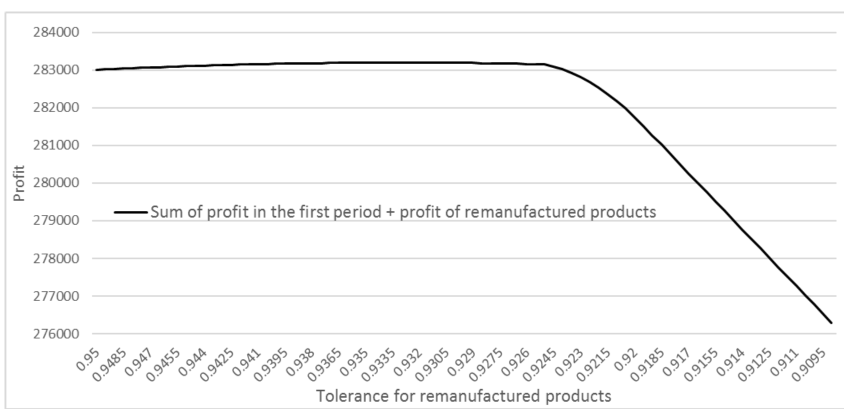

Figure 4.7: Relationship between price difference and α^{II} in two-period model

According to Figure 4.6, the general trend of the total profit is same as what was observed for the one-period model. Overall, the higher the customers' tolerance for remanufactured products is, the more profit the company can obtain. However, for extremely high values of α^{II}, the total profit exhibits a slight decrease as shown in Figure 4.7. This decrease, as explained before, is due to the fact that when customers are highly favourable toward remanufactured products, the company has to sell more new products in the first period at a lower than normal price in order to guarantee sufficient returns that will be used for remanufacturing. Thus, the company cannot obtain more profit by producing more remanufactured products and has to reduce the quantities of remanufactured products and new products in the first period by adjusting their prices as can be seen in Figures 4.9 and Figure 4.8. The price adjustments have to satisfy two constraints: demands for both types of products have to be non-negative and new products are sold at a price at least equal to the price of remanufactured ones. So when the company is unable to compensate negative effect caused by the increasing customers' tolerance for remanufactured products, the total profit drops.

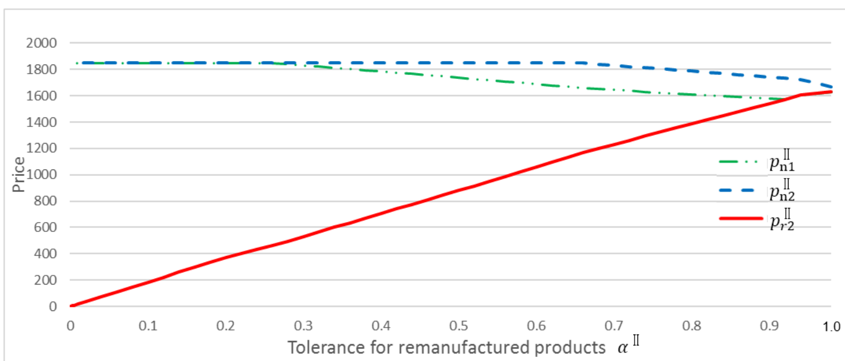

Figure 4.8: Relationship between optimal prices and α^{II} in two-period model

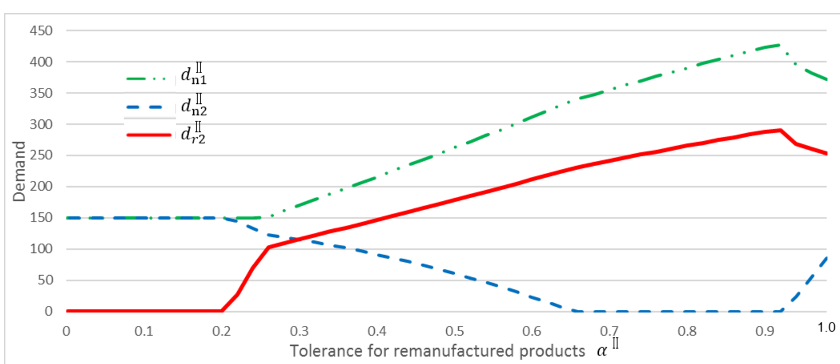

Figure 4.9: Relationship between demands and α^{II} in two-period model

For low values of α^{II}, the behaviour of the prices and demands in the second period as the customers' tolerance for remanufactured increases is similar to what was observed in the one-period model. The price for new products stays constant and is exactly the same in the first and second period. As α^{II} increases to reach a mid-scale range, the prices for new decrease slightly. This behavior is explained by the fact that when α^{II} is small, the company remanufactures no or very few products to satisfy the market. Having so few remanufactured products on the market, the company can set the price of the new products in the second period to be the same as the price for new in the first period because there is no competition from remanufactured and also because there is no need to increase the sales in the first period. However, when α^{II} increases, the quantity of the remanufactured products produced by the company grows and as a result there is a need for more products returns at the end of the first period. Therefore the company lowers the price of new products in the first period in order to increase demand, which is shown in Figure 4.9.

Another interesting behavior is observed in Figure 4.8 is that when the value of α^{II} is close to 1: the prices for new or remanufactured products in both periods converge to a single value. This occurs for two main reasons. The first reason is that the price for new products in the first period cannot be lower than the price for remanufactured products. So in order to obtain enough returned products at the end of the first period, the price for new products in the first period needs to be set at it lowest level, which is the price for remanufactured products. The second reason is that, when the customers' tolerance for remanufactured products is close to 1 (i.e., they perceive no difference between new and remanufactured), the company can set the price for remanufactured products to its highest possible value, which is the price for new, without decreasing the demand for remanufactured.

4.2 Sensitivity to the proportion of high quality returns

In the second test, the sensitivity to the proportion of high quality returns is analyzed by varying β^k and c_r^k while keeping all other parameters as: $\alpha^k = 0.9, \gamma^k = 0.5, c_n^k = 1500, c_c^k = 0.1$, and $Q^k = 2000$ $(k = I, II)$. In the following experiments, without loss of generality, we vary β^k between 0 and 0.5 because it would be rare in practice to have more than half of the returns which are in high quality that do not require some additional processing.

4.2.1 One-period model

Figure 4.10 depicts the selection of optimal production and related pricing strategies for the one-period model when the proportion of high quality returns increases.

Figure 4.10: Optimal production strategies in one-period model

The possibility/probability of producing only new products decreases when the proportion of high quality returns increases and the deceleration is positive. On the other hand, the possibility of producing only remanufactured products shows an increasing trend as depicted in Figure 4.10. High quality returns do not need to be remanufactured and can directly be sent back to the market after quick testing and repackaging. So when the proportion of high quality returns increases, the average unit remanufacturing cost decreases and the remanufacturing activities become more profitable. Moreover, the optimal production strategy in producing both new and remanufactured is not impacted by the value of β^I.

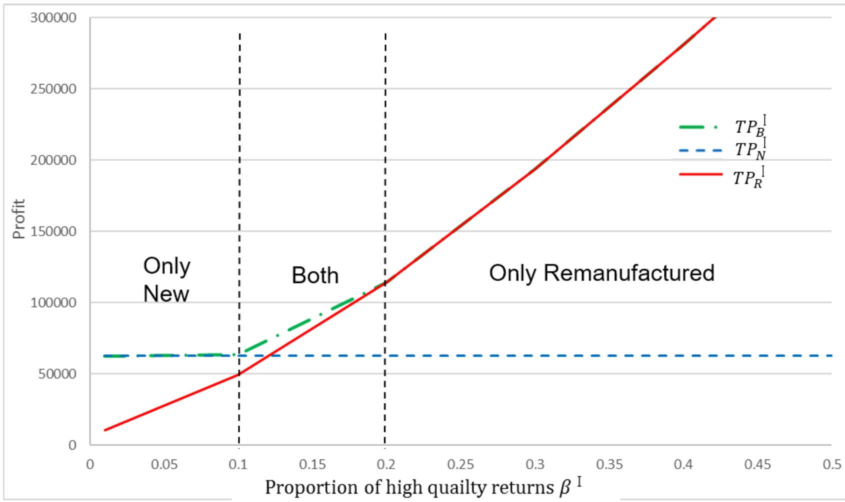

Figure 4.11: Relationship between profits and β^I in one-period model

Figures 4.11, 4.12, and 4.13 are plotted for a specific value $c_r^I = 800$. Figure 4.11 depicts the trend of the profit when the proportion of high quality returns increases. According to the figure, it can be seen that the total profit increases with the growth of the proportion of high quality returns, when $\beta^I \geq 0.1$. For $\beta^I < 0.1$, the total profit is independent of the proportion of high quality returns, because the company does not engage in remanufacturing. Furthermore, the total profit increases more rapidly when producing only remanufactured is the optimal strategy (i.e., $\beta^I \geq 0.2$). Therefore, the company can afford to invest on improving the proportion of high quality returns.

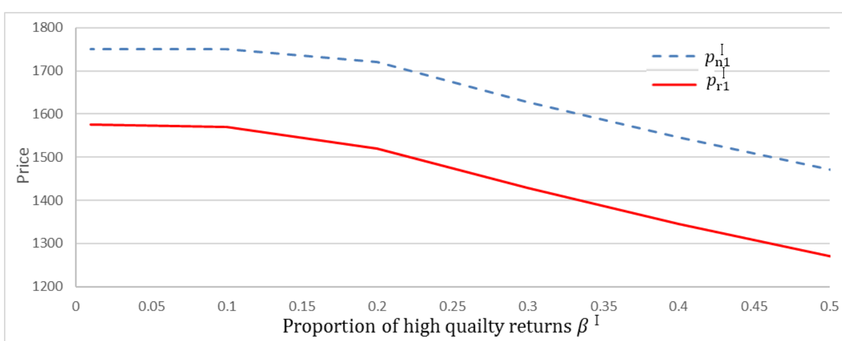

Figure 4.12: Relationship between optimal prices and β^I in one-period model

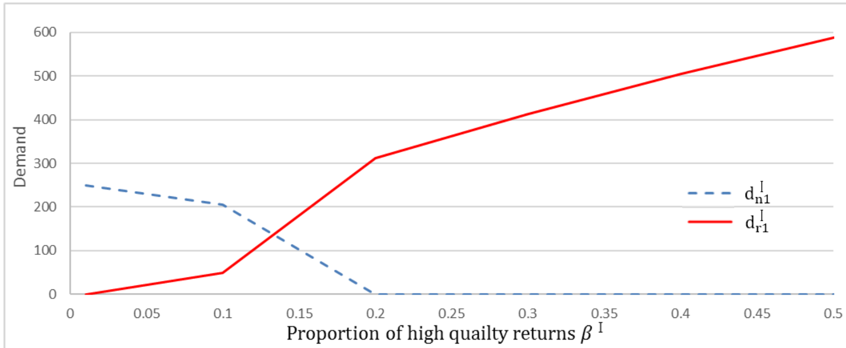

Figure 4.13: Relationship between demands and β^I in one-period model

Figures 4.12 and 4.13 show the profiles of the optimal demands and prices of the products when the proportion of high quality returns changes. In general, when the proportion of high quality returns increases, the prices of both new and remanufactured products keep decreasing because when β^I increases, the average remanufacturing cost decreases and the company can afford to lower the prices in order to obtain more profit. The demand for new products decreases until reaching 0 around $\beta^I=$ 0.2 when the optimal strategy is to produce only remanufactured. Meanwhile the demand for remanufactured products keeps rising continuously.

4.2.2 Two-period model

In the two-period model, the thresholds of the unit manufacturing cost (c_{n1}^{II}) is affected by the proportion of high quality returns. Based on Figure 4.14, when the proportion is low, then $c_n^{II} < c_{n1}^{II}$, and the selection of the optimal policy depends on the unit remanufacturing cost (c_r^{II}) and its thresholds (c_{r1}^{II}, c_{r2}^{II}, and c_{r3}^{II}). Moreover, when the proportion is high, then $c_n^{II} > c_{n1}^{II}$ and the selection depends on the value of c_r^{II}, c_{r1}^{II}, c_{r2}^{II}, c_{r4}^{II}, c_{r5}^{II}, and c_{r6}^{II}.

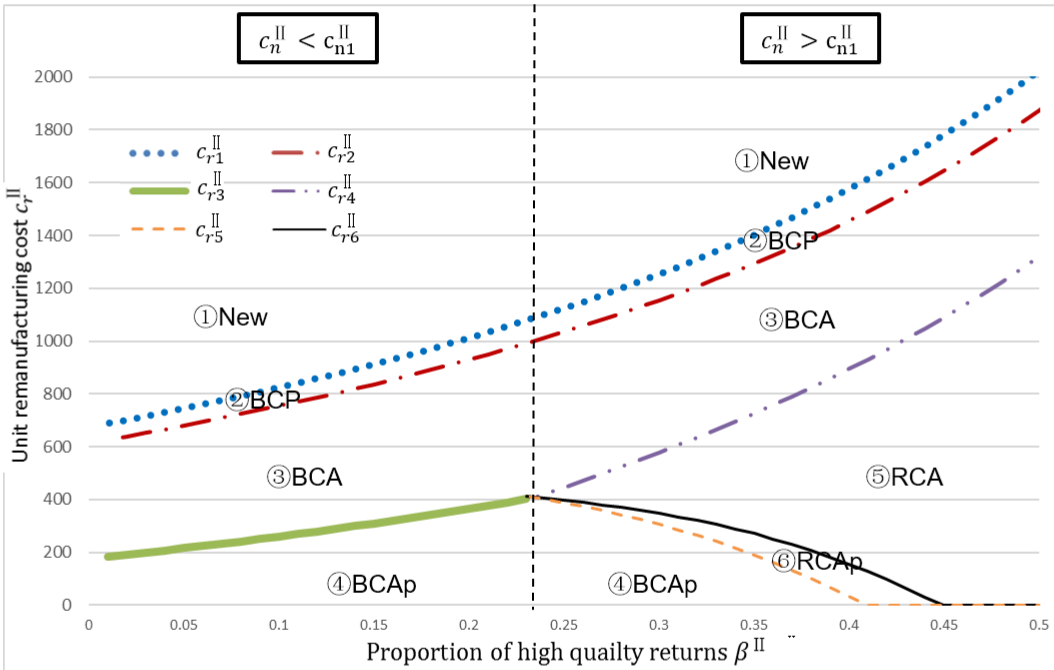

Figure 4.14: Optimal production strategies in two-period model

The left part of Figure 4.14 shows the case when $c_n^{II} < c_n^{II}$. In this case, producing only remanufactured products will never be an optimal decision for the company. The possibility for the company to produce only new products in the second period (policy 1-New) decreases when the proportion of high quality returns increases. But the opportunity to use policy 2-BCP stays fairly constant and the opportunity to adopt policies 3 and 4 increases slightly in the meantime.

The right part of Figure 4.14 depicts the case when $c_n^{II} > c_n^{II}$. According to the figure, the possibility for the company to produce only new products in the second period (policy 1-New) goes down when the proportion of high quality returns increases. However, the opportunity to adopt policies 2-BCP and 3-BCA stays constant. Two new policies (5-RCA and 6-RCAp) appear and become significant. In particular, the share of policy 5-RCA grows rapidly to the detriment of policy 4.

Another insight based on Figure 4.14 is related to the selection sequence of the optimal production and pricing policies. For high values of c_r^{II}, the general selection sequence is: policy 1, policy 2, policy 3, and policy 5. For small values of c_r^{II}, the general selection sequence is: policy 3, policy 4, policy 6, and policy 5. It should be noted that depending on the actual value of the unit remanufacturing cost, some of the policies may not be adopted regardless of how β^{II} changes. Although these two sequences show little difference, they imply that the company focuses more on the remanufactured activities, when the β^{II} increases, which is similar to what was observed in the one-period model as well.

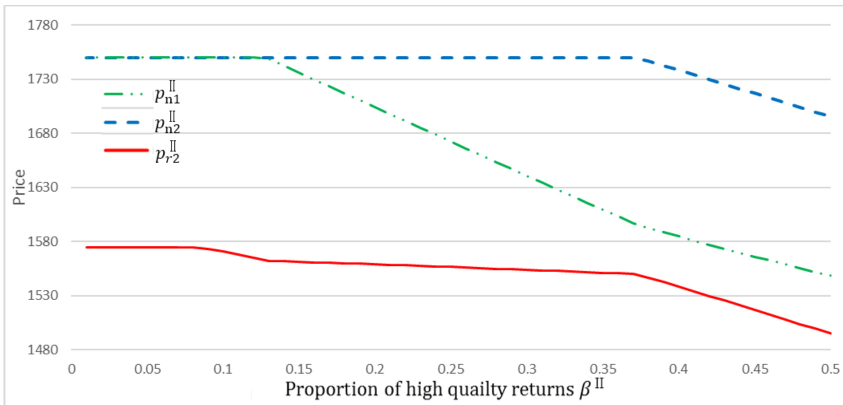

Figure 4.15: Relationship between optimal prices and β^{II} in two-period model

Figures 4.15, 4.16, and 4.17 are plotted for a specific value $c_r^{II} = 800$. According to Figure 4.15, the behavior of the prices in the second period when the proportion of high quality returns increases is similar to what was observed in the one-period model. They almost stay constant in the beginning and then decreases as β^{II} increases. Moreover, the price of the new products in the first period has a similar trend. It coincides with the price of the new products in the second period at the beginning and then starts to decrease when $\beta^{II} > 0.13$. This decrease is due to the fact that when the proportion of high quality returns increases, the company will engage more in the remanufacturing business by increasing the demand of remanufactured products, which is depicted in the Figure 4.16. As a result, with increasing β^{II}, the demand for new products in the first period needs also be increased, thus their price will be decreased.

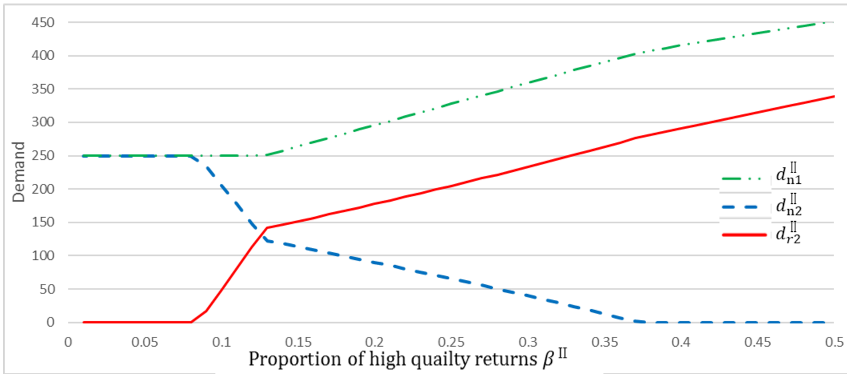

Figure 4.16: Relationship between demands and β^{II} in two-period model

From Figure 4.16, when the proportion of high quality returns increases, the demand for new products in the first period stays constant in the beginning and then increases. The demand for remanufactured products shows a similar trend and it increases more rapidly when the company just collects some of the used products from the customers at the end of the first period. In contrast, the demand for new products in the second period coincides with the demand for new products in the first period for low values of β^{II}. After that, it drops dramatically until reaching zero around $\beta^{II} = 0.35$.

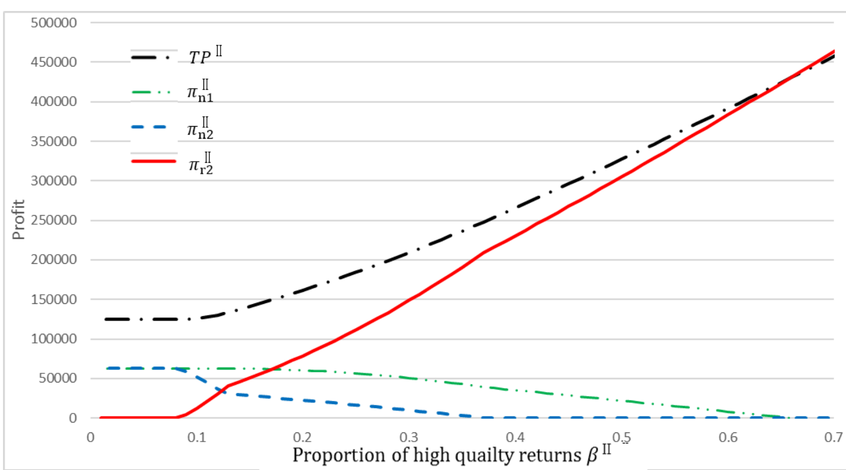

Figure 4.17: Relationship between profits and β^{II} in two-period model

From Figure 4.17, when the proportion of high quality returns increases, the total profit stays constant in the beginning and then increases. The constant profit phase corresponds to the case where the optimal strategy is to produce only new products in both periods and not collect any used product. This happens when β^{II} is small. When the proportion of high quality returns become higher, the remanufactured products will be more profitable for the company due to a lower average remanufacturing cost and the company will engaged more in remanufacturing. This is shown in Figure 4.17 with a rapidly increasing profit from remanufacturing (red solid line). Moreover, when the value of the proportion of high quality returns is high, the profit from remanufactured products is higher than the total profit of both products (i.e., the solid red curve is above the dashed black one when $\beta^{II} > 0.65$). When β^{II} is high, the average remanufacturing cost is low and this allows the company to trade-off profit from new products in the first period for more profit from remanufactured products in the second period (i.e., the green solid line keeps decreasing when β^{II} increases).

4.3 Sensitivity to the remanufacturability rate

In the next set of numerical experiments, the sensitivity to the remanufacturability rate factor is analyzed by varying γ^k and c_r^k, while keeping all other parameters as: $\alpha^k = 0.95, \beta^k = 0.2, c_n^k = 1500, c_c^k = 0.1, andQ^k = 2000$ $(k = I, II)$.

4.3.1 One-period model

Figure 4.18 depicts the selection of optimal production and related pricing strategies for the one-period model when the remanufacturability rate increases.

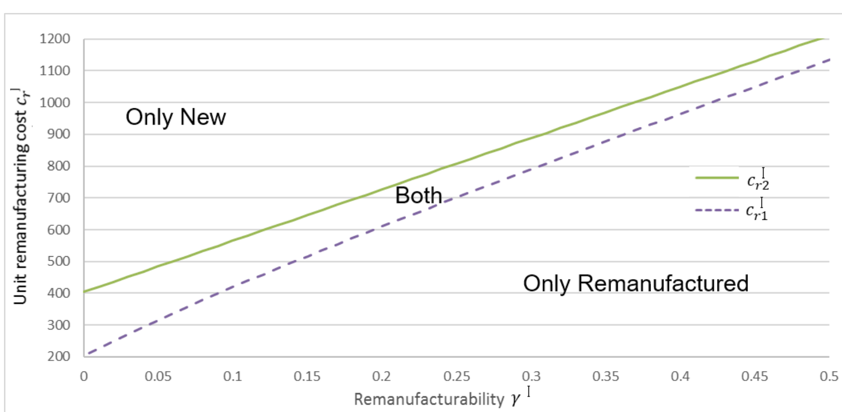

Figure 4.18: Optimal production strategies in one-period model

Producing only new products is more likely to be the optimal policy, when the remanufacturability rate is low. When the losses during the remanufacturing process decrease, the opportunity to produce only remanufactured products increases and the opportunity to produce both new and remanufactured products decreases. When the remanufacturability rate increases, the losses during the remanufacturing process decreases resulting in a decrease of the average unit remanufacturing cost. As a result, the remanufacturing activity become profitable for the company.

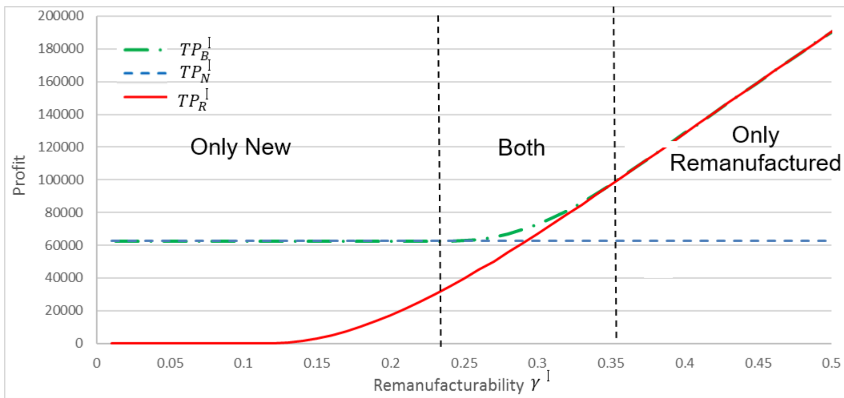

Figure 4.19: Relationship between profits and γ^I in one-period model

Figures 4.19, 4.20, and 4.22 are plotted for a specific value $c_r^I = 700$. Figure 4.19 depicts the trend of the profit when the remanufacturability rate increases. The optimal total profit stays constant for low remanufacturability rates then increases as γ^I increases. This trend is due to the fact that when $\gamma^I < 0.24$, the company does not engage in remanufacturing activities. For $\gamma^I > 0.24$, the increasing remanufacturability rate leads to lower average unit remanufacturing cost and increased total profit. Moreover, the optimal total profit increases more rapidly when the optimal policy is to produce only remanufactured products. Therefore, the company can afford to invest more on improving the remanufacturability rate by using Design for X (DfX) principles, improving employees skills through training, etc.

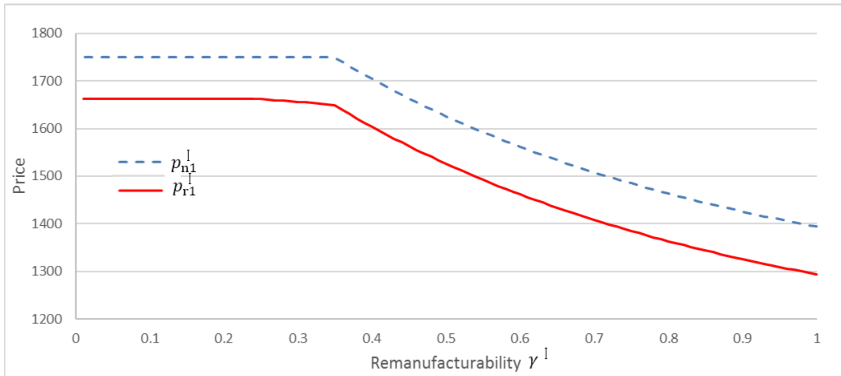

Figure 4.20: Relationship between optimal prices and γ^I in one-period model

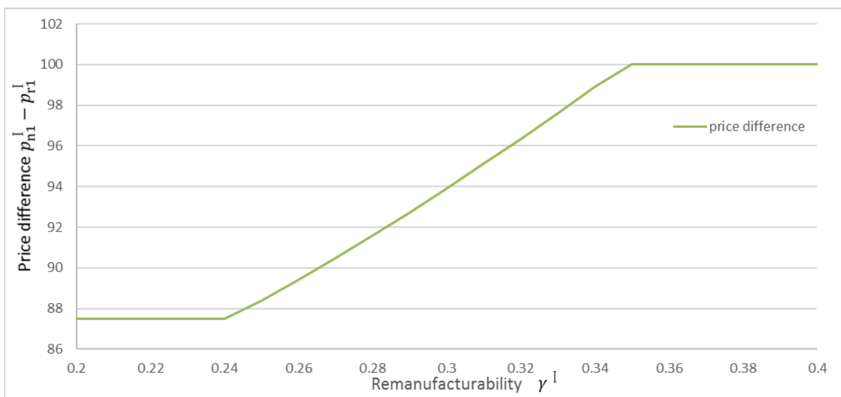

Figure 4.21: Relationship between price difference and γ^I in one-period model

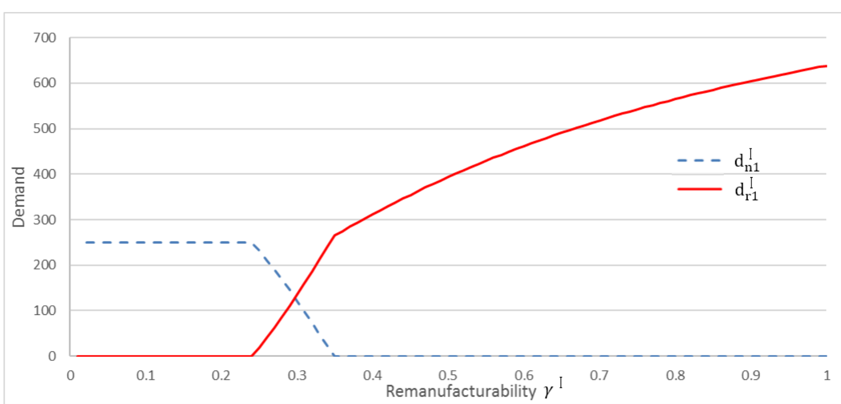

Figure 4.22: Relationship between demands and γ^I in one-period model

The profiles of the optimal prices and demands for the products with the increasing remanufacturability are shown in Figure 4.20 and Figure 4.22.

- When $0 < \gamma^I < 0.24$, the optimal prices for both new and remanufactured products stay fairly constant. The demand for new products stays constant while there is no demand for remanufactured products.

- For $0.24 < \gamma^I < 0.35$, the price for new products still stays constant, while the price for remanufactured products starts decreasing. So the price difference between new and remanufactured begins to increase (see Figure 4.21), which causes the demand for new products to decrease until reaching 0 and the demand for remanufactured products to increase when the remanufacturability rate increases as can be seen on Figure 4.22. Increasing remanufacturability rate means that the remanufacturing process is more efficient resulting in a lower average remanufacturing cost which leads to higher profit margin per product. The company can then afford to decrease price such that the demand for remanufactured products increases and the total profit is increased.

- For $\gamma^I \geq 0.35$, the price for remanufactured continues to decrease and demand increases steadily but at a slower speed than before. The reason for this deceleration can be explained by analyzing the expression of d_r^I which is given by Eq. (3.9):

$$d_r^I = \frac{\alpha^I p_n^I - p_r^I}{\alpha^I \left(1 - \alpha^I\right)}$$

$$d_r^I = \frac{\alpha^I \left(p_n^I - p_r^I\right) - \left(1 - \alpha^I\right) p_r^I}{\alpha^I \left(1 - \alpha^I\right).} \tag{4.1}$$

It can be seen that d_r^I increases if the price difference between the new and remanufactured products $(p_n^I - p_r^I)$ grows or if the price for remanufactured p_r^I decreases.

When $0.24 < \gamma^I < 0.35$, the price difference grows and the price for remanufactured decreases simultaneously causing the demand to grow faster than when $\gamma^I \geq 0.35$ where the price difference is constant and only the price for remanufactured decreases. The reason for the constant value of the price difference is due to the fact that the price difference between the new and remanufactured products affects the cannibalization between the new and remanufactured.

When the price difference increases, the cannibalization is strengthened and then more customers switch from purchasing new products to buying remanufactured products. However, when $\gamma^I \geq 0.35$, the demand for new products stays zero. Thus, there is no more customers switching from purchasing new products to remanufactured products and then the price difference stays constant.

Another observation in the case $\gamma^I \geq 0.35$ shows that when the remanufacturability rate increases, the rate of increase of d_r^I gradually slows down. This is due to the convex collection and inspection cost. When the demand grows, the average unit collection and inspection cost increases resulting in a decrease of profit.

4.3.2 Two-period model

In the two-period model, the remanufacturability rate affects the thresholds of the unit remanufacturing cost, which is shown in Figure 4.23. When the value of the remanufacturability rate is small ($\gamma^{II} < 0.53$), then $c_n^{II} < c_{n1}^{II}$ and the optimal production and related pricing strategies depend on the unit remanufacturing cost (c_r^{II}), and its thresholds (c_{r1}^{II}, c_{r2}^{II}, and c_{r3}^{II}). On the other hand, when the value of the remanufacturability rate is high, then $c_n^{II} > c_{n1}^{II}$ and the optimal policies depend on the values of c_r^{II}, c_{r1}^{II}, c_{r2}^{II}, c_{r4}^{II}, c_{r5}^{II}, and c_{r6}^{II}.

The left part of Figure 4.23 shows the case when $c_n^{II} < c_{n1}^{II}$. As remanufacturability rate increases, the opportunity for the company to produce only new products in the second period (policy 1-New) decreases while the possibility to adopt policies 2-BCP and 3-BCA stays fairly constant and the probability to adopt policy 4-BCAp becomes significant. As stated before, when the remanufacturability rate increases, the average unit remanufacturing cost also decreases resulting in more profit from remanufacturing activities.

The right part of Figure 4.23 depicts the case when $c_n^{II} > c_{n1}^{II}$. The probability to produce only new products (policy 1-New) shows a similar trend as in the case

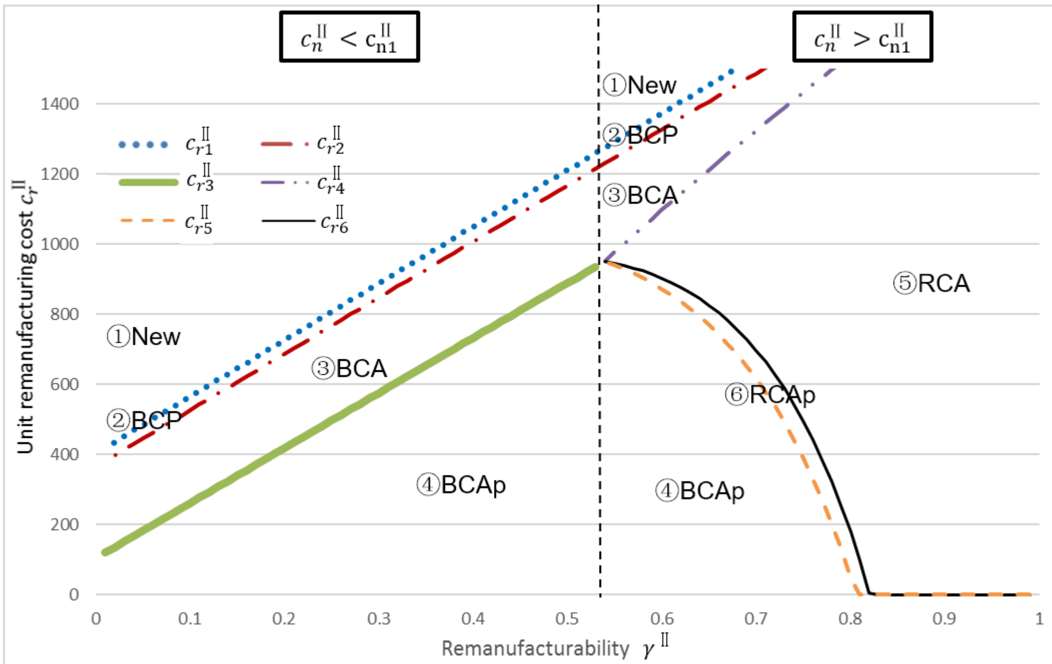

Figure 4.23: Optimal production strategies in two-period model

when $c_n^{II} < c_{n1}^{II}$. The probability of selecting policy 1-New decreases when the losses in the remanufacturing process decrease for the same reasons as before. On the other hand, the opportunity to use policy 2-BCP stays fairly constant. The opportunity to adopt policies 3-BCA and 4-BCAp decreases as γ^{II} increases. This decrease is due to the appearance of two new policies: 5-RCA and 6-RCAp. In particular, the share of policy 5-RCA grows rapidly.

Another insight from Figure 4.23 is the selection sequence of the optimal production and related pricing strategies with the increasing remanufacturability rate. When the value of c_r^{II} is high, the general selection sequence of the optimal production and related pricing strategies is: policy 1-New, policy 2-BCP, policy 3-BCA, and policy 5-RCA. On the other hand, for small value of c_r^{II}, the general selection sequence is: policy 1-New, policy 2-BCP, policy 3-BCA, policy 4-BCAp, policy 6-RCAp, and policy 5-RCA. It should be noted that depending on the actual value of the unit remanufacturing cost, some of the policies may not be adopted regardless of how γ^{II} changes. Although these two sequences shows a little difference, they both imply that when the remanufacturability rate increases, the company should engage more in the remanufacturing activities in the second period. This is the same result that is observed in the one-period model.

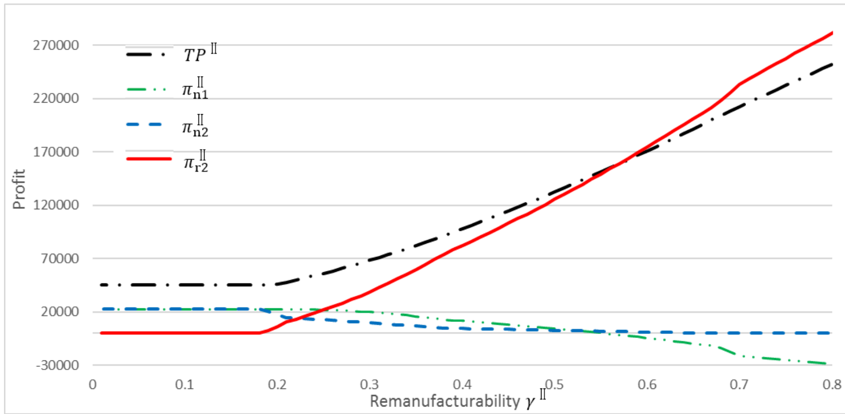

Figure 4.24: Relationship between profits and γ^{II} in two-period model

Figures 4.24, 4.25, and 4.26 are plotted for a specific value $c_r^{II} = 700$. According to Figure 4.24, the optimal total profit stays constant in the beginning and then increases when the losses in the remanufacturing process decrease. The reason is that when the value of the remanufacturability rate is small, the average remanufacturing cost is high. So the company will produce only new products and then the total profit is independent of the remanufacturability rate. When the value of the remanufacturability rate increases, the losses in the remanufacturing process decrease and then the remanufacturing activities become more profitable. So the company will engage more in the remanufacturing activities and obtain more profit (i.e., the red solid line increases rapidly with the increasing remanufacturability rate). As in the one-period model, increasing remanufacturability rate means more profit and the company can afford to invest more to improve the remanufacturability rate. Furthermore, for high values of remanufacturability rate, the total profit is less than the profit from the remanufactured products (i.e., the red solid line is above the black dashed line when $\gamma^{II} > 0.6$). This phenomenon is due to the fact that when remanufacturability rate is high, the company may trade-off the profit from the new products in the first period for more profit from the remanufactured products in the second period (i.e., the green solid dashed line goes down when the red solid line goes up).

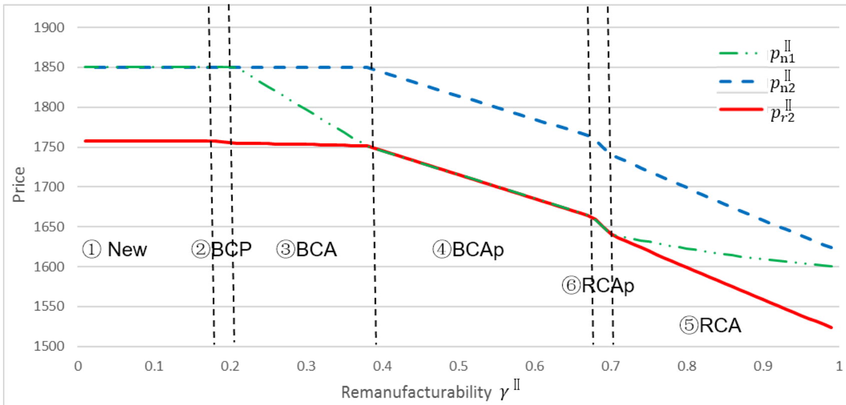

Figure 4.25: Relationship between optimal prices and γ^{II} in two-period model

Figure 4.25 depicts the variation of the prices across all 6 policies when remanufacturability rate increases. The policy boundaries are defined by the threshold values in Table 3.6. The following observations are made.

- The general trend is that the prices for new and remanufactured are constant or decreasing and constitute extreme values between which the price for new in the first period evolves. This is similar to what was observed in the one-period model.

- When policy 2-BCP is optimal (low remanufacturability rate), there are very few remanufactured products made therefore there is no need to sell more new products in the first period. Thus, there is no need to decrease the price p_{n1}^{II} which stays constant and equal to p_{n2}^{II}.

- Overall for $\gamma^{II} \geq 0.2$, as remanufacturability rate increases, the average unit remanufacturing cost decreases resulting in a decrease in p_{r2}^{II} and increased demand for remanufactured products in the second-period. Thus, there is a need to sell more products in the first period which is achieved by lowering the price for new p_{n1}^{II}. In order to control the increase in demand for remanufactured products, the model lowers the price for new products in the second period through Eq. (3.9):
$$d_r^{II} = \frac{\alpha^{II} p_n^{II} - p_r^{II}}{\alpha^{II}\left(1 - \alpha^{II}\right)}.$$

- For mid-range values of remanufacturability rate ($0.4 \leq \gamma^{II} \leq 0.7$), the price for new products in the first period decreases until it coincides with the price for remanufactured products in the second period $p_{n1}^{II} = p_2^{II}$. The price for new products cannot decrease further because of the assumption that remanufactured products cannot cost more than new products in any period.

- For very high remanufacturability rate, the remanufacturing losses are very low such that the quantity to be collected is almost equal to the demand for remanufactured products. As a result, when the value of the remanufacturability is high, even though the company does more remanufacturing, the rate of increase of the demand for the new products sold in the first period decreases (i.e., the red solid line in Figure 4.26 increases with a fairly constant rate, while the slope of the green dashed line flattens when the value of γ^{II} is high). In the meantime, the decrease rate of the price for new products in the first period also slows down.

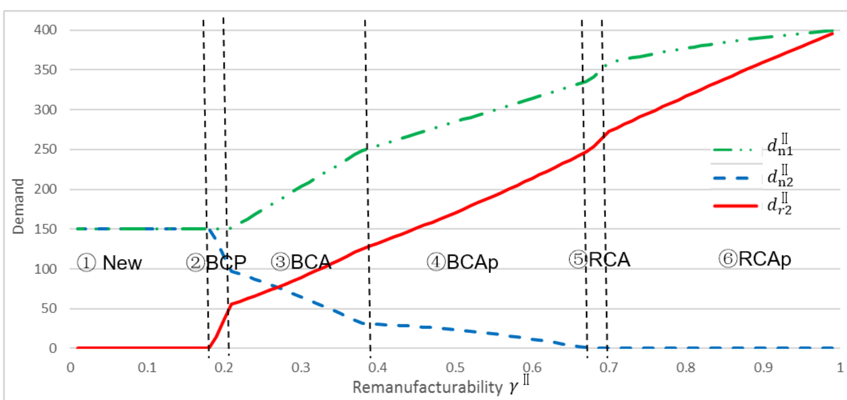

Figure 4.26: Relationship between demands and γ^{II} in two-period model

4.4 Sensitivity to market size

In the fourth set of experiments, the sensitivity to market size is analyzed by varying the values of Q^k and c_r^k, while keeping all other parameters as: $\alpha^k = 0.95, \beta^k = 0.2, \gamma^k = 0.85, c_n^k = 1700$, and $c_c^k = 0.1$ $(k = I, II)$.

4.4.1 One-period model

Figure 4.27 shows the selection of the optimal production and related pricing strategies for the one-period model as market size increases.

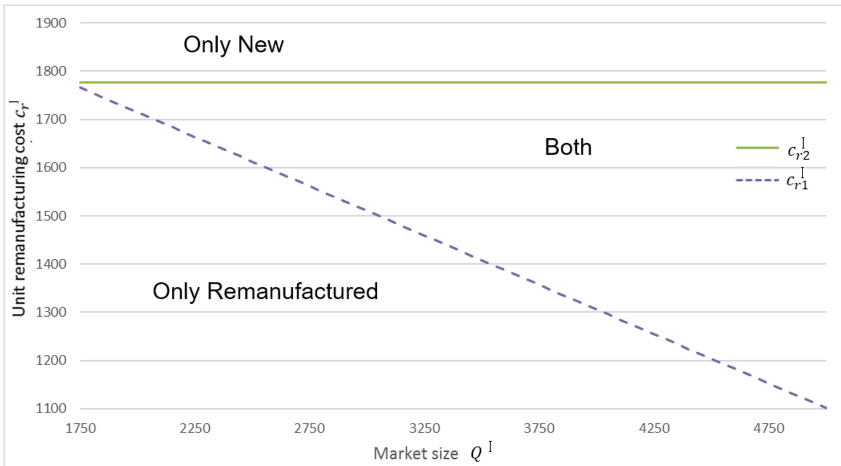

Figure 4.27: Optimal production strategies in one-period model

Figure 4.27 shows a constant value of threshold c_{r2}^{II} as the market size increases. Thus, when the value of the unit remanufacturing cost is sufficiently high, producing only new products will be the optimal production strategy for the company regardless of the market size. For low values of the unit remanufacturing cost, when the market size increases, the opportunity for the company to produce only remanufactured products decreases, while the opportunity to produce both new and remanufactured products increases. This results from the fact that when the market size increases, the demand for the remanufactured products also increase and thus the remanufactured products become less profitable because of the convex collection and inspection cost. As a result, the company should control the demand for remanufactured products and produce some additional new products to satisfy demand.

Figures 4.28, 4.29, and 4.30 are plotted for a specific value $c_r^I = 1200$. Figure 4.28 depicts the case when $c_r^I < c_{r2}^I$. The optimal total profit increases as the market size grows and its acceleration is positive. This is due to the fact that on one hand, the increasing market size leads to an increasing demand and on the other hand, the company can raise the price for both new and remanufactured products without decreasing their demands. Therefore, the company can afford to invest more

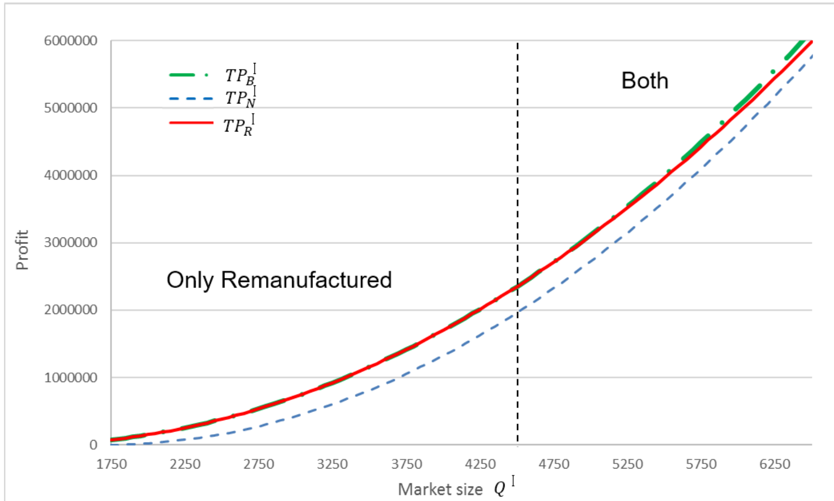

Figure 4.28: Relationship between profits and Q^I in one-period model $(c_r^I < c_{r2}^I)$

on expanding its market with initiatives such as advertisements, and discounts.

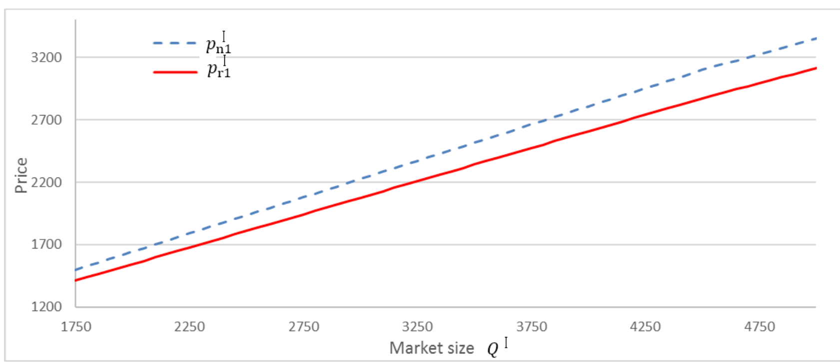

Figure 4.29: Relationship between optimal prices and Q^I in one-period model

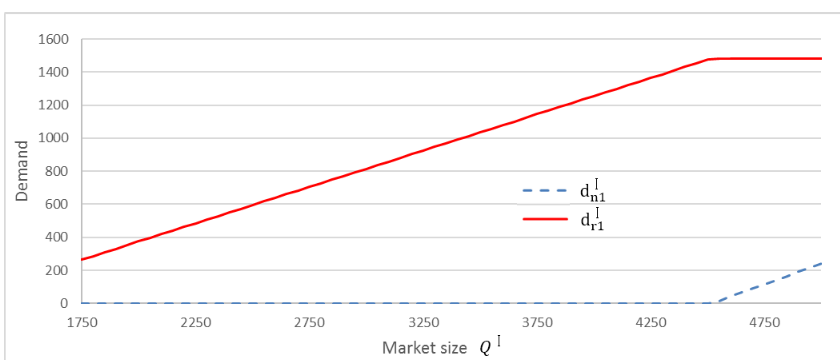

Figure 4.30: Relationship between demands and Q^I in one-period model

Figure 4.29 shows price increases for both new and remanufactured products when the market size grows. In particular, the price for new products rises a little faster because when the price difference between new and remanufactured products increases, more customers switch from purchasing new products to buying remanufactured products. Therefore the demand for remanufactured products increases and yields more profit.

In Figure 4.30, the demand for new products stays constant when the market size is relatively small ($Q^I < 4500$), and then increases as the market size grows. On the other hand, the demand for remanufactured products increases until reaching its peak when the market size is about 4500. Then it stays constant and is not affected by the market size. This result is due to the convex collection and inspection cost. When the demand for the remanufactured products reaches a high-range, the company needs to collect a large number of returns resulting in high collection and inspection costs which significantly affect the total profit. Therefore, as the market size increases, the company should increase the price of the remanufactured products instead of stimulating demand in order to obtain increase profit. In the meantime, the company can produce more new products to satisfy demand.

4.4.2 Two-period model

In the two period model, the threshold of unit remanufacturing cost (c_{n1}^{II}) is affected by the market size. From Figure 4.31, when the market size is big, if $c_n^{II} < c_{n1}^{II}$, then the selection of the optimal production and related pricing policies depends on the unit remanufacturing cost (c_r^{II}) and its thresholds (c_{r1}^{II}, c_{r2}^{II}, and c_{r3}^{II}). On the other hand, when the market size is small, if $c_n^{II} > c_{n1}^{II}$, then the selection is dependent of the value of c_r^{II}, c_{r1}^{II}, c_{r2}^{II}, c_{r4}^{II}, c_{r5}^{II}, and c_{r6}^{II}.

The left part of Figure 4.31 depicts the case when $c_n^{II} > c_{n1}^{II}$. The opportunity for the company to produce only new products in the second period (policy 1-New), i.e. $c_r^{II} > 1800$, is independent of the market size. A similar result was observed in the one-period model. The opportunity to produce both new and remanufactured products in the second period (policy 2-BCP and policy 3-BCA) increases as the market size grows while the probability of producing only remanufactured

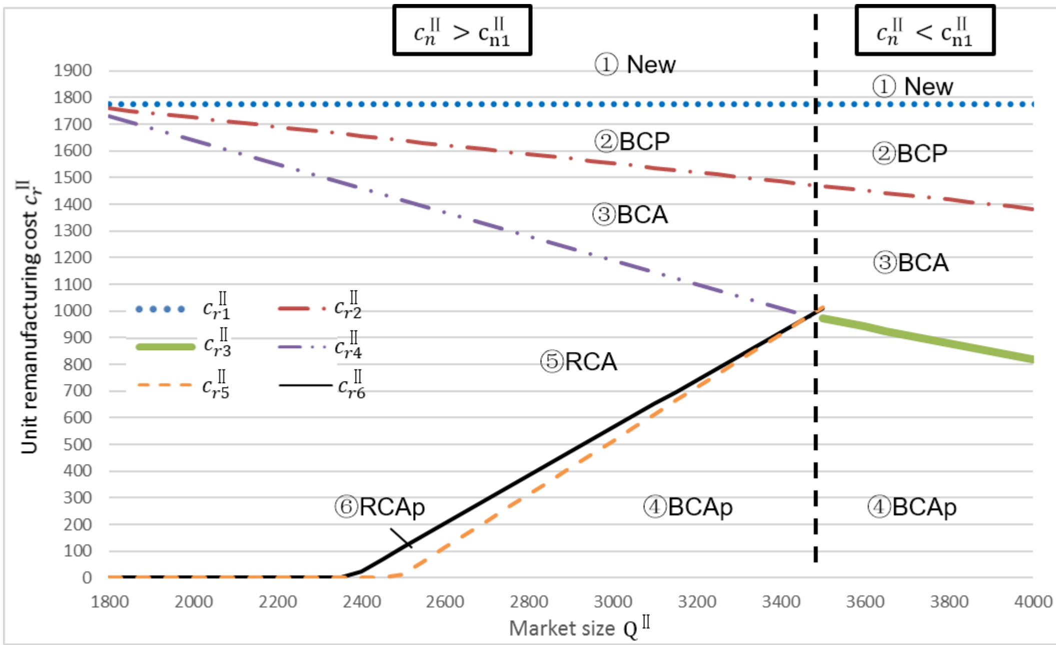

Figure 4.31: Optimal production strategies in two-period model

products (policy 5-RCA and policy 6-RCAp) decreases. In particular, the opportunity to use policy 5-RCA decreases more rapidly due to appearance of policy 4-BCAp.

The right part of Figure 4.31 shows the case when $c_n^{II} < c_{n1}^{II}$. The probability to produce only new products in the second period (policy 1-New) still stays constant as market size grows. On the other hand, the opportunity for the company to use policies 2-BCP and 3-BCA increases as the opportunity to adopt policy 4-BCAp decreases.

Another insight based on Figure 4.31 is that the selection sequence of the production and related pricing strategy is affected by the unit remanufacturing cost when the market size increases. When the value of c_r^{II} is large, the company always produces only new products (policy 1-New) regardless of the market size. When c_r^{II} reaches mid-range values, the production strategy selection sequence is: policy 5-RCA, policy 3-BCA, and policy 2-BCP. On the other hand, when c_r^{II} is small, the selection sequence is: policy 5-RCA, policy 6-RCAp, policy 4-BCAp, and policy 3-BCA. It should be noted that depending on the actual value of the unit remanufacturing cost, some of the policies may not be adopted regardless of how Q^{II} changes. Based on these three sequences, it is obvious that as the market expands, when the unit remanufacturing cost is high, the company should only produce new products in the second period and in other cases, the company is more likely to produce both new and remanufactured products. A similar result was observed in the one-period model.

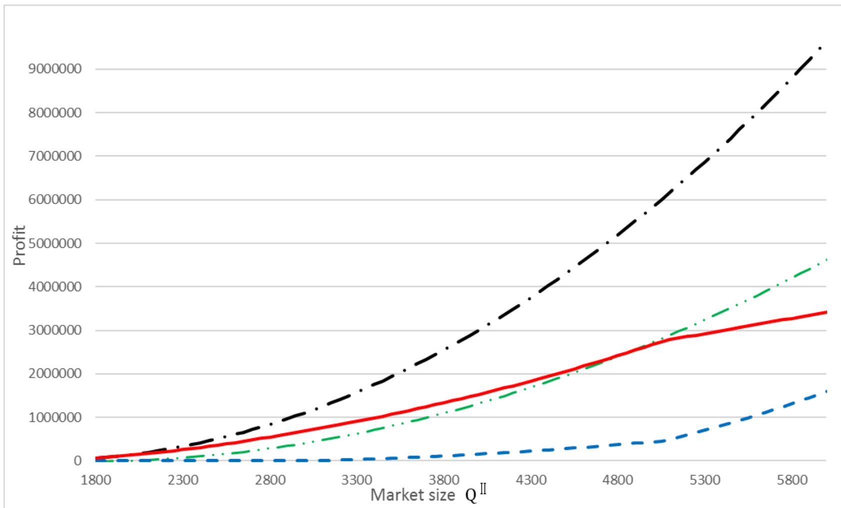

Figure 4.32: Relationship between profits and Q^{II} in two-period model

Figures 4.32, 4.33, and 4.34 are plotted for a specific value $c_r^{II} = 1200$. Figure 4.32 shows that when the market expands, the optimal total profit increases. Moreover, the increasing rate of the profit for the remanufactured products decreases when the value of the market size is over 5000. The decrease is due to the fact that when the demand of the remanufactured products is sufficiently high, increasing the demand is not profitable because of the convex collection and inspection cost. So when Q^{II} is large, the company increases the profit of the remanufactured products only by raising its price.

Figure 4.33 clearly shows that all product prices increase with the market size. The price for new products in the second period and the price for the remanufactured products constitute extreme values between which the price for new in the first period evolves.

- For small values of the market size ($Q^{II} < 3000$), the price difference between new p_{n2}^{II} and remanufactured products p_{r2}^{II} increases because producing remanufactured products is much more profitable than producing new products. As a result, all demand goes toward the remanufactured products (i.e., the blue dashed line stays zero, while the red solid line increases rapidly in Figure 4.34). In the meantime, the company reduces the increase rate of p_{n1}^{II} in order to have sufficient returns to collect (i.e., the green dashed line is close to the red solid line in Figure 4.33).

- When the market size reaches mid-range values ($3000 < Q^{II} < 5000$), the increase rate of the demand for remanufactured products slows down because of the convex collection and inspection cost. The company needs to control the growth of the demand for the remanufactured products without making the collection and inspection cost increase too fast. The company increases the price for new products in the first period at a faster rate in order to obtain more profit (i.e., the green line starts to increase rapidly in Figure 4.33). On the other hand, the company increases the demand for new products to satisfied customers.

- When the market size reaches a high values ($Q^{II} > 5000$), the demand for remanufactured products is so high that to avoid extreme collection and inspection cost, the company stops to produce more remanufactured products (i.e., the red solid line stays constant in Figure 4.34) and additional demand due to the increasing market size in the second period is fulfilled by producing new products (i.e., the blue dashed line increases rapidly in Figure 4.34, when $Q^{II} > 5000$).

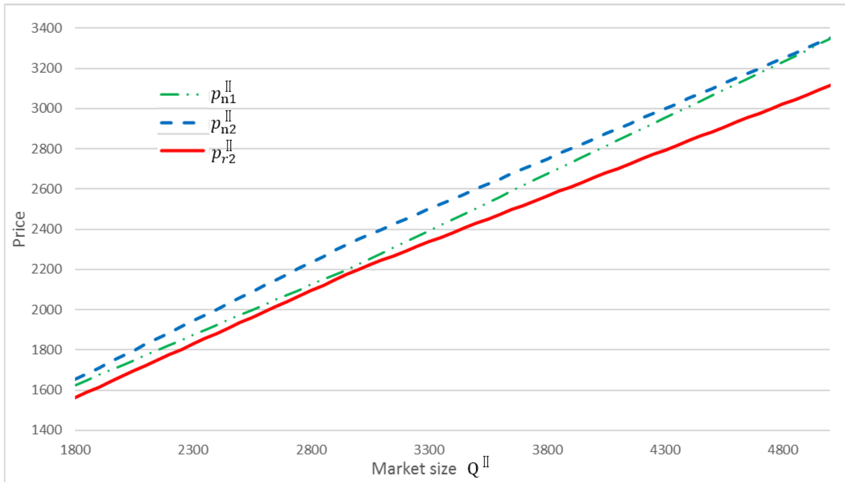

Figure 4.33: Relationship between optimal prices and Q^{II} in two-period model

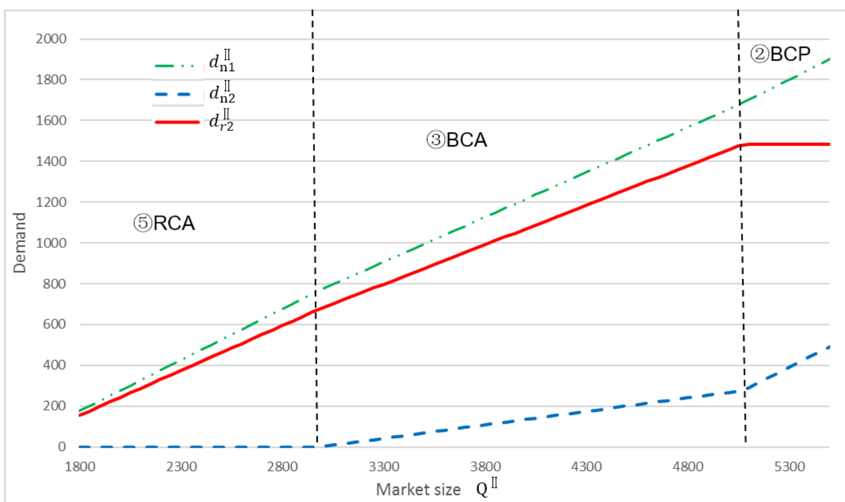

Figure 4.34: Relationship between demands and Q^{II} in two-period model

4.5 Sensitivity to the unit collection and inspection cost rate

In this series of experiments, the sensitivity to the unit collection and inspection cost rate is analyzed by varying c_c^k and c_r^k while keeping all other parameters constant as: $\alpha^k = 0.95, \beta^k = 0.2, \gamma^k = 0.6$, and $Q^k = 2000$ $(k = I, II)$.

4.5.1 One-period model

Figure 4.35, which is plotted for $c_n^I = 1700$, depicts the selection of the optimal production and related pricing strategies as the unit collection and inspection cost rate c_c^I increases in the one-period model.

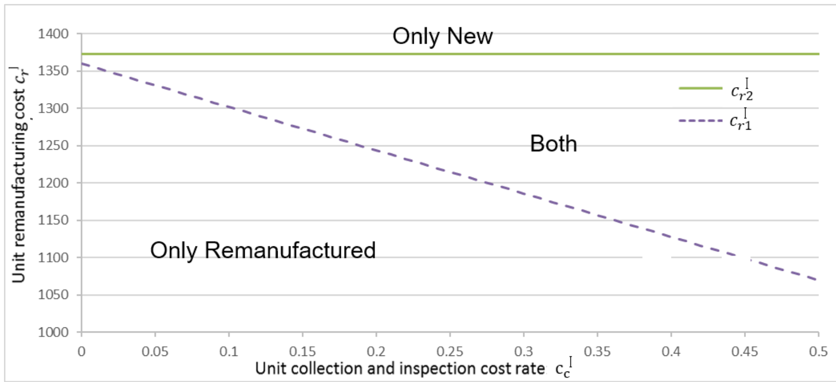

Figure 4.35: Optimal production strategies in one-period model

Figure 4.35 shows that the threshold of the unit remanufacturing cost (c_{r2}^I) stays constant as the unit collection and inspection cost rate c_c^I increases. On the other hand, the threshold c_{r1}^I decreases when c_c^I increases. This implies that when the unit remanufacturing cost is sufficiently high, producing only new products is the optimal production strategy regardless of the value of the unit collection and inspection cost rate c_c^I.

For low values of c_r^I, the optimal production strategy varies from only remanufactured to produce both when c_c^I increases. This is due to the fact that when the unit collection and inspection cost rate increases, producing remanufacturing products becomes less profitable. Therefore, the company should decrease the demand for the remanufacturing products and produce new products to satisfy the demand.

Figures 4.36, 4.38, and 4.39 are plotted for a specific value $c_r^I = 800$. Figure 4.36 depicts the profiles of the optimal prices for varying unit collection and inspection cost rate in the case $c_r^I < c_{r2}^I$.

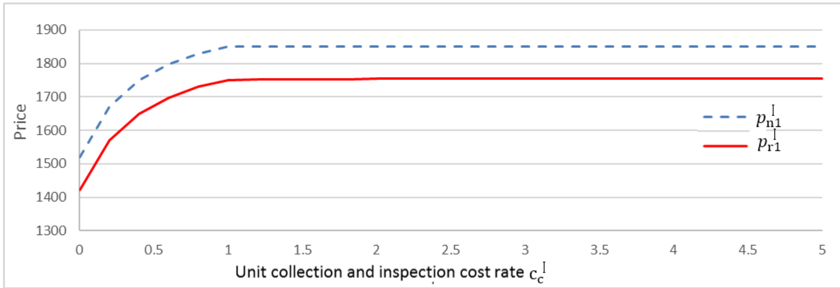

Figure 4.36: Relationship between optimal prices and c_c^I in one-period model

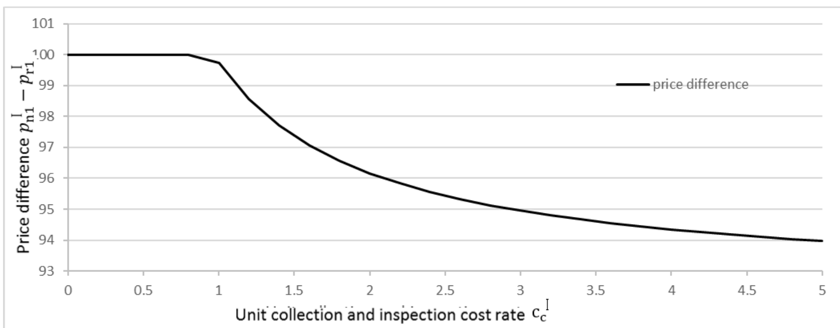

Figure 4.37: Relationship between price difference and c_c^I in one-period model

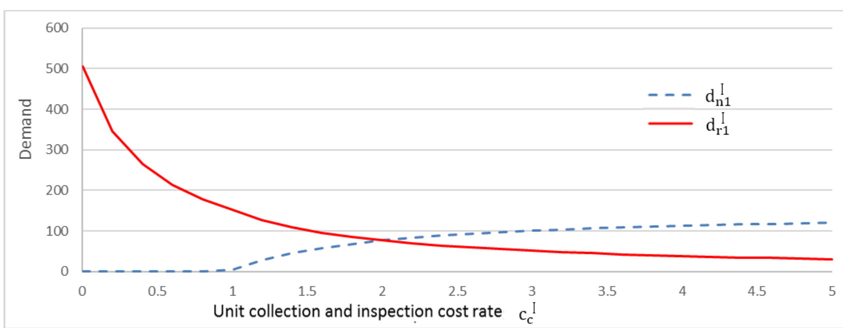

Figure 4.38: Relationship between demands and c_c^I in one-period model

For low values of the unit collection and inspection cost rate ($c_c^I < 1$), the increase rate of the prices for both new and remanufactured products slowly decreases as c_c^I increases. This trend is due to the fact that increasing c_c^I makes the remanufacturing products less profitable. Therefore, the company needs to decrease demand for the remanufactured products by increasing the price. However in order to prevent profit from dropping too fast, the reduction in demand has to gradually slow down, which causes the price increase to slow down as well. Moreover, the price difference between new and remanufactured products stays constant because there are no customers switching from new to remanufactured as the company does not produce any new products given that the optimal policy is to produce only remanufactured.

For high values of unit collection and inspection cost rate ($c_c^I > 1$), the prices of new and remanufactured products stay fairly constant. The demand for new products starts to increase, while the demand for remanufactured products deceases continuously. The price difference between new and remanufactured products begins to decrease as can be seen in Figure 4.37. This decrease is due to the fact that the remanufacturing products become less profitable as c_c^I increases. Therefore, the company needs to control the prices for new and remanufactured products in order to enable some customers to switch from remanufactured products to new products.

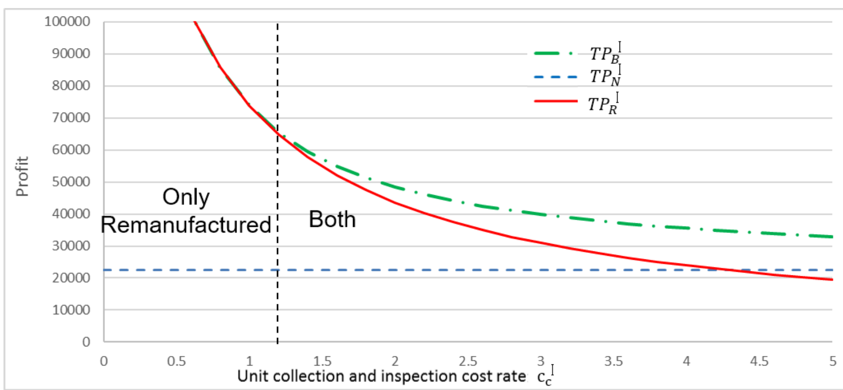

Figure 4.39: Relationship between profits and c_c^I in one-period model ($c_r^I < c_{r2}^I$)

Figure 4.39 shows that when the unit collection and inspection cost rate increases, the optimal total profit decreases with a positive deceleration. As the demand for remanufactured products decreases, the impact of increasing unit collection and inspection cost reduces therefore the rate of decrease of the total profit slows down.

For very high values of c_c^I, the curve of the optimal total profit is almost flat and demand for remanufactured is at its lowest. Thus the company has very little incentive to invest in reducing the unit collection and inspection cost rate.

4.5.2 Two-period model

In the two period model, the threshold of the unit manufacturing cost (c_{n1}^{II}) is not affected by the market size. Figure 4.40 plotted for a specific value $c_n^{II} = 1700$ depicts the case $c_n^{II} > c_{n1}^{II}$, in which the selection of the optimal production strategy is based on the values of c_r^{II}, c_{r1}^{II}, c_{r2}^{II}, c_{r4}^{II}, c_{r5}^{II}, and c_{r6}^{II}. Figure 4.41 plotted for a specific value $c_n^{II} = 1400$ depicts the case $c_n^{II} < c_{n1}^{II}$, in which the selection of the optimal production and related pricing policies depends on the unit remanufacturing cost (c_r^{II}) and its thresholds (c_{r1}^{II}, c_{r2}^{II}, and c_{r3}^{II}).

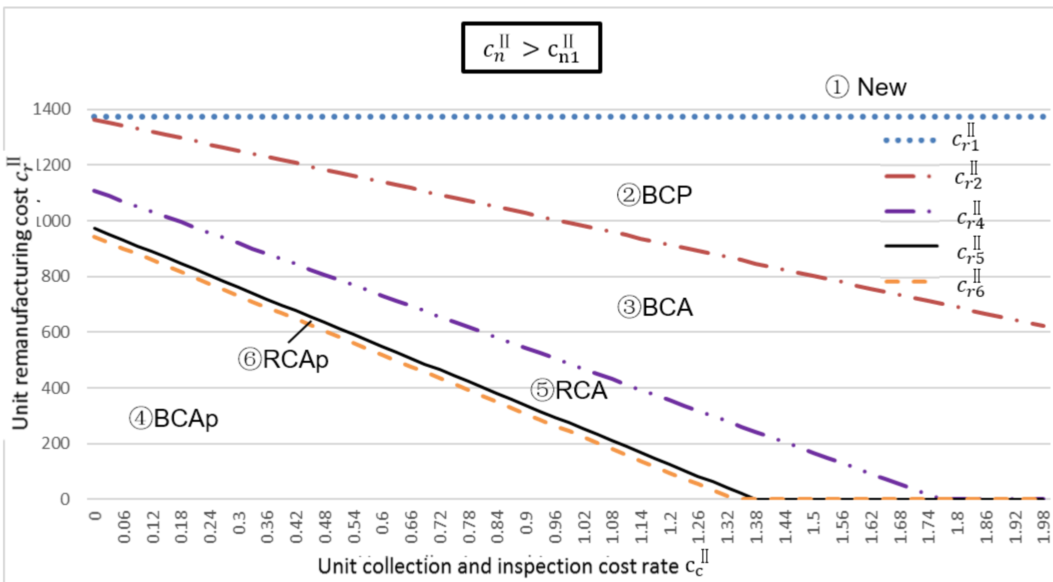

Figure 4.40: Optimal production strategies in two-period model ($c_n^{II} > c_{n1}^{II}$)

Figure 4.40 shows that the threshold c_{r1}^{II} stays constant when the unit collection and inspection cost rate increases, which is similar to the result obtained in the one-period model. Moreover, the probability for the company to adopt policies 2-BCP and 3-BCA increases rapidly in the beginning and then stays constant when the unit collection and inspection cost rate is more than 1.76. Furthermore, the opportunity for the company to produce only the remanufactured products in the second period (policy 5-RCA and policy 6-RCAp) stays fairly constant until the unit collection and inspection cost rate reaches 1.35 and then it decreases rapidly. Policy 4-BCAp is more likely to be adopted when the value of the unit collection and inspection cost rate is low.

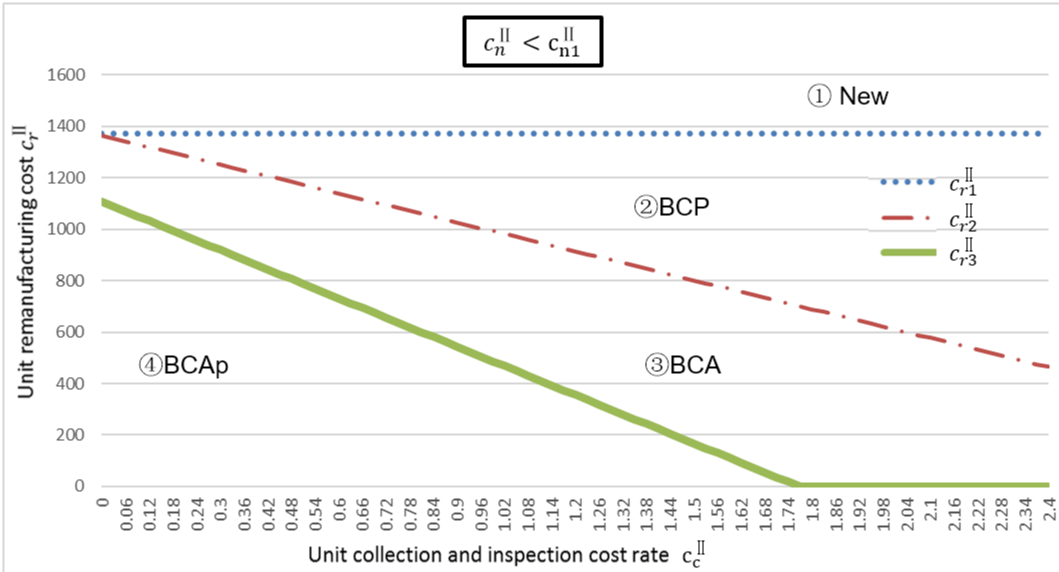

Figure 4.41: Optimal production strategies in two-period model ($c_n^{II} < c_{n1}^{II}$)

Figure 4.41 shows that the opportunity for the company to produce only new products in the second period is still independent of the unit collection and inspection cost rate. However, the opportunity to use policy 2-BCP and policy 3-BCA increases as the opportunity to adopt policy 4-BCAp diminishes.

Another insight based on Figure 4.40 and Figure 4.41 is that the selection sequence of the optimal production and pricing strategies is affected by the unit manufacturing and remanufacturing costs when the unit collection and inspection cost increases. It should be noted that depending on the actual value of the unit remanufacturing cost, some of the policies may not be adopted regardless of the values of c_c^{II}. We summarize the insights as follows.

- When the unit remanufacturing cost is sufficiently large, the company always produces only new products regardless of the values of the unit manufacturing cost and unit collection and inspection cost rate.

- When $c_r^{II} < c_{r1}^{II}$ and the value of the unit manufacturing cost is sufficiently high, the selection sequence is: policy 4-BCAp, policy 6-RCAp, policy 5-RCA, policy 3-BCA, and policy 2-BCP.

- When $c_r < c_{r1}^{II}$ and the value of the unit manufacturing cost is insufficiently high, the selection sequence is: policy 4-BCAp, policy 3-BCA, and policy 2-BCP.

The above result is different from what was observed in the one-period model. When $c_n^{II} > c_{n1}^{II}$, and c_r^{II} and c_c^{II} are sufficiently small, the optimal production strategy in the second period changes from 4-BCAp to 6-RCAp, which is unlike the one-period model, in which the optimal policy is to produce only remanufactured products. Producing more remanufactured products in the second period requires more new products to be sold in the first period at a lower price to guarantee enough returns. Therefore, although the unit collection and inspection cost rate is small, the company needs to control the demand for remanufactured products to avoid incurring losses in the first period which will cause the total profit to drop. Thus the company needs to limit its production of remanufactured and produce enough new products to satisfy demand.

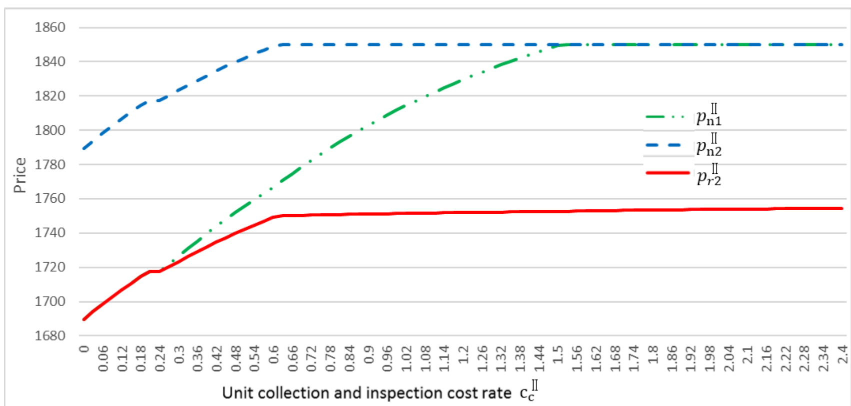

Figure 4.42: Relationship between optimal prices and c_c^{II} in two-period model

Figure 4.43: Relationship between demands and c_c^{II} in two-period model

Figures 4.42, 4.43, and 4.44 are plotted for the specific values $c_r^{II} = 800$ and $c_n^{II} = 1700$. The behavior of the price functions when c_c^{II} varies is depicted in Figure 4.42. The price for new and remanufactured products in the second period shows the same trend that was observed in the one-period model. When the unit collection and inspection cost rate increases, the prices increase until reaching maximum values where they stay constant.

The price for new products in the first period coincides with the price for remanufactured products when $c_c^{II} < 0.25$ (i.e., $p_{n1}^{II} = p_{r2}^{II}$). For $c_c^{II} > 0.25$, the price for new products in the first period increases much faster than the price for remanufactured products and finally coincides with the price for new products in the second period (i.e., $p_{n1}^{II} = p_{n2}^{II}$). This trend is due to the fact that when c_c^{II} is sufficiently small, the demand for remanufactured products is high which requires the collection a large quantity of returns. Thus, the price for the new products in the first period needs to be set at its lowest level (equal to p_{r2}^{II}) to guarantee enough returns. When c_c^{II} increases, the demand for manufactured products decreases (i.e., the red solid line decreases continuously in Figure 4.43) and then the required quantity of returns also decreases. Therefore the company can afford to increase the price for new products in the first period rapidly without causing the total profit to drop too fast.

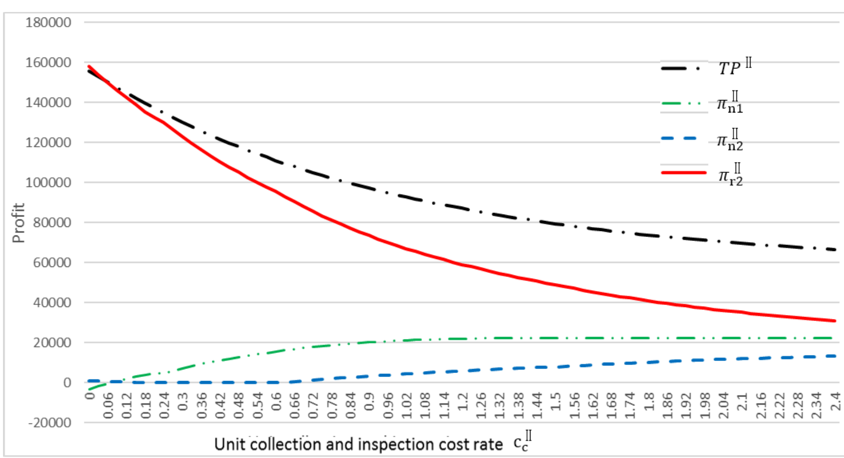

Figure 4.44: Relationship between profits and c_c^{II} in two-period model

Figure 4.44 shows the behavior of the profits when the unit collection and inspection cost rate increases. The optimal total profit decreases due to the rapid decrease of the profit from remanufactured products. A similar result was observed in the one-period model. The profit from new products in the second period rises slightly in the meantime. This increase is due to the fact that when the unit collection and inspection cost rate increases, producing remanufactured products become less profitable and then the company engages less in the remanufacturing activities. The profit from new products in the first period also increases as explained in the previous paragraph.

4.6 Sensitivity to the unit manufacturing and remanufacturing costs

In this set of numerical experiments, the sensitivity to the unit manufacturing and remanufacturing costs are analyzed by varying c_n^k and c_r^k, while keeping all other parameters constant as follows: $\alpha^k = 0.95, \beta^k = 0.3, \gamma^k = 0.6, c_c^k = 0.1$, and $Q^k = 2000$ $(k = I, II)$.

4.6.1 One-period model (unit manufacturing cost)

Figure 4.45 depicts the selection of the optimal production and pricing strategies as the unit manufacturing cost c_n^I increases in the one-period model.

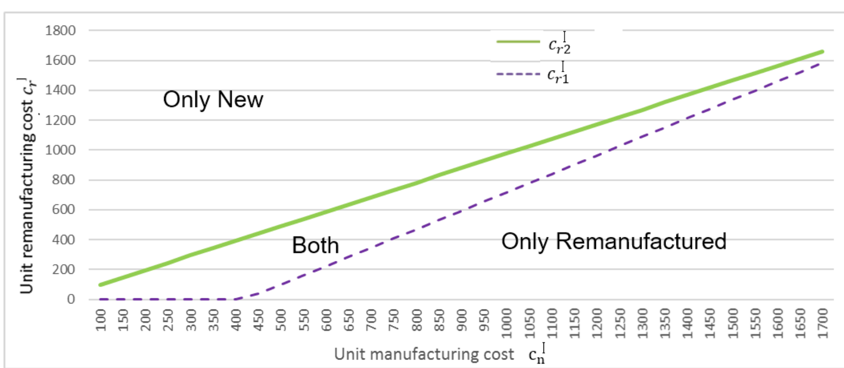

Figure 4.45: Optimal production strategies in one-period model

In Figure 4.45, when the unit manufacturing cost increases, the probability for the company to produce only new products decreases. On the other hand, the opportunity to produce both new and remanufactured products increases when $c_n^I \in [0, 400)$ and decreases beyond 400. The opportunity to produce only remanufactured products increases as the unit manufacturing cost increases because when the unit manufacturing cost increases, producing new products becomes less profitable and then the company is encouraged to engage more in remanufacturing activities.

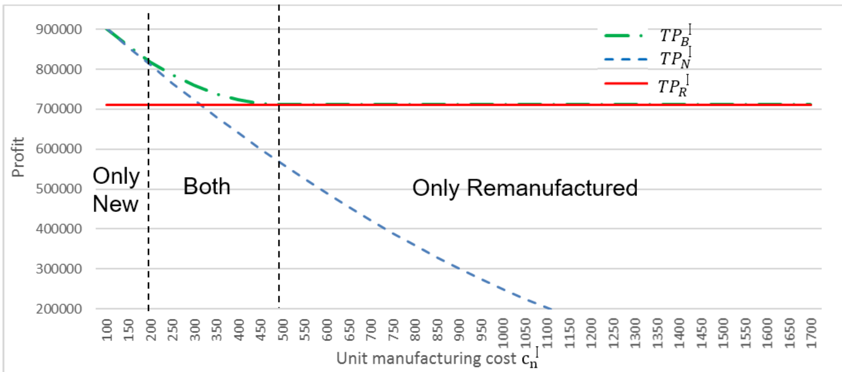

Figure 4.46: Relationship between profits and c_n in one-period model

Figure 4.46 to 4.48, which are plotted for a specific value $c_r^{II} = 100$, depict the behavior of the prices, demands and profits as the unit manufacturing cost increases in the two-period model.

Figure 4.46 shows the behavior of the optimal total profit as the unit manufacturing cost increases. The optimal total profit decreases from the start and stays constant when the unit manufacturing cost is over 500. This is due to the fact that when the unit manufacturing cost is sufficiently high, producing remanufacturing product is much more profitable than producing new products. Thus producing only remanufactured products is the optimal production strategy and the company will produce no new products.

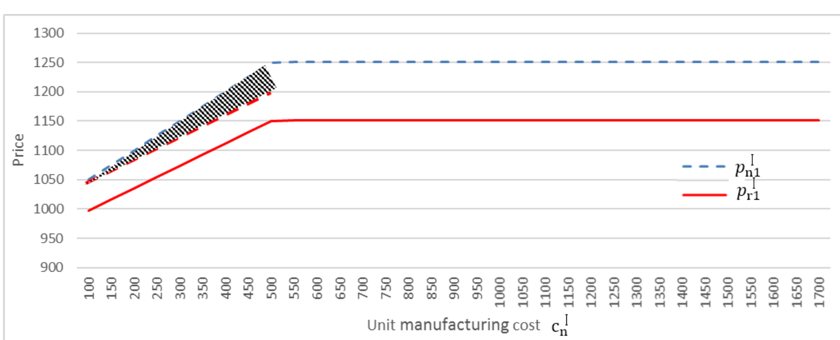

Figure 4.47: Relationship between optimal prices and c_n^I in one-period model

Figure 4.47 shows that as the unit manufacturing cost increases, the prices for both new and remanufactured products increase from the start before staying constant after reaching their respective maximum values. The price difference between the new and remanufactured products increases when the unit manufacturing cost is lower than 500 as depicted by the shaded area. Higher manufacturing cost makes the new products less profitable. Thus, the company needs to discourage the purchase of new products in favor of the remanufactured ones. Hence, the rapid price increase is observed for new products.

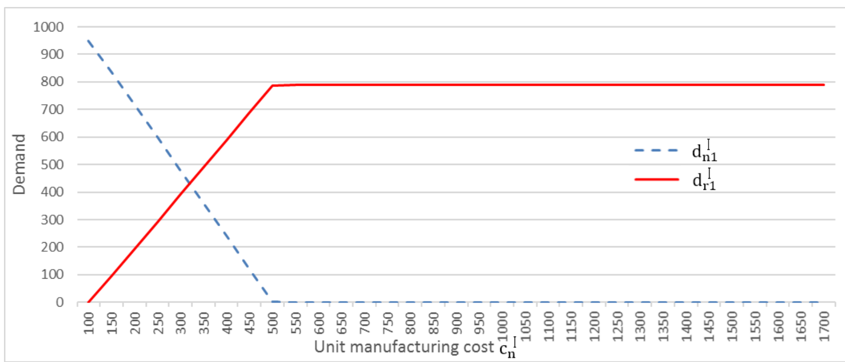

Figure 4.48: Relationship between demands and c_n^I in one-period model

The behavior of the demand functions when the unit manufacturing cost increases is shown in Figure 4.48. The demand for new products decreases sharply from the start until reaching zero when the unit cost is approximately 500 and stays there. The demand for remanufactured products rises quickly and then keeps constant after reaching a maximum value.

4.6.2 Two-period model (unit manufacturing cost)

In the two period model, the selection of the optimal production and pricing strategies when the unit manufacturing cost increases has already been discussed in Figure 3.6.

Figure 4.49 to 4.52, which are plotted for a specific value $c_r^{II} = 100$, depict the behavior of the prices, demands and profits as the unit manufacturing cost increases in the two-period model.

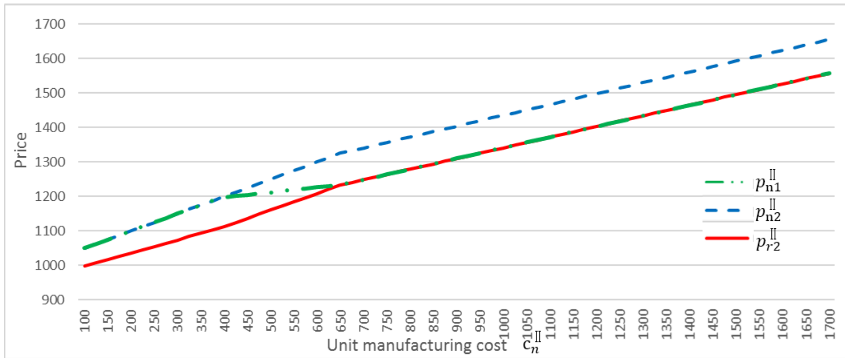

Figure 4.49: Relationship between optimal prices and c_n^{II} in two-period model

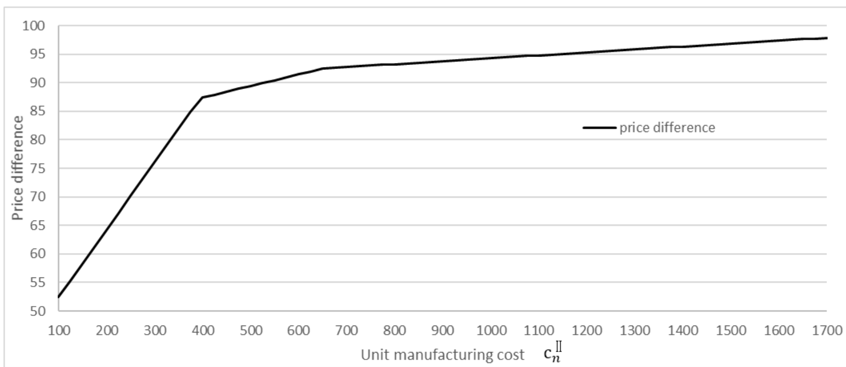

Figure 4.50: Relationship between price difference and c_n^{II} in two-period model

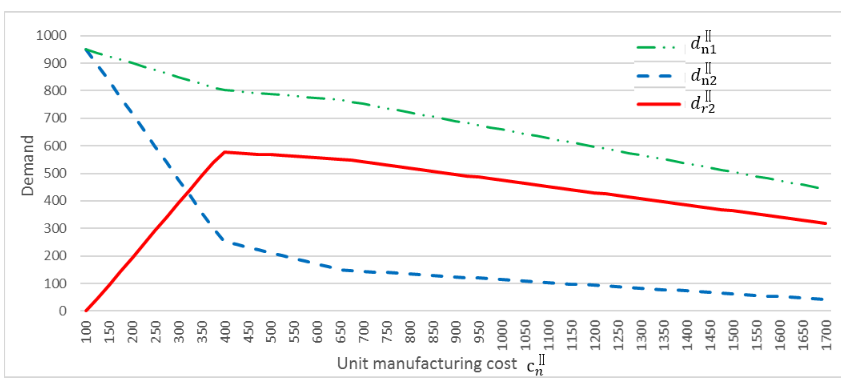

Figure 4.51: Relationship between demands and c_n^{II} in two-period model

Figure 4.49 clearly shows that all products prices increase with the increasing of the unit manufacturing cost. The price for new products in the second period and the price for remanufactured products constitute extreme values between which the price for new in the first period evolves.

For small values of the unit manufacturing cost $c_n^{II} < 400$, the price difference between new and remanufactured products in the second period increases (see Figure 4.50) because producing new products becomes less profitable and thus the company needs to discourage the purchase of new in favor of remanufactured products (i.e., the blue dashed decreases while the red solid line increases in Figure 4.51). The price for new products in the first period coincides with the price for new products in the second period ($p_{n1}^{II} = p_{n2}^{II}$) because the demand for remanufactured is not sufficiently high to require a decrease of p_{n1}^{II} to generate sufficient returns from which the remanufactured products will be made.

For large values of the unit manufacturing cost $c_n^{II} > 400$, the increase of the price for the new products in the first period slows down and coincides with the price for remanufactured products when $c_n^{II} > 650$. The reason for this is that company needs to control the price of new products in the first period in order to generate enough returns at the end of the first period.

Another interesting insight when the unit manufacturing cost is over 400 is that the increasing rate of the price difference between new and remanufactured products in the second period is reduced. The reason for this decrease is that when the unit manufacturing cost increases, the profit losses in the first period increase due to the large quantity of required returns. So the company stops stimulating customers to buy remanufactured products and control the demand for remanufactured products in order to slow down the decrease of the total profit (i.e., the red solid line starts to decrease while the decreasing rate of the blue dashed line is reduced in Figure 4.51 when $c_n^{II} > 400$).

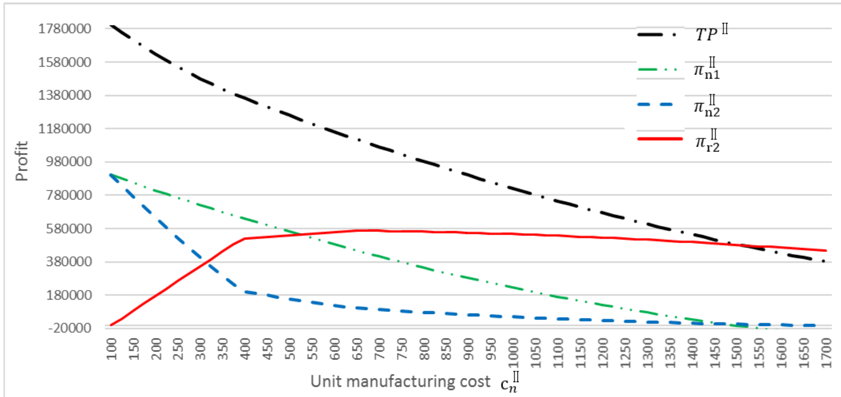

Figure 4.52: Relationship between profits and c_n^{II} in two-period model

Figure 4.52 shows the behavior of the profits when the unit manufacturing cost increases. The total profit decreases continuously when the unit manufacturing cost increases. The result is similar to what was observed in the one-period model. The profit from the remanufactured products increases from the start and decreases after reaching a maximum.

4.6.3 One-period model (unit remanufacturing cost)

The sensitivity to the unit remanufacturing cost in the one-period model is analyzed in this chapter by varying c_r^k. In the one-period model, the selection of production and pricing strategies as the unit remanufacturing cost increases has already been discussed in Figure 3.3.

Figures 4.53 to 4.55, which are plotted for a specific value $c_n^{II} = 1700$, depicts the behaviour of the prices, demands and profits as unit remanufacturing cost increases in the one-period model.

The behaviour of price functions is shown in Figure 4.53. When $c_r^I < 1600$, the prices for both new and remanufactured products increase and their difference stays constant. This is due to the fact that when the unit remanufacturing cost increases, the company raises the price of the remanufactured products in order to decrease their demand (i.e., the red solid line decreases in Figure 4.54) which then slows the decline of the total profit. On the other hand, when the unit remanufacturing cost is less than 1600, producing only remanufacturing products is the optimal production strategy for the company (i.e., the blue dashed line stays zero in Figure 4.54 when $c_r^I < 1600$). As a result, there is no need for the company to adjust the prices in order to stimulate customers to buy new products.

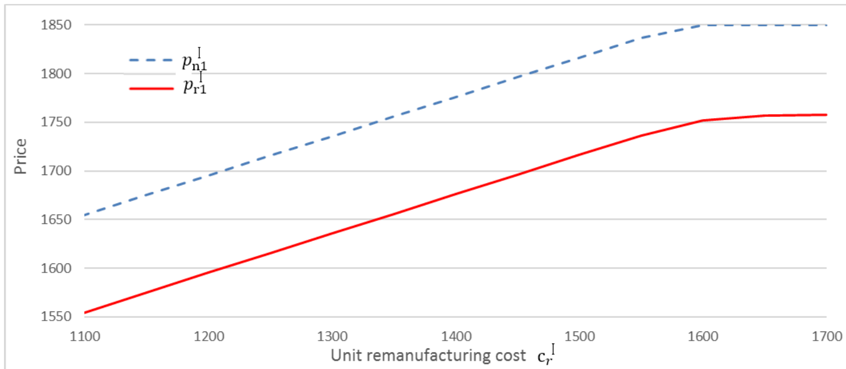

Figure 4.53: Relationship between optimal prices and c_r^I in one-period model

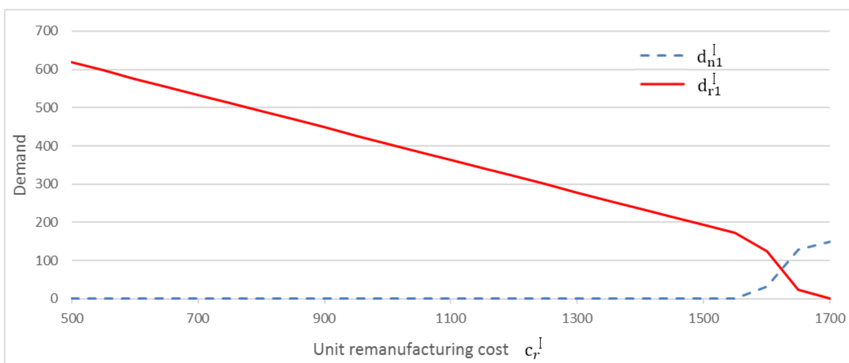

Figure 4.54: Relationship between demands and c_r^I in one-period model

When $c_r^I > 1600$, the price for new products stays constant as the unit remanufacturing cost decreases, while the price for remanufactured products increases slowly. The demand for the new products increases while the demand for the remanufactured products decreases. This is due to the fact that when the unit remanufacturing cost increases, producing remanufactured products becomes less profitable and the company has to slightly raise the price for remanufactured products to discourage their purchase in favour of the new products.

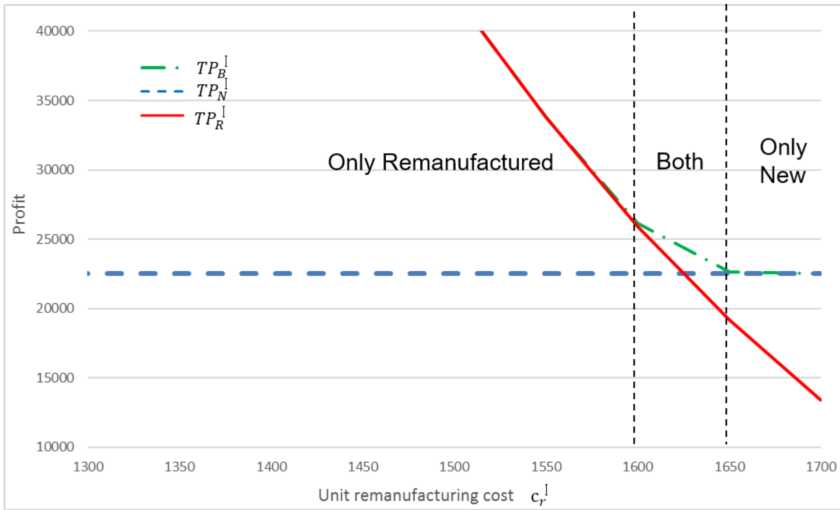

Figure 4.55: Relationship between profits and c_r^I in one-period model

The behaviour of total profit functions is shown in Figure 4.55. As the unit remanufacturing cost increases, the total profit decreases in the beginning and stays constant when the unit remanufacturing cost is over 1650 When $c_r^I > 1650$, producing only new products becomes the optimal production strategy for the company. Moreover, when the unit remanufacturing cost is sufficiently high, due to the low demand for remanufactured products, there is no incentive for the company to invest in reducing the unit remanufacturing cost.

4.6.4 Two-period model (unit remanufacturing cost)

For the two-period model, the selection sequence of the optimal production and pricing strategies with increasing of the unit remanufacturing cost has already been discussed in Figure 3.6.

Figures 4.53 to 4.55, which are plotted for a specific value $c_n^{II} = 1700$, depict the behaviour of the price, demand and profit functions as the unit remanufacturing cost increases in the two-period model.

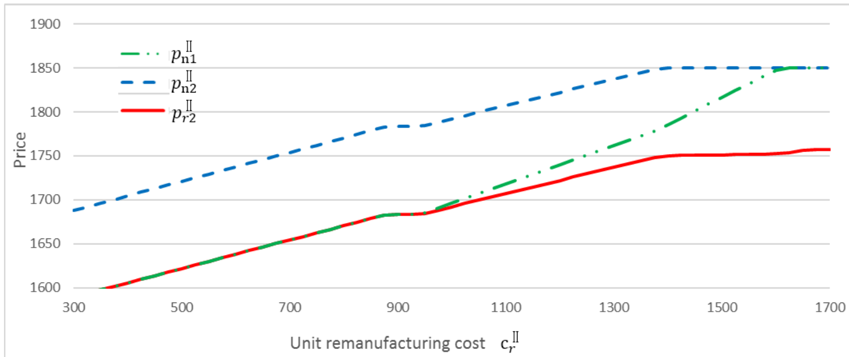

Figure 4.56: Relationship between optimal prices and c_r^{II} in two-period model

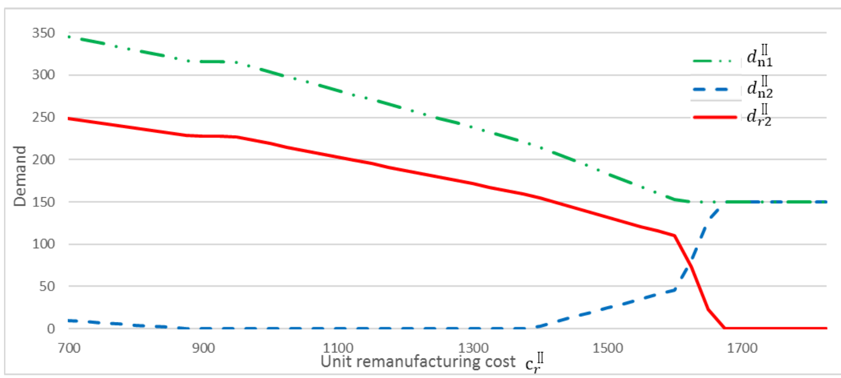

Figure 4.57: Relationship between demands and c_r^{II} in two-period model

In general, the prices for new and remanufactured product in both two periods increase in the beginning and stays fairly constant as the unit remanufacturing cost increases. The price for new products in the second period and the price for remanufactured products constitute extreme values between which the price for new in the first period evolves.

- For small values of unit remanufactured cost ($c_r^{II} < 900$), the price for new products in the first period is the same as the price for remanufactured products because when the unit remanufacturing cost is sufficiently low, it is more beneficial to produce large quantity of remanufactured products. Therefore, the company needs to set the price for the new products in the first period at the lowest level (equals to p_{r2}^{II}) in order to obtain enough returns.

  Another interesting insight is that the company produces some new products even though the remanufacturing cost is sufficiently small (i.e., the blue dashed line in Figure 4.57 is above zero when $c_r^{II} < 900$). Producing more remanufactured products in the second period requires more new products to be sold in the first period at a lower price to guarantee enough returns. Thus, although the unit remanufacturing cost is low, the company needs to control the increase of the demand for remanufactured products in order to avoid huge losses in the first period. Therefore, the company also produces additional new products to satisfy demand.

- When the unit remanufacturing cost reaches mid-range values ($900 < c_r^{II} < 1400$), the price for new products in the first period increases faster than the price of remanufactured products. This is due to the fact that, when the unit remanufacturing cost increases, producing remanufactured products becomes less profitable and the company engages less in the remanufacturing activities (i.e., the red solid line in Figure 4.57 decreases continuously). Therefore, there is no incentive for the company to sacrifice the profit in the first period (setting a low price for new in the first period) to obtain enough returns.

- For high values of unit remanufactured cost ($c_r^{II} > 1400$), the behaviour of the prices for new and remanufactured products in the second period is similar to what was observed in the one-period model. The demand for the new products in the second period begins to increase because the remanufactured products become less profitable and the company adjusts the prices for the new and remanufactured products in the second period in order to stimulate some customers to buy new products rather than purchase remanufactured products

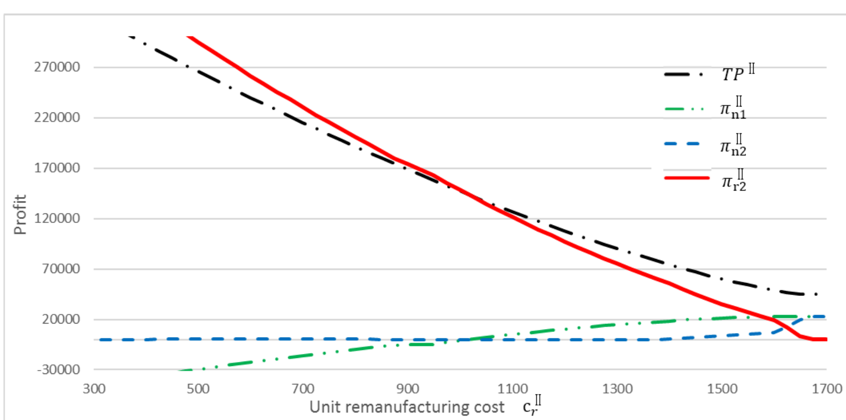

Figure 4.58: Relationship between profits and c_r^{II} in two-period model

The profile of the profit functions in the two-period model is shown in Figure 4.58. In general, the total profit decreases with the increase of the unit remanufacturing cost, which is similar as what was observed in the one-period model. When the unit remanufacturing cost increases, the profit from the remanufactured products decreases rapidly, while the profit from new products in the first period increases and the profit from new products in the second period almost keeps constant in the beginning and increases when the cost is over 1400.

4.6.5 One-period model (cost saving)

In this chapter, the sensitivity to both the unit manufacturing and remanufacturing costs is analyzed by varying c_n^k and c_r^k simultaneously. A new parameter denoted by s^k and defined as the difference between the unit manufacturing cost and the unit remanufacturing cost is introduced: $s^k = c_n^k - c_r^k$. In the following analysis, two values of s^k representing two levels of the cost saving are used: $s^k = 200$ for high level and $s^k = 30$ for low level.

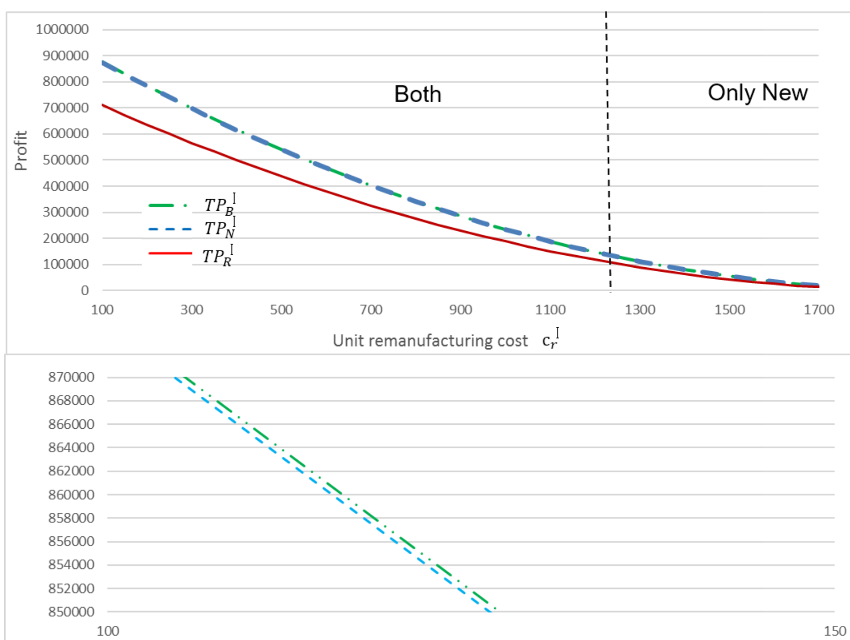

Figure 4.59: Relationship between profits and c_r^I, c_n^I in one-period model ($s^I = 30$)

The profiles of total profit functions are shown in Figure 4.59, when the cost saving is set to a low value ($s^I = 30$). When the unit manufacturing and remanufacturing costs both increase, the total profit decreases at a slower rate. This is because both new and remanufactured products become less profitable due to the increase in the unit manufacturing and remanufacturing costs. Thus the company engages less in manufacturing and remanufacturing activities and then the impact of the increasing unit manufacturing and remanufacturing costs reduces. Moreover, when both unit manufacturing and remanufacturing costs are sufficiently low, producing both new and remanufactured products is the optimal production strategy. Otherwise, the company should produce only new products.

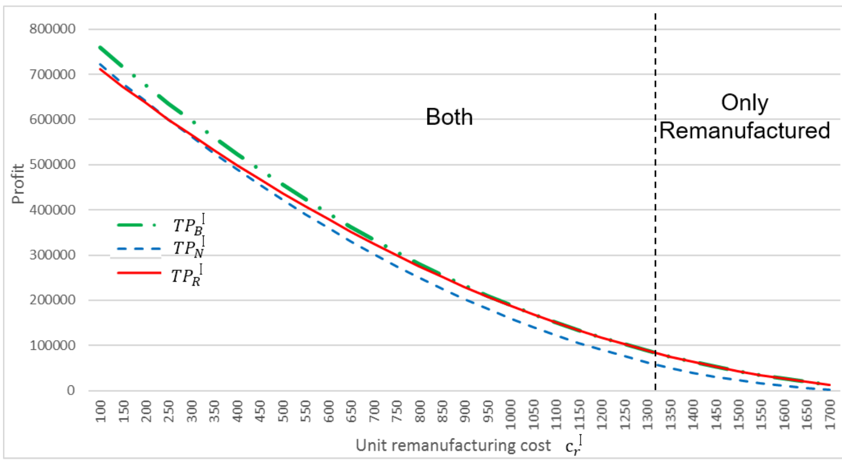

Figure 4.60: Relationship between profits and c_r^I, c_n^I in one-period model ($s^I = 200$)

Figure 4.60 shows the behavior of the profit functions when both the manufacturing and remanufacturing cost increase for a high value of the cost saving ($s^I = 200$). When both unit manufacturing and unit remanufacturing cost increass, the total profit decreases continuously as explained in the previous paragraph. When the unit manufacturing and remanufacturing costs are both sufficiently low, producing both new and remanufactured products is the optimal production strategy. Otherwise the company should produce only remanufactured products instead of producing only new products, which is the opposite of what was observed in the low cost saving case. When s^I is sufficiently small and the unit manufacturing and remanufacturing cost are sufficiently high, the average unit remanufacturing cost is higher than the unit manufacturing cost due to the following three reasons: the convex collection and inspection cost, the losses in the remanufacturing process, and customers preference for new products. Therefore, producing only new products is more profitable than producing only remanufactured products. When s^I is sufficiently high, the difference between the unit manufacturing cost and the unit remanufacturing cost cannot be offset by the previously stated three reasons. Therefore, producing only remanufactured products is the optimal production strategy for the company.

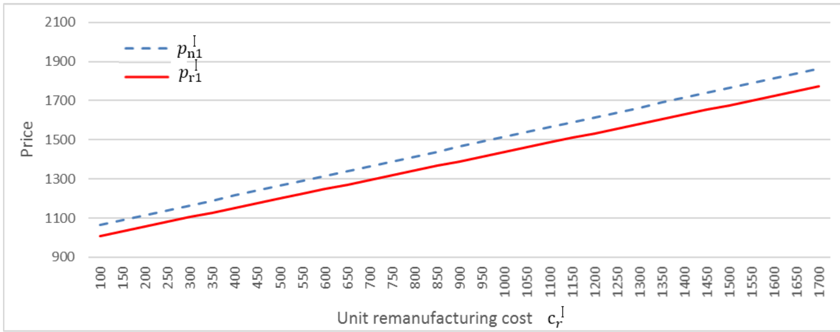

Figure 4.61: Relationship between optimal prices and c_r^I, c_n^I in one-period model ($s^I = 30$)

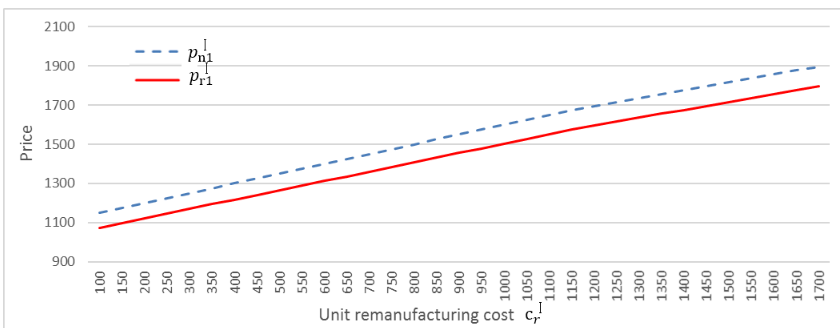

Figure 4.62: Relationship between optimal prices and c_r^I, c_n^I in one-period model ($s^I = 200$)

The behavior of the price functions with the increase of the unit manufacturing and remanufacturing costs is shown in Figure 4.61 and 4.62. There is no significant difference between the profiles of the prices regardless of the value of the cost saving. When both c_n^I and c_r^I increase, the prices of both new and remanufactured products increase and their difference stays almost constant.

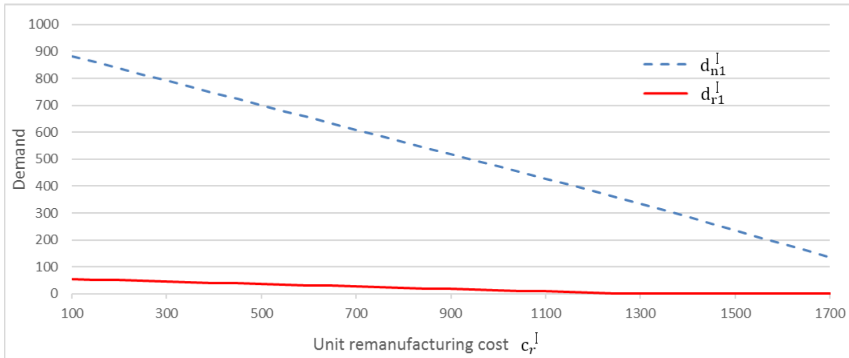

Figure 4.63: Relationship between demands and c_r^I, c_n^I in one-period model ($s^I = 30$)

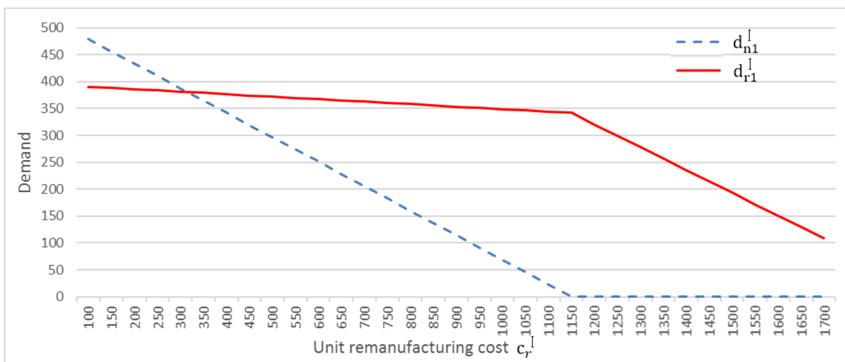

Figure 4.64: Relationship between demands and c_r^I, c_n^I in one-period model ($s^I = 200$)

Figures 4.63 and 4.64 show the behavior of the demand functions when the unit manufacturing and remanufacturing costs increase. When the cost saving is sufficiently low, the demand for both new and remanufactured products decreases. The demand for new products is always larger than the demand for remanufactured products because when the cost saving is sufficiently low, the convex collection and inspection cost, the losses in the remanufacturing process, and customers' preference for new products, cause the production of remanufactured products to be less profitable than the production of new products.

When the cost saving is sufficiently high, the demand for new products decreases until reaching zero when $c_r^I = 1150$. The demand for remanufactured products decreases continuously and its deceleration increases when the unit remanufacturing cost reaches 1150.

4.6.6 Two-period model (cost saving)

Figures 4.65 to 4.70 depict the behaviour of the price, demand and profit functions as both the unit manufacturing and remanufacturing cost increase in the two-period model.

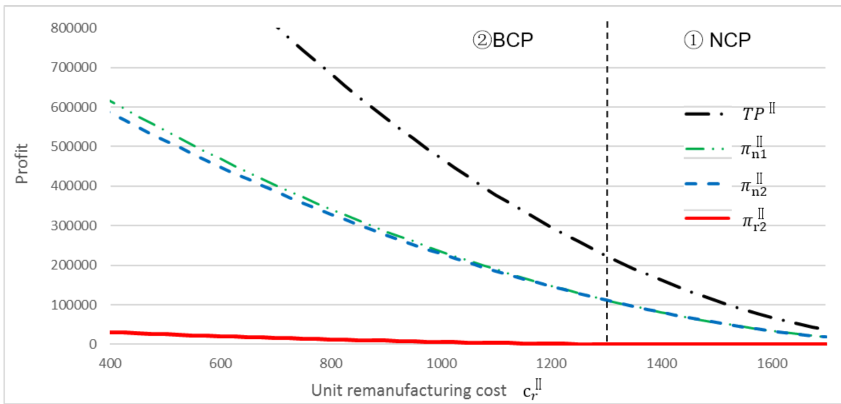

Figure 4.65: Relationship between profits and c_r^{II}, c_n^{II} in two-period model ($s^{II} = 30$)

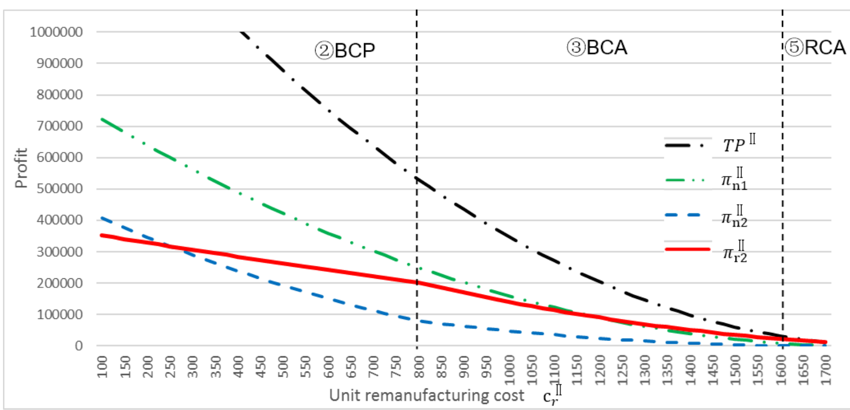

Figure 4.66: Relationship between profits and c_r^{II}, c_n^{II} in two-period model ($s^{II} = 200$)

Figures 4.65 and 4.66 show that whether the cost saving is low or high, the profiles of the total profit are similar. When both the unit manufacturing and remanufacturing cost increase, the total profit decreases with a slowing rate as already explained for the one-period model.

The profit from remanufactured products is much higher in the case when the cost saving is sufficiently high than when the cost saving is low. This is because when the cost saving is large, producing remanufactured products is much more profitable than when the cost saving is small.

Moreover, when the unit manufacturing and remanufacturing cost are both high, the optimal production strategy is to produce only new products in the second period for low values of the cost saving parameter. However, for high values of cost saving, producing only remanufactured products is the optimal strategy. This is the similar to what was observed in the one-period model.

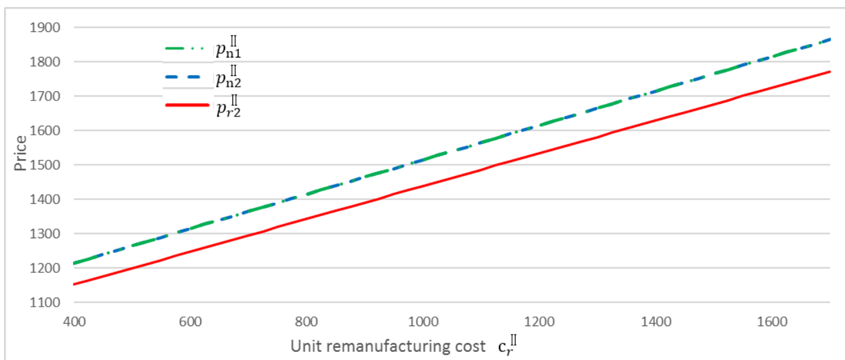

Figure 4.67: Relationship between optimal prices and c_r^{II}, c_n^{II} in two-period model ($s^{II} = 30$)

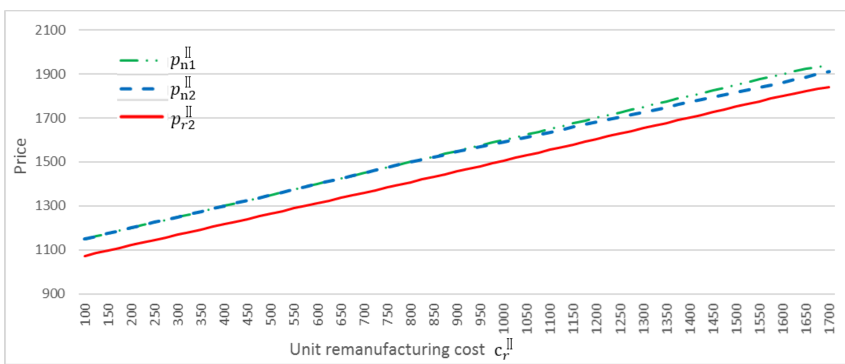

Figure 4.68: Relationship between optimal prices and c_r^{II}, c_n^{II} in two-period model ($s^{II} = 200$)

The behavior of the price functions are shown in Figure 4.67 and 4.68. When the unit manufacturing and remanufacturing cost increase, the prices for new and remanufactured products in both periods increase regardless of the value of the cost saving. When the cost saving is at a high level and the unit manufacturing and remanufacturing costs are sufficiently large, the price for new products is higher in the first period than in the second period.

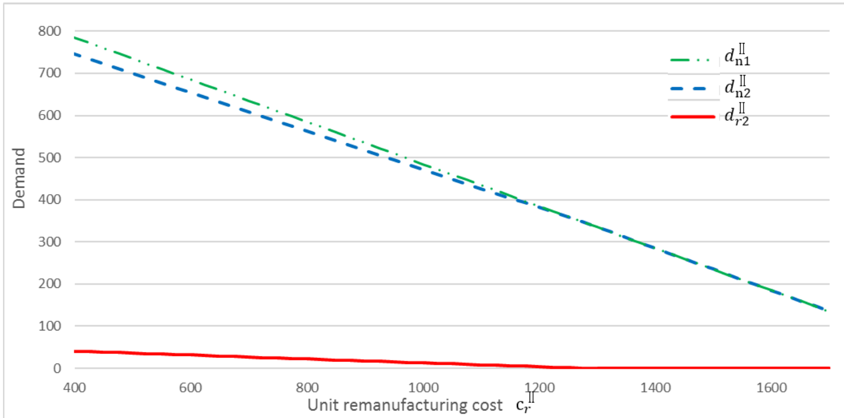

Figure 4.69: Relationship between demands and c_r^{II}, c_n^{II} in two-period model ($s^{II} = 30$)

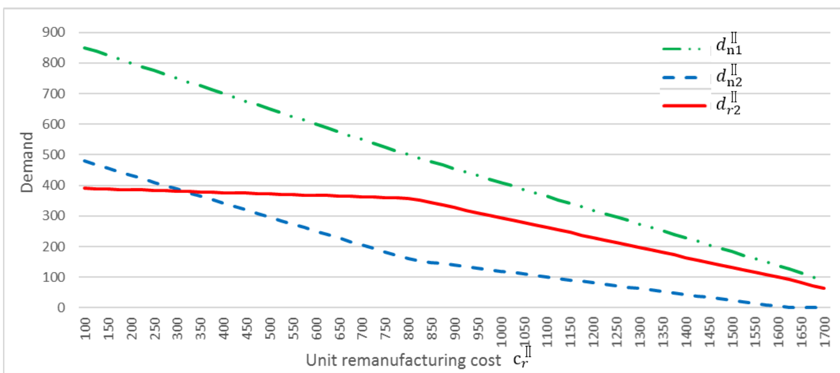

Figure 4.70: Relationship between demands and c_r^{II}, c_n^{II} in two-period model ($s^{II} = 200$)

Figures 4.69 and 4.70 show the profiles of the demand functions for the products in the second period which is similar to the observations made in the one-period model. The demand for new products in the first period decreases significantly as the unit manufacturing and remanufacturing cost increase.

4.7 Summary of the sensitivity of analysis and managerial insights

Multiple sets of numerical experiments have been conducted above and have shown that our models lead to valid and logical decisions. A summary of key sensitivity results and managerial insights is proposed as follows.

For the selection of production strategies:

- In the one-period model, the increase of customers' tolerance for remanufactured products enables the company to engage more in remanufacturing activities. However, in two-period model, when customers' tolerance for remanufactured products is too high, the company should produce both products instead of only remanufactured products in the second period because of the convex collection and inspection costs and profit losses incurred in the first period to generate sufficient returns.

- In both the one- and two-period models, when either the proportion of high quality returned products, or the remanufacturability, or both increase, producing remanufactured products becomes more profitable.

- In the both one- and two-period models, when the value of the unit remanufacturing cost is sufficiently high, producing only new products will be the optimal production strategy for the company regardless of how the market size and the unit collection and inspection cost rate change. For low values of the unit remanufacturing cost, when either the market size, or the unit collection and inspection cost rate, or both increase, in general the selection sequence of the optimal production strategies may be from producing only remanufactured products to produce both new and remanufactured products.

- In the one-period model, the decrease in the unit manufacturing or remanufacturing costs leads the company to producing more new or remanufactured products, respectively. On the other hand, in the two-period model, the decrease in the unit manufacturing cost stimulates the company to produce more new products in the second period, while produce both new and remanufacturing products instead of only remanufactured products in the second period when the unit remanufacturing cost is sufficiently low and the unit manufacturing cost is relatively high.

  When both the unit manufacturing and remanufacturing costs are sufficiently high, producing only new products may be the optimal production strategy in the presence of a large cost saving. Otherwise, producing only remanufactured products may be the optimal production strategy.

For setting the optimal prices:

- As customers become more tolerant towards the remanufactured products, the company should decrease the price for new products and increase the price for remanufactured products in the one-period model or in the second period of two-period model. In the two-period model, the price for new products in the first period decreases in the beginning and then increases as customers' tolerance for remanufactured products increases.

- In both the one- and two-period models, when either the proportion of high quality returns, or the remanufacturability rate, or both increase, the prices for new and remanufactured products decrease.

- In both the one- and two-period models, when either the unit manufacturing cost, or unit remanufacturing cost, or unit collection and inspection cost rate, or the market size, or all increase, the prices for new and remanufactured products increase.

For generating optimal demands:

- In the one-period model, as customers become more tolerant towards the remanufactured products, the company should decrease the demand for new products and increase the demand for remanufactured products. In the two-period model, the behavior of demand functions in the second period is similar to what was observed in the one-period model, except when the customers' tolerance for remanufactured products is sufficiently high, the demand for new products in the second period may increase and the demand for remanufactured products may decrease. The demand for new products in the first period may first decrease and then increase.

- In the one period model, when either the proportion of high quality returns, or the remanufacturability rate, or both increase, the company should stimulate the demand for remanufactured products and let the demand for new products decrease. In the two period model, the profiles of the demand functions in the second period is the same as in the one-period model. The demand for new products in the first period increases when either the proportion of high quality returns, or the remanufacturability rate or both increase.

- In both one- and two-period models, when the market size increases, the demands for new and remanufactured products increase.

- In the one-period model, with the increase of the unit remanufacturing cost and unit collection and inspection cost rate, the company should increase the demand for new products and decrease the demand for remanufactured products. In the two-period model, the behavior of the demand functions in the second period is similar to the behavior in the one-period model, except when the unit remanufacturing cost is sufficiently low, the demand for new products in the second period may decrease. The demand for new products in the first period decreases continuously as the unit remanufacturing cost and unit collection and inspection cost rate increase.

- In the one-period model, with the increase of the unit manufacturing cost, the company is stimulated to decrease the demand for new products and increase the demand for remanufactured products. In the two-period model, the demand for new products in both periods decreases, while the demand for remanufactured products increases firstly and then decreases slightly as the unit manufacturing cost increases.

For generating the optimal total profit:

- As customers' tolerance for remanufactured products increases, the optimal total profit increases in the one-period model. However, excessively high customers' tolerance for remanufactured products results in the decrease of the optimal total profit in the two-period model.

- In both one- and two-period models, when either the proportion of high quality returns, or the remanufacturability rate, or the market size, or all increase, the optimal total profit increases.

- In both one- and two-period models, when either the unit manufacturing cost, or unit remanufacturing cost, or unit collection and inspection cost rate, or all increase, the optimal total profit decreases.

Tables 4.1 and 4.2 summarize the responses of the total profit, prices and demands as each of the seven parameters under consideration in the sensitivity analysis increase.

Table 4.1: Summary of sensitivity analysis - one-period model

	TP^I	p_n^I	p_r^I	d_n^I	d_r^I
α^I	$\nearrow$	$\searrow$	$\nearrow$	$\searrow$	$\nearrow$
β^I	$\nearrow$	$\searrow$	$\searrow$	$\searrow$	$\nearrow$
γ^I	$\nearrow$	$\searrow$	$\searrow$	$\searrow$	$\nearrow$
Q^I	$\nearrow$	$\nearrow$	$\nearrow$	$\nearrow$	$\nearrow$
c_c^I	$\searrow$	$\nearrow$	$\nearrow$	$\nearrow$	$\searrow$
c_n^I	$\searrow$	$\nearrow$	$\nearrow$	$\searrow$	$\nearrow$
c_r^I	$\searrow$	$\nearrow$	$\nearrow$	$\nearrow$	$\searrow$

Table 4.2: Summary of sensitivity analysis - two-period model

	TP^{II}	p_{n1}^{II}	p_{n2}^{II}	p_{r2}^{II}	d_{n1}^{II}	d_{n2}^{II}	d_{r2}^{II}
α^{II}	$\nearrow\searrow$	$\nearrow\searrow$	$\searrow$	$\nearrow$	$\nearrow\searrow$	$\nearrow\searrow$	$\nearrow\searrow$
β^{II}	$\nearrow$	$\searrow$	$\searrow$	$\searrow$	$\nearrow$	$\searrow$	$\nearrow$
γ^{II}	$\nearrow$	$\searrow$	$\searrow$	$\searrow$	$\nearrow$	$\searrow$	$\nearrow$
Q^{II}	$\nearrow$	$\nearrow$	$\nearrow$	$\nearrow$	$\nearrow$	$\nearrow$	$\nearrow$
c_c^{II}	$\searrow$	$\nearrow$	$\nearrow$	$\nearrow$	$\searrow$	$\nearrow$	$\searrow$
c_n^{II}	$\searrow$	$\nearrow$	$\nearrow$	$\nearrow$	$\searrow$	$\searrow$	$\nearrow\searrow$
c_r^{II}	$\searrow$	$\nearrow$	$\nearrow$	$\nearrow$	$\searrow$	$\nearrow\searrow$	$\searrow$

[1] $\nearrow$: increasing; $\searrow$: decreasing; $\nearrow\searrow$: increase and/or decrease.

Chapter 5

Conclusion

In this thesis, we have reviewed the literature on pricing and production strategies for remanufacturing. Shortcomings identified by this review led us to develop two mathematical models in the context of a monopoly. Demands for both new and remanufactured products were derived using utility theory. Prices were assumed to be always higher for new products than for remanufacturing products. In the reverse supply chain, we considered a convex collection and inspection cost, different qualities of returned products, and losses in the remanufacturing process. The convex programming models obtained in the one-period and two-period settings are solved according to the conditions. Different production and pricing strategies and their existence conditions were derived. Through sensitivity analysis, the influence of different key parameters on selecting the optimal production and pricing strategies were investigated and discussed.

Results from the sensitivity analysis chapter shows that overall the one- and two-period models behave in a similar way. The additional constraints in the two-period model (the number of returned products is limited by the number of new products sold in the first period), make the results from the two-period model are more realistic.

Although the models in this thesis provide us with new insights on pricing and remanufacturing strategies, there are several ways our work can be extended in the future.

- Results from the two-period model include policies where the company should collect all new products sold in the first period as raw materials for producing remanufactured products. Such complete collection would be prohibitively costly. Thus, the current model can be quickly extended to the case where only a fraction of first-period sales can be collected.

- For the two-period model in the thesis, we assumed that the market size does not change between the first and second period. In practice, the market size usually changes according to the success or failure to capture market share in anterior. Thus it would be interesting to model how sales of products in previous affect market size changes in subsequent periods. An empirical analysis would be needed to capture such relationship before including it in a mathematical formulation.

- We have considered two quality-bins in sorting the returns and associated different unit remanufacturing costs to each bin. However, we used the same unit collection cost for all products even when they were of different quality grade. An extension would be to consider that customers know the health condition of their returns and command refunds that are proportional to the quality of their returned products. For example, the refund obtained for returning a non-operational laptop would be smaller than the refund obtained from returning an operational equivalent laptop. Hence, the collection cost can be made proportional to the quality of the return.

- The thesis considered only a monopoly for both one- and two-period models. It is worth examining the pricing and production strategies for the manufacturer in a competitive environment in which multiple manufacturers compete.

- This research work can also be extended to include all members of the supply chain: suppliers, manufacturer, retailers, collectors, third-party remanufacturers, etc. It would be interesting to investigate how decisions made by the manufacturer will influence or be influenced by the other members.

- The convex collection and inspection cost was modelled as a quadratic function. Future extensions will investigate the use of different convex cost structures such as piecewise linear, step functions, etc.

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