Revenue Management and Strategy for the Refurbishing Economy

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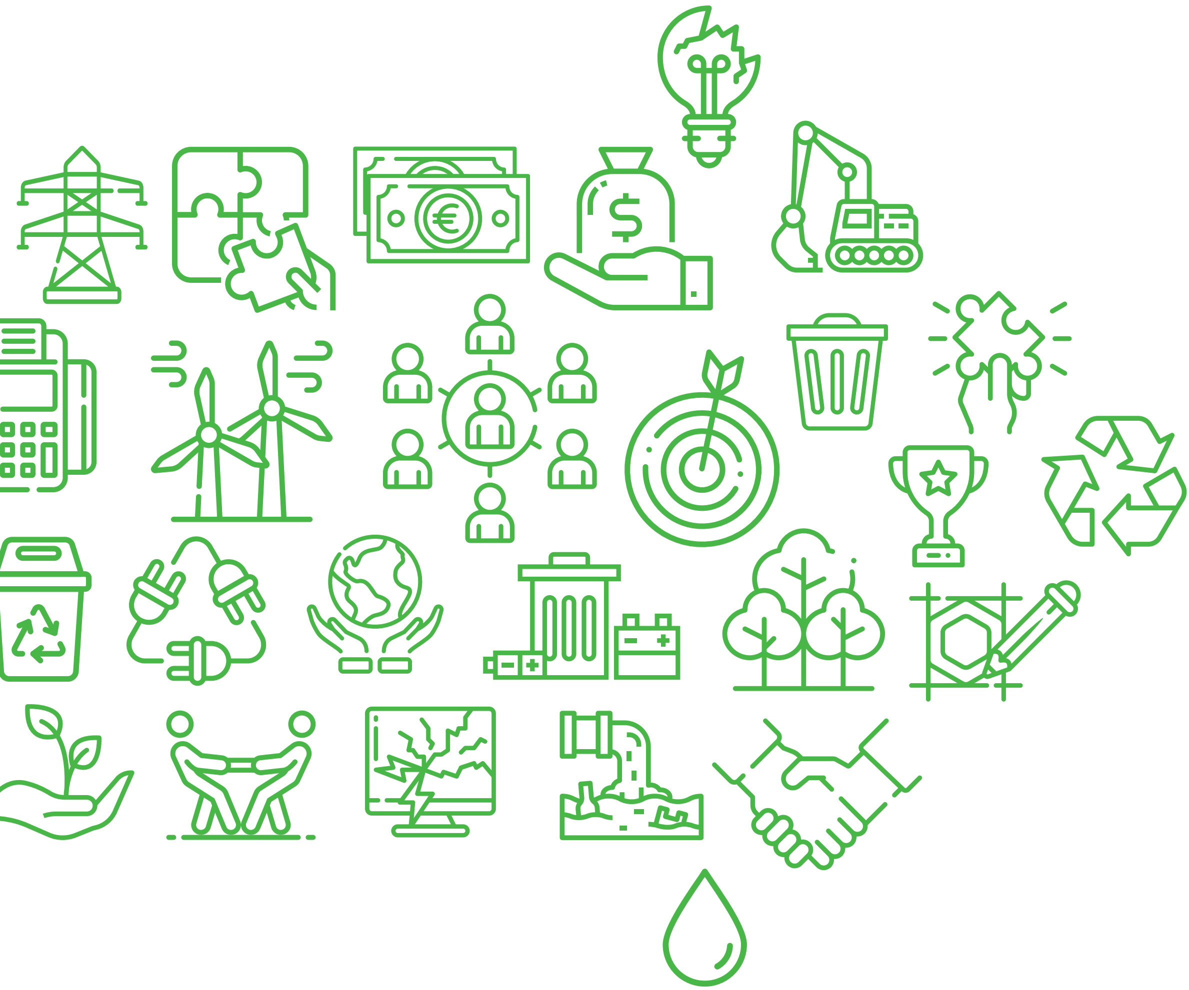
NUGHTHOH ARFAWI KURDHI



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Nughthoh Arfawi Kurdhi

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Introduction

Due to environmental regulations, customer concerns and social awareness, limited natural resource availability and economic reasons, refurbishing (remanufacturing) is becoming increasingly important for industries. Refurbishing is an industrial process of restoring a discarded product back to like-new condition by improving the product quality and its life span. Following industry usage, in this thesis we will use the terms "remanufacturing" and "refurbishing" interchangeably (see Thierry et al. (1995) for the detailed definition). Comparing to other product recovery activities such as recycling, repair, and reuse, refurbishing guarantees that the quality of refurbished products is as good as that of new products (Reike et al., 2018). Every refurbished product completes a rigorous refurbishment process that includes full testing that meets the same functional standards as new products. Refurbishing is appearing as one of the closed-loop supply chain approaches for the circular economy where end-of-life (EOL) and end-of-use (EOU) products are returned to the original condition. By refurbishing used products, companies extend their products' life cycles and thus help keeping them out of landfills. Hence, in a long term perspective, refurbishing could reduce landfill usage. According to Ferguson and Souza (2010), this practice should in turn improve the positive environmental perception of firms and could avoid not only negative publicity by environmental organizations, but also additional environmental legislation. Compared to direct landfill or conventional material recycling, refurbishing is much more environmentally friendly and energy efficient. A refurbishing process only uses on average approximately 20 – 25% of the energy required for the initial production (Lund, 1985). Due to the importance of waste reduction and in order to achieve sustainability, many governments around the world have enacted laws to encourage refurbishing, such as Waste Electrical and Electronic Equipment (WEEE) Directive of European Commission, Electronic Waste (e-waste) Take-Back Laws of 25 states in United State, Waste Vehicle Treatment Regulations of Germany, Specified Household Appliances Recycling Law (SHARL) of Japan, and Circular Economy Promotion Law of China (Esenduran et al., 2017; Wang et al., 2018a).

In addition to its environmental benefits, refurbishing has led to substantial economic benefits, and its profitability has resulted in increased growth in the industry. Refurbishing has become widespread in many industry sectors such as consumer products, electrical appliances, aerospace, automotive, and machinery (Lund, 1996; Directive, 2012). Some original equipment manufacturers (OEMs) have also engaged in refurbishing as a part of their corporate strategy, including Apple, Samsung, Fuji, Xerox, Kodak, IBM, HP, Bosch, Boeing, and Caterpillar. Refurbishing is (almost) always cheaper than manufacturing a new product since many components and parts can be reused, thus avoiding the need to procure them from suppliers. In fact, refurbishing can result in average profit margins that can exceed 20%; it is estimated that a refurbishing policy can save 40 – 65% of the cost of producing a new product (Savaskan et al., 2004; Genc and De Giovanni, 2017). These benefits allow refurbishing firms to broaden their market share by selling refurbished products at low prices. This will provide advantage to the firm's position in a competitive environment and allow the firm to share this advantage with its customers. In 2011, the US refurbishing industry was valued at $43 billion (Williamson et al., 2012). In the Asia-Pacific region, refurbishing is growing and has been discussed in the Asia-Pacific Economic Cooperation forum (APEC) since 2006 (APEC and US-AID, 2013). Based on the latest statistical data (Parker et al., 2015), refurbishing in the European Union generates around €30 billion in turnover, and it is expected that by 2030, it could attain an annual value of €90 billion. Several studies state that the sales of refurbished products surpass $100 billion per year with consumer markets capturing about $10 billion in sales per year (Atasu, 2016). It is clear that there is a big refurbished products market, and that it is only going to grow in the future. The growing of consumer markets for refurbished products is accelerated by the widespread popularity of on-line auctions and internet sales. The increased demand and refurbished products availability pose a complex challenge for the manufacturer who produce new products.

Given the large economic impact and the increasing importance of refurbished products in the strategy, sales, and operations of many companies, this thesis is focused on corporate decision making under traditional economic objectives. The economic benefits of refurbishing for firms are currently the most important consideration of firms in making decisions on their refurbishing strategy (Wu, 2012). According to Guide Jr and Van Wassenhove (2009), much research focuses on product returns management (e.g. timing, quantity, quality of used products; product acquisition, return rates) and operational issues (e.g. reverse logistics, test, sort, disposition, disassemble, repair, remanufacture) pertaining to closed-loop supply chain (CLSC). They develop a five-phase framework to show the growth trends of CLSC: (1) the golden age of refurbishing, (2) from refurbishing to valuing the reverse logistics process, (3) coordinating the reverse supply chain, (4) closing the loop, and (5) prices and markets. Recently, there is a strong need to investigate refurbishing from market (demand) side (Souza, 2013; Póvoa et al., 2016; Atasu, 2016; Govindan et al., 2019). Guide Jr and Van Wassenhove (2009) point out that markets and prices become barriers if they are not fully understood, no matter how well the operational system is designed. Hence, in this dissertation we focus on three key aspects of the decision problem, namely consumer behavior, demand cannibalization between new and refurbished products, and competition with other manufacturers' new and refurbished products. In fact, the quality of refurbished products not only refers to the functional aspect, but also to the image of the products and the consumers' perception. Due to its perception by consumers, the price of refurbished products is usually lower than its new version, even if they have the similar characteristics as the original ones. Therefore, it is important to understand how consumers perceive the refurbished products quality. Moreover, the pricing policy should be taken into account by firm that engages in refurbishing, especially in a competitive environment. An optimal pricing strategy is necessary for reinforcing the refurbished products demand and for maximizing the profitability of the firm.

To this end, we conduct behavioral experiments among consumers to characterize consumer behavior. We deploy the resulting behavioral insights in mathematical models that allow us to study between-product cannibalization and interfirm competition.

Our research is positioned in the mobile phone refurbishing industry, which has a massive worldwide impact (Directive, 2012; Marcussen, 2003). The refurbished smartphone market is the fastest growing smartphone segment. In 2015, smartphones worth over $11 billion were either sold in the used product market or traded in with an average value of $135 (Deloitte, 2016). This number has only grown in the last few years. In 2017, it grew 17% YoY compared to a modest 3% growth in the new smartphone segment and it is estimated that the refurbished smartphone market is close to 10% of the global smartphone market (Counterpoint, 2018). In 2017, worldwide sales of refurbished and used phones was estimated to account for over $19 billion in revenue, and will increase to $40 billion by 2025 (PMR, 2017). However, still only a small share of used smartphones are being collected for refurbishment. According to the Environmental Protection Agency of the USA, there has been an increase of 120% in electronic waste in the past decade but only 25% of it was collected. This has prompted multiple countries (including the USA and Canada) to impose strict regulations on electronic waste. In the report, the IDC (2020) forecast that over 330 million refurbished smartphone units will be shipped in 2023, accounting for a 13.6% growth from 2018 to 2023. Another report by Intelligence (2019) states that refurbished smartphone market is expected to grow at a CAGR of 12.61% during the forecast period 2020 to 2025.

1.1. Cannibalization, Competition, Consumer Behavior

Although refurbishing has a good potential in delivering extensive economic benefit and has been implemented in a variety of industries, many firms still do not adopt refurbishing as an important business strategy. These manufacturers are worried about potential cannibalization, which may reduce the market of new products and the profit margin due to underpricing. The problem of cannibalization is getting more attention when new and refurbished products are differentiable to customers and the margin on the refurbished version is less than the margin on the new one. Some firms are concerned as they do not know precisely how refurbishing sales influence the sales of new products. Some managers believe that one new product can be cannibalized by four refurbished products sold in the market (Atasu et al., 2010a). An increase in refurbished products sales might hence lead to a decrease in new products sales. Therefore, it is important to consider the pricing decision for new and refurbished products in order to optimize profit. However, offering refurbished products could also have benefits to the overall level of sales, especially when such products could be sold at a lower price and are offered to a specific market segment that is very sensitive to price (Gallo et al., 2012). Deploying a series of behavioral studies, in Chapter 2 we investigate the cannibalization structure in various types of markets and then incorporate the results into analytical models in Chapter 3 and 4. Chapter 5 of this dissertation investigates whether the cannibalization could be reduced by differentiating the quality of new products from that of refurbished ones by introducing a new product generation.

The presence of other firms (other manufacturers, third parties) also selling refurbished products, is a further major issue for firms. In this case, the firms face external competition and strive to evolve a reasonable refurbishing strategy - whether to put refurbished product into the market and, if so, how to manage the quantities and prices of both new and refurbished products. For example, in the consumer electronics industry, global brands such as Apple, Samsung, Lenovo, Dell, HP have made product refurbishing a key part of their strategy. These companies have launched both new and refurbished products in the market. In such competitive environment with potential cannibalization of new product sales, setting the product prices and quantities correctly will determine the profitability of the firm. If not done correctly, entering the refurbished products market may reduce profitability altogether. Chapter 3 of this dissertation models the duopoly competition between two firms selling both new and refurbished products. They simultaneously set their pricing and sales strategy to maximize their profits.

In many cases where a manufacturer does not refurbish, the void is filled by third party firms whose primary business is to offer refurbished versions of new products of large global brands. According to Ferguson (2010), most refurbishing sectors have been dominated by such third party firms. Hauser and Lund (2008) found that approximately 94% of roughly 2,000 refurbishing firms were third parties. According to Liu et al. (2018), the existence of third party refurbishing firms cannot be controlled by manufacturers, especially for electrical and electronic consumer products. Third-party-refurbished products cannibalize manufacturers' new products, resulting in competition between refurbished and new products (Atasu et al., 2008b; Agrawal et al., 2015b; Liu et al., 2018). In response to the entry of third party firms, some manufacturers try to deter the secondary market for their products by creating policy based on authorization (relicensing) fees. Chapter 4 of this dissertation examines the conditions under which both the manufacturer and the third party may benefit from such authorization strategies.

Researchers have recognized that consumers' perception about the quality of new and refurbished products is different (McKie et al., 2018). Hence, the consumer behavior towards these products also plays an important role in the pricing problem since it can influence the demands of both types of products. In the literature, consumer behavior and demand issues are commonly used as an assumption in many analytical models. For example, many analytical models assumed that demand is a linear function of price. Such assumption arises from one of the fundamental principles of economic theory, known as the law of demand. The demand for a product increases with a decrease in its price. However, using a behavioral experiment, Ovchinnikov (2011) shows in a monopolistic setting that there exists a consumer segment where the purchasing behaviour is an inverted U-shaped function of discount rate. At moderate discount levels, the number of consumers switching from new to refurbished products increases when the discount increases. At large discount levels, consumers may doubt the refurbished products' quality and consequently decide to either buy the new product or not make any purchase. Further, Atasu et al. (2008b) point out that market segmentation could affect the refurbishing strategy. Ovchinnikov (2011) classifies consumers into high-end customers who prefer to buy both the new and refurbished products and low-end customers who only want to purchase refurbished products. An experimental study by Abbey et al. (2015a) identifies two distinct consumer segments: a new product only segment who would only purchase the new product, and an indifferent segment who was roughly indifferent between refurbished and new products. The above studies show that it is important to observe and understand the consumer purchasing behavior when dealing with pricing of refurbished products before incorporating it into an analytical model, and an empirical study could be used to help analyze the behavior. Chapter 2 of this dissertation presents some behavioral studies that cover the gap in the current literature by examining the impact of brand and competitive intensity on the relationship between price and perceived quality of refurbished products. In our behavioral studies, we involve brands with different strength and consider both monopolistic and duopolistic markets.

1.2. Research Objective and Contributions

Research on consumer behavior starts with estimating realistic behavior of consumers using a behavioral study before incorporating it into an analytical model. On the one hand, this brings new research opportunities to revisit the cannibalization model in refurbishing. On the other hand, this also implies great challenges because the consumer behaviors are of high dimensionality and heterogeneity. In turn, this demands refurbishing firms to gain profound understanding of their customers' behavioral responses to their production and pricing policies. The current thesis contributes to both behavioral studies and analytical models. From the behavioral study perspective, the thesis contributes to the literature on the behavioral research in the refurbished economy. From analytical model perspective, the thesis contributes to the literature on product-line competition, cannibalization, and incorporating consumer behavior. In this section we briefly discuss the research objectives and contributions of each chapter separately.

1.2.1 Price-Perceived Quality Relationship for Refurbished Products (Chapter 2)

In Chapter 2, we conduct three behavioral studies to examine the relationship between price and perceived quality for refurbished products in various types of markets: a secondary market for consumers who want to purchase a refurbished product (Study 1), a market with competition between new and refurbished products (Study 2), and the case of a market with competition between brands (Study 3). In particular, we examine the existence of an inverted U-shaped switching function in those various situations. The assumption that underlies the research is that consumers might use price as an indicator of refurbished products' quality, and begin to doubt the quality of the products when the price is relatively cheap. Based on the research evidence concerning consumers' price awareness, consumers may not only use price as a measure of cost, but also as an indicator of product quality. Moreover, the consumers behavior toward refurbished products also may depend on the relative strength of its brand. "Brand is a product or service or organization, considered in combination with its name, its identity and reputation" (Anholt, 2007). According to Monroe (2002), brand name has been found to relate price and perceived quality. The effect of brand name on quality perceptions could be larger than price, and thus will effect the price-perceived quality relationships. van Weelden et al. (2016) point out that the positive brand reputation may reduce the negative perception of consumers towards the refurbished products. In Study 1 and 2, we employ Apple as a high-end brand, to be consistent with previous studies (e.g., Abbey et al., 2017; Agrawal et al., 2015b; Abbey et al., 2019), and include Motorola as a low-end brand. In Study 3, we investigate duopoly competitions among the following brands: Apple versus Motorola, Samsung versus Motorola, and Apple versus Samsung[1]. To the best our knowledge, this is the first study to explore how brands and competitive intensity affect the price-perceived quality relationship for refurbished products. Methodologically, we consider different approaches, i.e., price categorization and discrete choice experiment (DCE), in analyzing how consumers use prices as quality reference. Price categorization is used to indicate acceptable and unacceptable prices, whereas DCE is based on random utility theory where respondents see a set of alternatives and choose their favorite. In this chapter, we mainly address the following research questions:

1. What is the impact of brand and competitive intensity on the price-perceived quality relationships?
2. What is the impact of brand value on the cannibalization structure of the duopoly competition?

Through the two research questions, Chapter 2 studies how brands and competitive intensity influences the price-perceived quality relationship for refurbished products. In Study 1 and 2, we conduct independent observations in which two different brands do not affect each other, whereas in Study 3 there is competition between the two brands. We also provide quantitative evidence on factors affecting consumers' acceptable price and individuals' choice among refurbished products. The results of the DCE indicate that firms with lower brand value experience the inverted U-shaped purchasing function, because consumers become suspicious of the quality as the discount increases. Firms with a high-end brand image or high-quality products experience linear cannibalization, because the consumers trust the refurbished version of the product. However, for the product and brands

[1] According to PMR (2017), Apple, Inc., Lenovo Group Limited (Motorola), and Samsung Electronics Co. Ltd. are key market players identified as refurbished and used mobile phone providers.

used in this study, we show that the inverted U-shaped cannibalization behavior demonstrated in previous studies is largely absent in a duopolistic setting. Our experimental results further show that cross cannibalization is an effect to be reckoned with, especially for low-end brands facing competition from high-end brands offering refurbished products. On the other hand, a high-brand firm should more concern on the internal cannibalization, while low-brand firm may no need to much worry about it. The duopoly analysis in this study serves as the first step in understanding the more general oligopoly case. The duopoly model is reasonable in a country like the United States, where Apple and Samsung market shares fared better than the overall market supported by a higher percentage of online sales (Counterpoint, 2020a). According to Counterpoint (2020b), Apple and Samsung continued to dominate the secondary market in 2019. A similar situation exists in several other Asian and South America countries as well. For example, the mobile vendor market share in Brazil was dominated by Samsung and Motorola in 2019 (Statcounter, 2019). We believe, intuitively, the purchasing behavior observed in the duopoly case will also be found in the oligopoly case since there will be an interaction between brands with different brand strength.

1.2.2 Revenue Management in Refurbishing Duopoly with Cannibalization (Chapter 3)

In Chapter 3, enlightened by the behavioral Study 3 conducted in Chapter 2, we develop and analyze a formal model to shed light onto how firms would need to make their strategic choices in a duopoly where firms have different brand strength, and under (often publicly set) collection constraints. Atasu et al. (2010a) point out that refurbished products produced by the firm with high brand name may compete against the firms producing low-priced products. Our work differs from other models in the literature in the sense that we consider symmetric firms with different brand recognition (high- and low-brand). Both of our firms offer a new product and its refurbished version, with similar features. This situation exists in practice - Apple, Samsung, Motorola among many smartphone manufacturers sell both new and refurbished versions of their premium smartphones. These firms have different brand recognition in the market. As we only consider duopoly markets in our behavioral studies and to make the analysis tractable and to derive clear insights, we present all theoretical results for the two-firm case and abstain in this dissertation from studying the multiple firm case (i.e., oligopoly). Our work contributes to the understanding of optimal refurbishment strategies in terms of the novelty of the model, which based on the experimental results in Chapter 2. We introduce two types of cannibalization: Internal cannibalization of a new product that is caused due to the refurbished product made available by the same firm as a function of discount; and external (or cross) cannibalization that is caused by the presence of a competitors' refurbished product. In addition, according to Mitra (2016), the used product of one firm cannot be considered as a source of supply for the other firm's refurbishing process. This is true for firms that have different manufacturing/refurbishing processes, and hence can refurbish only their own brands. A manufacturer will sell its own refurbished products only in the secondary market, and thus there is no point in refurbishing a competitor's brand. Hence, there is no substitutability of used products for refurbishing from the point of view of manufacturers. Chapter 3 of this dissertation addresses the following research questions:

1. What are the pricing strategy in equilibrium when two competing manufacturers with different brand recognition (high- and low-end brands) selling both the new and refurbished products.
2. In competition with a high-brand valued firm, does the low-brand valued firm have an incentive to continue refurbishing?

The first question is the core subject to be explored in Chapter 3. We do analysis to obtain closed-form solutions for prices in Nash equilibrium and characterize the optimal solution region. To investigate the second research question, we do analytical and numerical analysis to explore the impact of model parameters such as internal and cross cannibalization coefficients, price competition, and used products quantity, on the firms' pricing strategy and equilibrium profits. We observe that in the competitive environment, a high-brand firm has bigger business opportunities in refurbishing since the presence of their refurbished products could attract consumers from lower brand competitors who are looking for a low price product, but one that has a better brand image. Hence, the high-brand valued firms can have huge potential gains in the market for their refurbished products. However, the firm should more concern on the internal cannibalization. This leads the high-brand firm to charge their refurbished products at high price in order to keep the high-end customers from being cannibalized and to increase the profit margin from the second-hand market. The firm with a higher-brand value will get more benefit by increasing its collection efforts due to its high potential market. On the other hand, a low-brand valued firm has low internal cannibalization. Hence, such a firm does not need to worry about cannibalization of new product sales. Hence, refurbishing could be a good strategy for the low-brand firm to increase the firm's profit and decrease the loss profit from new product sales due to cross cannibalization by its competitor's refurbished products. Generally, the low-brand firm should sell the refurbished products at a price lower than its competitor in order to compete with the high-brand firm. We find that refurbishing would be more profitable for low-brand firm and should invest more in collection efforts when the high-brand competitor only sells few refurbished products or even does not engage in refurbishing. If the high-brand firm sell a few refurbished products, it would decrease the low-brand competitor's profit.

1.2.3 Authorization Strategy in Refurbishing with Consumer Behavior (Chapter 4)

In Chapter 4, we consider a supply chain consisting of two members, a manufacturer (OEM) that produces and sells new products and a refurbishing third party (3P) that produces and sells refurbished products. We develop and analyze a formal model to examine the conditions under which both the OEM and the 3P may benefit via an authorization strategy. We study the trade-off between the indirect benefit from authorizing a 3P and the effect of cannibalization on new product sales. In our model, we only consider the scenario under which the OEM does not directly participate in the secondary market and instead enters the market by authorizing a 3P. In such a business model, the OEM does not only focus on the new products, but also can fulfill its environmental responsibility while obtaining shared profit from the secondary market. On the other hand, the 3P does not produce their own product, but instead collects and refurbishes used products produced by the OEM. In the refurbishing authorization program, the OEM sets an authorization fee. The OEM can set the fee as high as needed, which is costless. The 3P chooses whether to take the authorization or not. Based on the experimental results in Chapter 2, we assume the consumers switching from new to refurbished products follow an inverted U-shaped function, i.e., they get suspicious when the refurbished product prices are too low. This cannibalization function can also be viewed as a linear function when the price-perceived quality threshold is sufficiently low. To the best our knowledge, we made the first attempt in the literature to incorporate the consumers purchasing behavior and the remanufacturable product supply in authorization refurbishing strategy. The research questions we address are as follows:

1. What are the optimal decisions of a 3P when the firm engages in refurbishing authorization?
2. Is it beneficial for an OEM to offer refurbishing authorization to a 3P? And is it beneficial for the 3P to accept the authorization scenario? Under what conditions can the two firms reach a win-win solution?

To study the first research question, we investigate the optimal pricing decision of the 3P by considering consumer behavior, authorization fee, and remanufacturable product supply which may impact it. The second research question is the core subject to be explored in Chapter 4. By comparing the profit of each firm before and after the 3P being authorized, we derive conditions such that both the OEM and the 3P can benefits from the refurbishing authorization. Our results show that the optimal decisions of the 3P is driven by the price-perceived quality threshold, i.e., the price of refurbished products such that the fraction of customers switching reaches a maximum value. The optimal solution for the 3P could be in a price-sensitive area, at the price-perceived quality threshold itself, or in a quality-sensitive area. In the price-perceived quality threshold and quality-sensitive area, customers become suspicious of the refurbished product quality, thus the fraction of customers switching decreases with the decreases of price. We show that the acceptable authorization fee for the 3P and the OEM is influenced by the pricing area of the third-party before and after being authorized. Hence, by knowing the pricing area of the optimal refurbished product price, it leads the two firms to reach a win-win solution. The 3P accept the authorization fee when it is relatively low, while the OEM obtain a higher profit in refurbishing authorization if the fee is relatively high. However, the OEM does not always benefit from higher authorization fee, because the 3P increases the price as the authorization fee increases, and consequently decreases the refurbished products quantity. Therefore, to reach an authorization agreement, the OEM does not need to offer its optimal fee because it might too high for the 3P to accept. Moreover, the maximum acceptable authorization fee for the 3P and the minimum acceptable fee for the OEM when the product supply is limited are always lower than when the 3P can satisfy all demand. Thus, the 3P prefers to accept authorization fees when remanufacturable supplies are relatively large or can access more used products after being authorized. On the other hand, due to cannibalization, if the low-end demand is relatively low, the OEM prefers to offer the refurbishing authorization to the 3P that has fewer refurbished products for sale. The possibility to reach a win-win solution for both the OEM and the 3P will increase as the increase of the low-end demand market base.

1.2.4 Strategic Decision Making for Refurbishing Across New Product Generations (Chapter 5)

In Chapter 5, we develop a two-period decision problem and analyze the interaction between refurbishing and product innovation. Many manufacturers intend to reduce the potential cannibalization by differentiating the quality level of new product from refurbished ones by upgrading. Manufacturers usually invest to release new generations (upgraded products) at an intensive rate to cater for consumer demands. For example, Apple annually releases new iPhone models. Our work differs from other models in the literature in the sense that we more focus on the impact of new product generation life cycle on refurbishing strategy, whether manufacturer should launch the refurbished products before (period 1) or after (period 2) the introduction of the new generation. Hence, the refurbished products could be available with new products belonging to an earlier generation and/or recently released new products with the latest technology. In addition, we incorporate the critical components such as the issues of demand cannibalization, secondary market or low-end demand, recovery fraction, and the drop of new product price, into our model. Intuitively, if a newer generation is introduced to the market, the previous generation becomes unattractive. The propensity of consumers to purchase the refurbished products will be smaller since the new technology development is not included. The refurbished product does not contain the latest innovation, and in turn, makes the product less attractive to customers compared to the new generation. On the other hand, higher price of the new generation may reduce this effect. Therefore, it could capture more new ("low-end") customers who do not want to purchase new products. However, the manufacturer may also need to consider the pricing decision of the refurbished products. The older generation usually falls sharply in price after the launch of newer generation and will impact the refurbished product price. This is because there is a significant difference in pricing between the new product and its refurbished version because of consumers' perception. In Chapter 5, we address the following research questions.

1. When should the manufacturer launch the refurbished products into a market? What is the impact of new product generation life cycle on the refurbishing strategy?
2. What is the impact of demand cannibalization, low-end demand market, and recovery fractions on the optimal decisions?

To address the first research question, backward induction is used to solve a dynamic program. To investigate the second research question, we do some numerical analysis to explore the impact of those components on the distribution of remanufacturable product supply over two periods. We show that the distribution of refurbished products should be produced and sold in each period is driven by the price-drop coefficient and the recovery fractions. When the total remanufacturable product supply in two periods is relatively high or the price-drop coefficient is relatively low, the decision makings in periods 1 and 2 are completely independent. Otherwise, the decision making in period 2 is dependent on that in period 1. In period 1, the manufacturer has three options: full refurbishing, partial refurbishing, and no refurbishing. Having lower cannibalization level in period 2 is not enough for the firm to introduce the refurbished products in that period. The firm also needs to take into account the new price of the new version and the potential of low-end demand. Higher price-drop coefficient and low-end demand lead the firm to sell more refurbished products or even introduce them in period 2. This is because if the product price cannot be charged at a high price, it decreases the profit margin and increases the cannibalization level on new product sales. In addition, if the recovery fractions are relatively high, it would be not profitable to sell all available refurbished products in just one period (period 2). The firm should distribute them in both periods 1 and 2 by determining the optimal production in each period.

In practice, many firms adopt a discount strategy by setting their refurbished product prices (Ovchinnikov, 2011; Abbey et al., 2015b). Hence, in Chapter 2 we consider the purchasing behavior of refurbished products as a function of discount levels relative to the new product price, in order to examine the nonlinearity and the negative effects at lower prices due to the potential effects of the price–perceived quality relationship. Moreover, in line with our empirical work in Chapter 2, our analytical models in Chapter 3, 4, and 5 consider the situation in which, when the firm decides to introduce the refurbished product, it would not influence the new products' prices. There is some evidence that some firms may not view refurbishing as a strategic initiative and not change the prices of the new products. For example, the mini-case study reported by Ovchinnikov (2011) states that refurbishing operations had no effect on the procurement, pricing, or other decisions about the new products. Hartl et al. (2019) also states that in practice, the new product's price of a given generation is fixed until the next generation is introduced. In this case (employed e.g. by Apple), the consumers do not have an incentive to wait with purchasing the new product until the price has dropped sufficiently.

1.3. Outline of the Thesis

The thesis is organised as follows. In Chapter 2 we conduct a behavioral study to examine the price-perceived quality relationships for refurbished products in various types of markets. In Chapter 3 we consider two competing firms, with different brand recognition, producing and selling both new and refurbished products in a single period. Chapter 4 examines the conditions under which both the manufacturer and the third party benefit via an authorization strategy. We study the trade-off between the indirect benefit from authorizing a third party and the effect of cannibalization on new product sales. Chapter 5 develops a two-period model to analyze the impact of new product generation life cycle on refurbishing decision. The chapters have been set up such that they can be read independently. Finally, Chapter 6 concludes with a summary and discussion.

2

Price-Perceived Quality Relationship for Refurbished Products

2.1. Introduction

In the last decade, researchers have given more attention to concepts such as the circular economy, the closed-loop supply chain, reverse logistics, and remanufacturing (refurbishing). Several papers comprehensively review various aspects of these areas (Atasu et al., 2008a; Guide Jr and Van Wassenhove, 2009; Souza, 2013; Agrawal et al., 2015a; Kumar and Ramachandran, 2016; Govindan et al., 2019). Much research focuses on product acquisition and operational issues pertaining to closed-loop supply chains and considers consumer behavior a given. However, consumer behavior regarding refurbished products is important, because profitability in a whole closed-loop supply chain can be achieved only with sufficient consumer acceptance of the products. Prior reviews do not extensively investigate marketing and accounting issues, such as cannibalization and returned product valuation (Guide Jr and Van Wassenhove, 2009), leading Souza (2013) to call for more work to understand the relationship between the refurbished product market and consumer behavior. Póvoa et al. (2016) note some research challenges for closed-loop supply chains from a demand point of view, including the need for more research into market and consumer aspects. Atasu (2016) points out that understanding the marketing of products has been an elusive challenge for firms that engage in closed-loop supply chain strategies. This challenge is exacerbated by the role of the brand value of the firms, which informs optimal pricing and brand investments for refurbished products (Govindan et al., 2019).

One of the fundamental principles of economic theory, known as the law of demand, states that the demand for a product should increase if its price decreases. In theory, firms should lower the refurbished product price to increase sales. In current closed-loop supply chain literature, a linear function of price is the basic demand function, commonly used as an underlying assumption of analytical models. The assumption has been used in some models of refurbishing such as Majumder and Groenevelt (2001), Bakal and Akcali (2006), and Wu (2012). In these studies, a lower price for a product leads to greater product demand, which may seem intuitively obvious. However, this behavior may not be consistent in the secondhand market for refurbished products. Consumers who want to buy refurbished products may base their decisions on price as a quality perception factor and judge a refurbished product as inferior in quality if its price is very low, which would prevent their purchase.

The relationship between price and perceived quality is well known in marketing literature. For example, Rao and Monroe (1989) and Völckner and Hofmann (2007) conduct meta-analyses of study results on the relationship between price and perceived quality, each including hundreds of studies of the topic. Rao and Monroe (1989) conclude that for consumer products, the relationship between price and perceived quality is positive and statistically significant. Monroe (2002) suggests that buyers use price not only as a measure of sacrifice but also as an indicator of product quality. But Völckner and Hofmann (2007) caution that managers should be aware that price–quality inferences remain important aspects of consumers' behavior and consider this factor when setting prices. If consumers seek value from a product, they usually relate its price to the perceived quality of the product. Consumers might use the price as an indicator of quality when it cannot be interpreted from other cues, as well as make negative price–quality inferences and begin to doubt the quality of a product with a low price. The nature of the price–perceived quality relationship is relevant to every firm making a consumer purchasing decision, as well as to firms in competitive environments, seeking to gain a competitive advantage.

In practice, consumer behavior toward refurbished products varies and depends on how they value a particular brand and their perception of the product quality. Consumer behavior influences demand for refurbished products; thus, the pricing decision of the products should be based on the demand. In turn, it is important to study consumer behavior when considering pricing for refurbished products. The principal elements in pricing decisions are consumers' willingness to pay (WTP) and consumer preferences (McKie et al., 2018; Zhou and Gupta, 2018). An empirical study is a valuable way to analyze this purchasing behavior. We illustrate the factors empirically proven to influence these principal elements in Table 2.1. According to several empirical studies, factors such as brand equity, price discount, seller identity, product condition, and eco-friendly certification influence consumers' WTPs and purchase decisions for refurbished products. For example, among auctions on eBay, Guide and Li (2010) find a clear difference in the WTP for new and refurbished products. By comparing the prices of refurbished and new products on eBay, Subramanian and Subramanyam (2012) show that discounts for refurbished products depend on the product category. Although few empirical (behavioral) studies investigate the price–perceived quality relationship for refurbished products and the implications for purchasing behavior, Ovchinnikov (2011) observes this relationship in a behavioral study that estimates the fraction of consumers who switch from new to refurbished products for a specific brand or product (i.e., Dell laptop computers in a monopoly setting). Using conjoint analysis for discounts above 60%, the utility function for a subset of respondents (quality-conscious high-end consumers) decreases. This analysis illustrates that a refurbished product price that decreases below a certain level decreases the likelihood of purchase, because consumers choose to purchase a new product instead. Furthermore, using the methodology suggested by Monroe (1990), Ovchinnikov (2011) finds that customer behavior is an inverted U-shaped function of price; that is, after a maximum discount rate (around 20%), the number of customers who switch decreases. Demand may decrease with the price decrease, because customers become suspicious of the product quality when the price is too low, and only a few switch. Yet when Abbey et al. (2015b) empirically investigate consumer perceptions of refurbished products, they conclude that discounting had a consistently positive, linear effect on refurbished product attractiveness. They reveal that for low brand-valued technology goods, overdiscounting exacerbates negative perceptions of refurbished products, but only when the discount is above around 80%. Abbey et al. (2015b) use an attractiveness rating as their experiment measure, which differs from a conjoint analysis or discrete choice experiment (DCE), which elicit information on values by asking respondents to choose among alternatives. For the attractiveness rating, respondents rank the attractiveness of a single product without choosing among alternatives. Therefore, different measures, product types (categories), brand equity, and competitive intensity seem to capture different results.

Table 2.1: Empirical studies on pricing refurbished products

Observed factor	Type of market	Principal key	References
Product category, product type	Monopolistic market/brand	WTP	Guide and Li (2010), Hamzaoui Essoussi and Linton (2010), Hamzaoui-Essoussi and Linton (2014), Harms and Linton (2016)
		Preference	Linton (2008), Abbey et al. (2015b), Zhou and Gupta (2020)
Seller identity, seller reputation	Monopolistic market/brand	WTP	Michaud and Llerena (2011), Subramanian and Subramanyam (2012), Agrawal et al. (2015b), Pang et al. (2015)
		Preference	van Weelden et al. (2016), McKie et al. (2018), Vafadarnikjoo et al. (2018), Esenduran et al. (2019)
	Competitive market (firm 1 vs firm 2)	Preference	Raz et al. (2017)
Product condition	Monopolistic market/brand	WTP	Neto et al. (2016)
		Preference	McKie et al. (2018)
	Competitive market (high-end vs low-end)	Preference	Ovchinnikov et al. (2014), Raz et al. (2017)
Brand equity	Monopolistic market/brand	WTP	Hamzaoui-Essoussi and Linton (2014), Agrawal et al. (2015b)
		Preference	Jiménez-Parra et al. (2014), Abbey et al. (2015b), de Vicente Bittar (2018), Abbey et al. (2019)
Product generation	Monopolistic market/brand	Preference	McKie et al. (2018), Zhou and Gupta (2019), Zhou and Gupta (2020)
Price discount	Monopolistic market/brand	Preference	Ovchinnikov (2011), Abbey et al. (2015a), Abbey et al. (2015b)
Perceived quality, perceived risk	Monopolistic brand	WTP	Hazen et al. (2012), Abbey et al. (2017), Abbey et al. (2019)
		Preference	Ovchinnikov (2011), Abbey et al. (2015b), Wang and Hazen (2016), Hazen et al. (2017a)
Government incentive	Monopolistic market/brand	Preference	Hazen et al. (2017b)
Social impact	Monopolistic market	WTP	Shao and Ünal (2019)
Eco-friendly certification, Environmental issue & attitude	Monopolistic market/brand	WTP	Michaud and Llerena (2011), Harms and Linton (2016), Shao and Ünal (2019)
		Preference	Jiménez-Parra et al. (2014), Abbey et al. (2015b), Wang and Hazen (2016), Hazen et al. (2017b), de Vicente Bittar (2018), Wang et al. (2018b)
Online market-place, e-services	Monopolistic market/brand	WTP	Xu et al. (2017)
		Preference	Esenduran et al. (2019)

We also might examine the market type from the perspective of the market structure, that is, monopolistic or competitive. Table 2.1 shows that most studies investigate consumer behavior toward refurbished products in a monopolistic setting, with the assumption that new and refurbished products are sold in the same or separate markets without any competition from other similar products or brands. For example, Ovchinnikov (2011) investigates the choice between new and refurbished laptops without considering seller identity attributes. Abbey et al. (2015b) and Abbey et al. (2019) consider two different brands with high- and low-equity in their online survey and laboratory experiment. However, they conducted independent observations in which the two brands did not affect each other. For competitive markets, Ovchinnikov et al. (2014) and Raz et al. (2017) empirically derive demand functions for a new smartphone as a high-end mobile communication device, a refurbished smartphone, and a new phone that has fewer features than a smartphone. All products increased in attractiveness as the price decreased.

Thus, recent literature does not provide a clear understanding of how brands influence the price–perceived quality relationship for refurbished products. In this chapter, we report on a behavioral study we conducted to examine the relationships among various types of markets, which we explain in more detail in Section 2.2. We also consider different approaches to investigating how consumers use price as a quality reference, and we provide quantitative evidence of which factors affect consumers' views on acceptable prices and individual choices among refurbished products.

2.2. Experimental Study

The objective of this study is to investigate the price–perceived quality relationship for refurbished products in three different scenarios, as presented in Table 2.2. In particular, we examine the nonlinearity of demand as a function of discount levels and the negative effects at higher discount levels due to the potential effects of price-quality relationship. In Study 1, respondents consider purchasing a single refurbished product offered to them. The study only considers a secondary market for consumers who want to purchase a refurbished product. Thus, there is no substitute between a new and refurbished product, and the refurbished product would not cannibalize the new product sales. Study 1 considers the price elasticity of demand, that is, how the volume sold of a refurbished product changes relative to a price change for that product. We use the price categorization and DCE to estimate the price-level sensitivity of the refurbished products and consumer purchasing behavior. In Study 2, we observe consumer behavior for the choice between refurbished and new products. The focus of this study is the cannibalization of new product sales. We also estimate the cross-discount elasticity of demand, that is, how the volume sold of new and refurbished products changes relative to a price change for the refurbished product. We conduct the first two studies with a specific product (i.e., a smartphone) for both a refurbished Apple phone and a comparably priced Motorola phone. We employ Apple as a high-end brand, to be consistent with previous studies (e.g., Abbey et al., 2017; Agrawal et al., 2015b; Abbey et al., 2019), and include Motorola as a low-end brand. Study 3 extends the second study by considering different, competing brands to estimate internal cannibalization, defined as customers who switch from a new to a refurbished product with the same brand, and cross cannibalization, or when customers switch from a new product from one brand to a refurbished product by the brand's competitor. In Study 3, we investigate duopoly competitions among the following brands: Apple versus Motorola, Samsung versus Motorola, and Apple versus Samsung. We use the DCE for the last two studies.

Table 2.2: Brief description of behavioral study

Goal(s)	Method	Respondents
Study 1: To assess consumer behavior toward refurbished products in a secondary market. We aim to estimate the price-level sensitivity for refurbished products from different brands (e.g., Apple, Motorola), the product conditions, seller identities, eco-friendly certification, product types, and online marketplaces.	Pricing categorization, Discrete choice experiment (DCE)	U.S.-based respondents from Amazon Mechanical Turk (MTurk)
Study 2: To assess consumer behavior when choosing between refurbished and new products. We aim to a. Estimate the switching behavior for refurbished products from high-end brands (e.g., Apple) and low-end brands (e.g., Motorola). b. Estimate the cross-discount elasticities among product conditions.	DCE	U.S.-based respondents from MTurk
Study 3: To assess consumer behavior in a competitive market. We aim to a. Estimate the switching behavior (internal and cross cannibalization) for refurbished products in a competitive environment for Apple versus Motorola, Samsung versus Motorola, and Apple versus Samsung. b. Estimate the cross-discount elasticities between product conditions and brands.	DCE	U.S.-based respondents from MTurk

2.2.1 Price Categorization

One of the methods used to measure the price–perceived quality relationship in Study 1 is price categorization. According to Monroe (2002), price categorization can determine the acceptable prices and price thresholds (price-level sensitivity) for products by respondents. The price categorization approach is used instead of only asking for the maximum amount the consumer is willing to pay for a product. In general, most respondents are willing to go a little bit lower or higher before the WTP completely stops. Therefore, it is useful to ask respondents to indicate acceptable and unacceptable prices. This method requires respondents to sort a set of prices for products into groups according to how the prices are similar or dissimilar from each other (based on the respondent's preferences). The respondents categorize already given prices into five groups (see Figure 2.1): not acceptable, because the price is clearly too low; acceptable, but the price is still low; the most acceptable price; an acceptable price but still high; and not acceptable, because the price is clearly too high. To prompt their views, respondents could be asked the following three questions for a specific refurbished product:

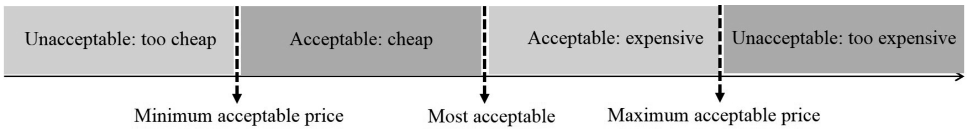


Figure 2.1: Price categorization

1. What is the maximum price you would be willing to pay for the product? (That is, beyond what price would you believe it is not worth paying more?)
2. What is the most acceptable price to pay?
3. What is the minimum price you would be willing to pay for the product? (That is, below what price would you seriously doubt its quality?)

The advantage of the price categorization method is that it does not implicitly assume there is only one definable set of acceptable prices in the market. Other methods, such as the direct question and price sensitivity meter approach (see Monroe (2002)), attempt to force the data onto one buyer response curve or distribution. In the price categorization approach, we can use a wide range of prices to determine the acceptable price ranges for respondents who accept relatively higher prices, respondents who accept medium-level prices, and those who are interested in relatively lower prices. In addition, asking respondents to indicate the most acceptable prices provides a means to determine whether one price clearly emerges as the best price for a refurbished product.

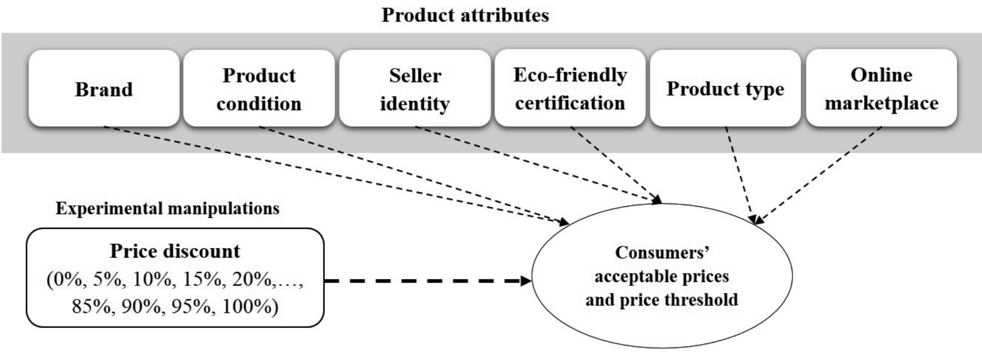


Figure 2.2: Theoretical model for pricing survey

Figure 2.2 illustrates the theoretical model used in Study 1 for the pricing survey using price categorization. We investigate the effects of product attributes such as brand (high- and low-end brands), product condition (open box, refurbished), seller identity (original equipment manufacturer, hereafter, OEM; authorized third party, hereafter, A3P; unauthorized third party, hereafter, U3P), eco-friendly certification (yes, not mentioned), product type (smartphone, MacBook, iPad, AirPods), and the online marketplace (Amazon.com, eBay) on the acceptable prices and price thresholds for discounts. According to Monroe (2002), based on the research evidence for buyers' price awareness, buyers do not use price as the sole measure of sacrifice (cost); they also use it as an indicator of product quality. However, buyers are likely to use brand and other product attributes as indicators of quality. In practice, many firms adopt a discount strategy by setting their refurbished product prices (Ovchinnikov, 2011; Abbey et al., 2015b). Because purchasing behavior is a function of discount levels (prices), there could be nonlinearity and negative effects at lower prices due to the potential effects of the price–perceived quality relationship. Thus, a wide range of prices or discount levels should be used in price categorization. For each product, we have listed 20 discount levels (i.e., 0%, 5%, 10%, ..., 90%, 95%, and 100%). In line with Thaler (1985), Ovchinnikov (2011) and Abbey et al. (2015b), we present discounts relative to the new product price. The respondents can choose a discount level of 0% if the low discount levels and high prices would not prohibit them from purchasing the product. The respondents can also choose a 100% discount level if they accept all prices, because they do not doubt the product quality.

2.2.2 Discrete Choice Experiment

We apply the DCE in all three studies. In this common consumer behavior elicitation technique in marketing literature, respondents see a set of alternatives and choose their favorite. According to Louviere et al. (2010), the DCE is based on random utility theory, which assumes that respondents seek to maximize their utility. It is more consistent with economic demand theory and provides a realistic view of people's decision making. The DCE has been adopted by many practitioners to develop empirical studies in marketing and other applied economic fields for which choices play important roles, due to its high interpretability, which enables practitioners to verify their compliance with well-established behavioral theories (McFadden, 1974). In general, the design of a DCE proceeds with the selection of attributes and levels, construction of the experimental design, and survey design (Botelho et al., 2018). In the DCE, we present respondents with several choice tasks that vary in their attribute levels. For each task, respondents review a set of options and choose their favorite. Table 2.3, 2.4, and 2.5 illustrate examples of tasks for each study in which the respondents had to make a choice. We selected the subset of choice tasks presented to the respondents based on efficient design using Ngene software version 1.2 (Choicemetrics, 2018). For each study, we designed 20 choice tasks.

In the first study, we investigate consumer behavior with regard to the choice between buying or not buying a refurbished product. We manipulated the seller identity (OEM, A3P, U3P), the product condition (used, refurbished, open box), the online marketplace (Amazon.com, eBay, official brand website), the eco-friendly certication (yes, not mentioned), and the discount from the full price of the new phone (at levels of 10%, 20%, ..., 90%, 95%). According to Ovchinnikov et al. (2014) and Abbey et al. (2015a), in practice, discounts for refurbished products typically range from 10 to 95% below the price of the new version. The discount range is also in line with Ovchinnikov (2011) and Abbey et al. (2015b). Each respondent faced 20 choice tasks, and each of these tasks was a choice between two refurbished options or not buying either option. In the second study, we investigate consumer behavior with regard to the choice between the new and refurbished products.

Table 2.3: Example of a choice task for Study 1

Attributes	Option A	Option B	Option C
Brand	Apple	Apple	
Product condition			Not buying
Seller identity	Unauthorized third party	Original manufacturer	
Eco-friendly certification	Not mentioned	Not mentioned	
Online marketplace	eBay	Apple website	
Price (discount)	\$100 (80% discount)	\$350 (30% discount)	
Your choice	□	□	□

Table 2.4: Example of a choice task for Study 2

Attributes	Option A	Option B	Option C
Brand	Apple	Apple	Apple
Product condition			
Seller identity	Unauthorized third party	Authorized third party	Original manufacturer (Apple Inc.)
Price (discount)	\$360 (40% discount)	\$60 (90% discount)	\$600
Your choice	□	□	□

We manipulated the seller identity (OEM, A3P, U3P), the product condition (used, refurbished, open box), and the discount from the full price of the new phone (at levels of 10%, 20%, ..., 90%, 95%). Each respondent faced 20 choice tasks. Each of these tasks was a choice between two refurbished options or a new product with no discount. In Study 3, we investigate consumer behavior with regard to the choice between the new and refurbished products of the two brands. The price of the new phones are fixed across the experiment, with the Apple and Samsung phones priced at $600 and the Motorola phone priced at $480. In the experiment, we manipulated the brand (Apple, Samsung, and Motorola), the product condition (either ”used” or ”refurbished”), and the discount from the full price of the new phone (at levels of 10%, 20%, ..., 90%, 95%). The respondents see both the discount (as a percentage) and the effective price. Each respondent faced 20 choice tasks. Each of these tasks was a choice between two new options with no discount and two refurbished options. These alternatives included two different brands. We concentrated on a specific product (smartphone) with three different brands that the respondents were familiar with: Apple, Samsung, and Motorola. We studied duopoly competitions among the brands, that is, Apple versus Motorola, Samsung versus Motorola, and Apple versus Samsung.

Table 2.5: Example of a choice task for Study 3

Attributes	Option A	Option B	Option C	Option D
Brand	Apple	Motorola	Apple	Motorola
Product condition				
Price (discount)	$540 (10% discount)	$384 (20% discount)	$600	$480
Your choice	☐	☐	☐	☐

Using Biogeme (Bierlaire, 2016, 2020), we fit the choice data to a multinomial logit model (MNL) and latent class (LC) model. Biogeme is open-source software designed to estimate various discrete choice models using maximum likelihood estimation. The MNL model is most widely used for discrete choice modeling. The underlying assumption in this model is that consumers are homogeneous in their preferences. We estimate the utility functions from the observed choices using the maximum likelihood estimation procedure, such that the probability of getting the observed choices is maximized. Let U_{ijk} is the estimated utility of alternative i to respondent j in question k. The MNL model defines the utility as

$$U_{ijk} = V_{ijk} + \epsilon_{ijk} = \beta.X_{ijk} + \epsilon_{ijk},$$

for $i = 1, ..., I$, $j = 1, ..., J$, and $k = 1, ..., K$, where V_{ijk} is a systematic observed component, ϵ_{ijk} is an unobserved random component, X_{ijk} is a vector of observed attributes of alternative i, and β is a vector of the utility weight in the population, defined as the value consumers associate with each attribute in X_{ijk}. The probability that consumer j chooses alternative i in question k is logit and given by

$$P(i|X_{jk}) = \frac{exp(\beta.X_{ijk})}{\sum_{i'=1}^{I} exp(\beta.X_{i'jk})},$$

where X_{jk} is the vector of attributes of all alternatives $i = 1, ..., I$. In the MNL model, the error terms for the alternatives are independent and identically distributed as Gumbel variables, which implies that the unobserved utility components are uncorrelated and that all alternatives have the same variance. That is, the alternatives do not share any unobserved characteristics, and the error terms help determine the utility to the same extent for all alternatives. Thus, cross elasticity among all pairs of alternatives is identical. According to Adamowicz et al. (1998), the probability ratios of choosing one alternative over another is not affected by the presence of additional alternatives in the choice set. Thus, the alternatives can be eliminated and introduced without reestimation (Train, 2009). In some cases, the utility function could be nonlinear, which can be represented by an inverted U-shaped parabola. For a certain price range, the utility function has a positive slope until it reaches a price threshold and changes to a negative slope. In other words, when the price is relatively low, the utility increases with price, which is used by respondents as a proxy for quality. The observed component is given by

$$U = \beta_p p + \beta_q p^2 + \sum \beta X,$$

where p is the attribute price, β_p is the price coefficient in the utility function, β_q is the coefficient of price^2, and X represents the product attributes except price. If $\beta_p < 0$ and $\beta_q > 0$, the indirect utility function becomes parabolic. Even if the parameter estimation is significant though, we cannot say an inverted U-shaped utility function exists. The position of price threshold should be observed carefully. The inverted U-shaped utility function does not exist when β_q is relatively small, such that the price threshold is lower than 0, or the discount threshold is higher than 100%. It also does not exist if the price threshold is relatively low, because a firm usually charges a refurbished product price higher than its refurbishing cost and takes a minimum profit margin.

Furthermore, the LC model states that the different classes exist in the consumer population, each with homogeneous preferences. However, these preferences differ among classes. To capture these preferences, we estimate each class with separate MNL models. The LC model is usually used when discrete heterogeneity is present in the population. Multiple homogeneous groups can be specified, with each group having its own choice behavior. We estimate the chance that a person belongs to a certain class. We intend to find whether any class has an inverted U-shaped utility in discount (price) and thus choose the model with two classes: a class with a linear price (discount) (class LD) and a class with a quadratic price (discount) (class QD). In class LD, the value of β_q is assumed to be 0, and higher utility is assigned to lower price (or higher discount). In contrast, we estimate parameter β_q in class QD. We group respondents with similar observed variable distributions into the same class. The two-class model has good interpretability, and by applying this model to all brands, the differences among classes become visible, and we can also observe the differences among brands.

2.2.3 Data Collection

We conducted the empirical study using the Amazon Mechanical Turk (MTurk) online panel, a crowdsourcing marketplace for simple assignments, including data collection, surveys, and text analyses. The low cost and high speed of data collection are two significant strengths of the MTurk. It has been successfully used in some empirical studies of refurbishing (Agrawal et al., 2015b; Hazen et al., 2017b; Abbey et al., 2017; Esenduran et al., 2020) and in other fields (Ülkü et al., 2012; Hutchison-Krupat and Chao, 2014; Tokar et al., 2016; Lee et al., 2018a). Paolacci et al. (2010) point out that MTurk offers a viable data collection alternative, in that results obtained from MTurk do not signicantly differ from those found in laboratory settings. Several studies confirm the lack of significant differences between traditional samples and online respondents (e.g., Horton et al., 2011; Suri and Watts, 2011; Goodman et al., 2013). For an extended discussion on the use of MTurk in behavioral studies, see Buhrmester et al. (2011), Peer et al. (2014), Landers and Behrend (2015), Follmer et al. (2017), and Lee et al. (2018b).

To validate our experimentation procedure, we conducted two pilot tests. We conducted the first test with 41 undergraduate students at the Eindhoven University of Technology to obtain feedback and ensure the procedure was clear, complete, and realistic. We conducted the second test with 200 MTurk workers. On the basis of responses to the pilot studies, we rewrote the introduction and survey questions for the experiments to clarify the experimental settings better. Our study was restricted to workers based in the United States, and respondents were required to have at least 100 approved human intelligence tasks and have a good reputation (i.e., above 95% approval rating). We applied such sample restrictions to ensure high-quality data (Peer et al., 2014; Hauser and Schwarz, 2016). Each worker was paid $1. When an MTurk participant completes a task, the requester of the task can reject or approve the submission based on the credibility and reliability of the data provided by the worker. We obtained responses from 1,014 workers after an attention check procedure on the response pattern and time. For example, we accept the respondents' responses whenever "the minimum acceptable price ≤ the most acceptable price ≤ the maximum acceptable price." We also added some validation questions to the surveys to check that the respondents clearly understood the differences among product conditions and seller identities. Appendix A lists some of these questions.

2.3. Experimental Results

In this section, we present the experimental results of all studies. We provide more detailed experimental outputs in Appendix A.

2.3.1 Study 1: Consumer Behavior toward Refurbished Products in a Secondary Market

In Study 1, we investigate the price–perceived quality relationship in a secondary market for consumers who want to purchase a refurbished product. In general, the respondents have two options: buy or do not buy a refurbished product. We adopt two approaches: price categorization and the DCE.

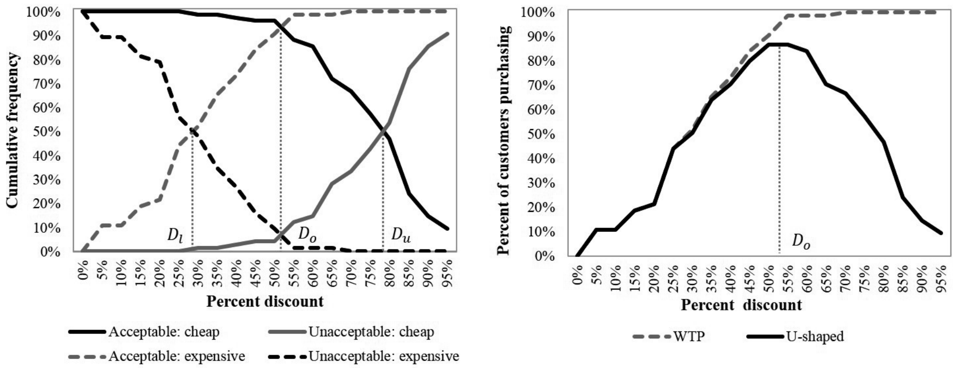
2.3.1.1 Price Categorization

Table 2.6 shows a sample data set for a refurbished iPhone sold by the OEM (Apple). For each discount, we collected the proportions of respondents who would not buy the product because it was too cheap or too expensive. We use the label C(D) for the cumulative proportion of those who find a discount unacceptable, because the price is too cheap; and we use the label E(D) for the cumulative proportion of those who find a discount to be unacceptable, because the price is too expensive. Subtracting E(D) from [1-C(D)] at each discount gives the proportion of respondents who would be willing to buy a product at each discount. To determine the lower and upper discount (price) limits for a product, usually the median percentage for each distribution (50% in the cumulative distribution) is used. In the table, the low-discount limit is 30%, and the high-discount limit is 75%. Eighty percent of respondents accepted discounts of 50% and 55%. Thus, a discount of around 52.5% would seem to have the greatest acceptance in the market.

Table 2.6: Determining discount limits

	Cheap			Expensive			
Discount %	Frequency %	Unacceptable cumulative C(D)	Acceptable cumulative [1-C(D)]	Frequency %	Unacceptable cumulative E(D)	Acceptable cumulative [1-E(D)]	Buy discount B(D)=[1-C(D)]-E(D)
.00	.00	.00	1.00	.11	1.00	.00	.00
.05	.00	.00	1.00	.00	.89	.11	.11
.10	.00	.00	1.00	.08	.89	.11	.11
.15	.00	.00	1.00	.03	.81	.19	.19
.20	.00	.00	1.00	.23	.79	.21	.21
.25	.01	.00	1.00	.08	.56	.44	.44
.30	.00	.01	.99	.13	.48	.52	.51
.35	.01	.01	.99	.08	.35	.65	.64
.40	.01	.03	.97	.11	.27	.73	.71
.45	.00	.04	.96	.07	.16	.84	.80
.50	.08	.04	.96	.08	.09	.91	.87
.55	.03	.12	.88	.00	.01	.99	.87
.60	.13	.15	.85	.00	.01	.99	.84
.65	.05	.28	.72	.01	.01	.99	.71
.70	.09	.33	.67	.00	.00	1.00	.67
.75	.11	.43	.57	.00	.00	1.00	.57
.80	.23	.53	.47	.00	.00	1.00	.47
.85	.09	.76	.24	.00	.00	1.00	.24
.90	.05	.85	.15	.00	.00	1.00	.15
.95	.09	.91	.09	.00	.00	1.00	.09

In Figure 2.3, the lower discount limit (D_l) is the point at which the "acceptable: expensive" and "unacceptable: expensive" curves intersect; 50% of the respondents are indifferent to the discount at this level because of the relative expensiveness. The upper discount limit (D_u) is the point at which the "acceptable: cheap" and "unacceptable: cheap" curves intersect; 50% of respondents are indifferent at this level because of quality concerns. The acceptable discount range is between those lower and upper discount limits, that is, [D_l, D_u]. If the discounts are set above the range, it could harm the firm's image. If the discount is below the range,



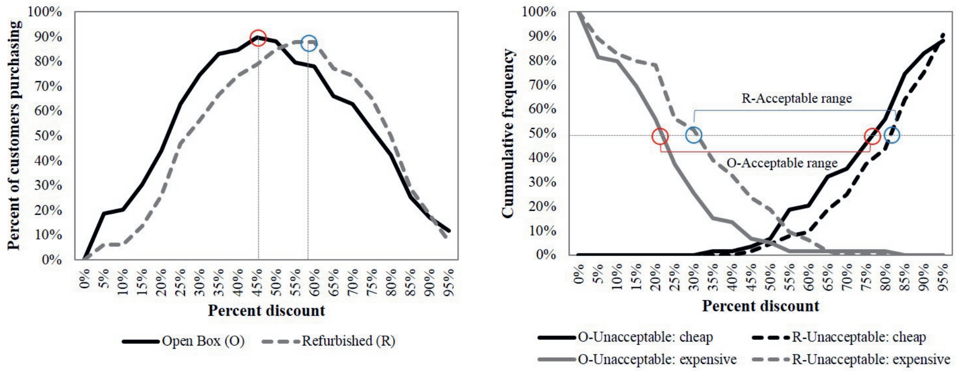
(a) Price sensitivity

(b) Purchasing function

Figure 2.3: (a) Price sensitivity: points of intersections; (b) Estimates for linear (WTP) and inverted U-shaped purchasing function

the number of respondents who consider the product too expensive exceeds the number of those who do not believe it is expensive. Moreover, the optimal discount point (D_o) is the point with the greatest market acceptance. At this discount point, the number of respondents who view the product as too expensive or too cheap is at a minimum. In addition, at this point, the two acceptable cumulative curves intersect, indicating the discount with the greatest receptivity. Thus, the number of respondents who would consider purchasing the product is at a maximum.

Figure 2.4 presents the price-level sensitivity for two product conditions: open-box and refurbished products. Customers are more sensitive to the cost of the refurbished product than the open-box product. If the price is relatively expensive, the percentage of customers purchasing the open-box product is greater than those who buy the refurbished product. In other words, the unacceptable-expensive cumulative for a refurbished product is greater than for an open-box product. As a consequence, the lower discount (price) limit for a refurbished product is greater (lower) than that of an open-box product. However, the percentage of customers purchasing refurbished products is higher than those buying open-box products when the discount is relatively high. In other words, the unacceptable-cheap cumulative for a refurbished product is lower than for an open-box product. In this case, customers are more sensitive to the quality of the open-box product than the refurbished product.



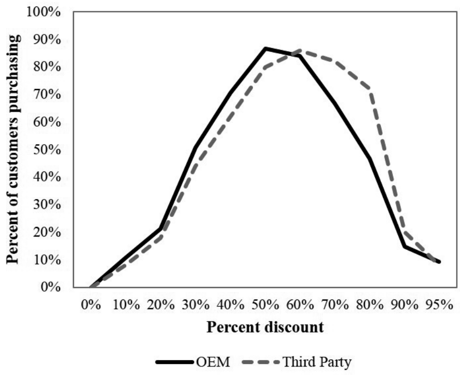
(a) Purchasing function

(b) Price sensitivity

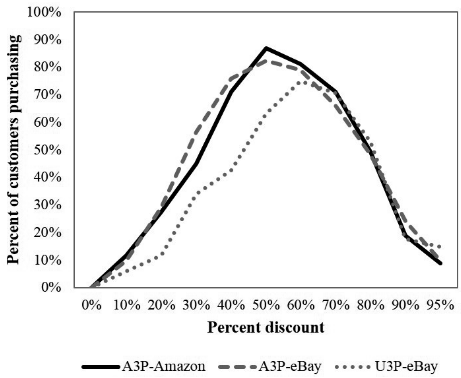
Figure 2.4: (a) U-shaped purchasing functions and (b) price sensitivity of refurbished products for different product conditions

Figure 2.5 shows similar results for different sellers (OEM, third party), authorizations and marketplaces (A3P, e.g., Amazon.com; U3P, e.g., eBay), eco-friendly certification statuses, and brands (Apple, Motorola). Online marketplaces such as Amazon.com and eBay do not have a significant impact on consumers' purchasing behavior. For a refurbishing authorization strategy, it would better for a third party to adopt the authorization scheme and sell the refurbished product only at a specific discount range. Figure 2.6 illustrates the purchasing functions for four different product types (i.e., MacBook, iPhone, iPad, and AirPods) from the same brand (Apple). The iPhone and iPad have the same new retail price ($500). Although consumers are a bit more sensitive to the expensiveness of an iPad than an iPhone, they have similar sensitivity to the quality of the two products. Moreover, MacBook and AirPods have different new product prices. A MacBook is a high-technology product and has more complicated technology than AirPods. Thus, the respondents are more quality sensitive to the MacBook when the discount price is relatively high.

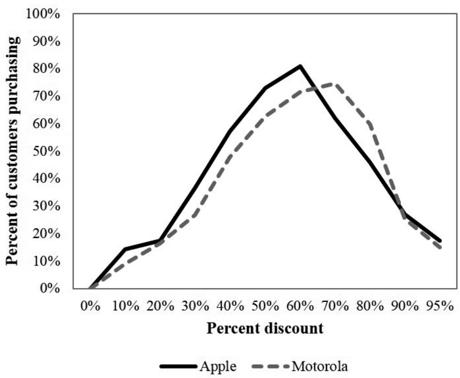
The results indicate that an inverted U-shaped purchasing function always exists when consumers are faced with a single refurbished product, and there is no substitute product available on the market. Moreover, the product condition, brand, seller identity, eco-friendly certification, and product type may influence the price-level sensitivity for refurbished products.



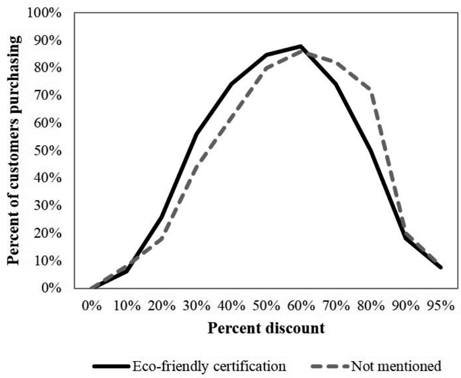
(a) Seller



(b) Authorization and Marketplace



(c) Brand

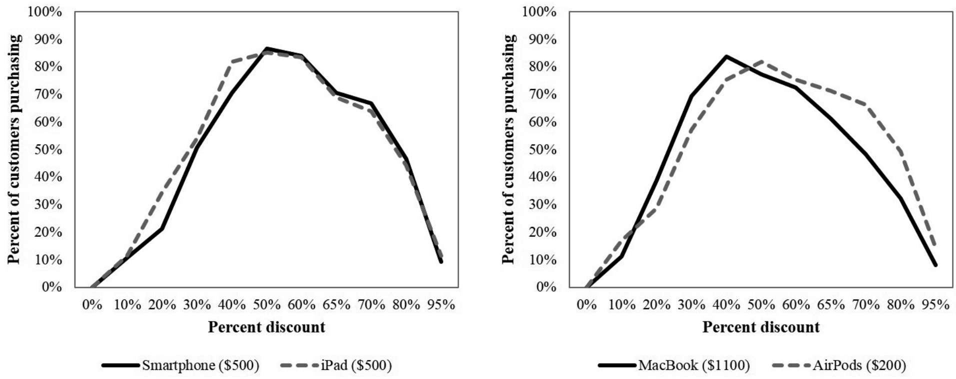


(d) Eco-friendly certification

Figure 2.5: U-shaped purchasing functions for different product attributes

2.3.1.2 Discrete Choice Experiment

Table 2.7 and Figure 2.7 present some statistics of interest for the MNL model; we present the complete DCE output in Appendix A. All attributes related to preferences for refurbished smartphones are at a statistically significant level. The utility function for the products is quadratic for the discount attribute and has a better fit than a linear function. We indicate the impact of the attributes on purchasing behavior by the range between the lowest and the highest utility of the attribute. For both high- and low-end brand refurbished products, the impact of the discount is greatest, and the utility function of the two brands increases as



(a) Same new product price   *(b)* Different new product price

Figure 2.6: Purchasing functions for different product types

the discount increases (see Figure 2.7). Respondents prefer refurbished products with lower prices sold by a seller with a good reputation. Moreover, for the Apple refurbished products, the impact of the online marketplace is greater than the product condition. We obtain the opposite result for the Motorola smartphone. For low-end brand refurbished products, the respondents first consider whether the products are in good condition before observing the seller details. Figure 2.8 shows that the choice of the marketplace (Amazon.com or eBay) for low-end brand refurbished products does not have a significant impact on sales.

Table 2.7: Relative importance of attributes for the MNL model

	Apple		Motorola	
Attributes	Utility range	Relative importance	Utility range	Relative importance
Product condition	.184	4.96%	.242	6.09%
Seller identity	1.103	29.74%	.968	24.36%
Marketplace	.316	8.52%	.098	2.46%
Eco-friendly certification	.090	2.42%	.200	5.03%
Price discount	2.016	54.36%	2.465	62.06%
Sum		100%		100%

We also present some statistics of interest for the LC model (see Table 2.8 and Figure 2.9). The complete experiment output is in Appendix A. Although the quadratic coefficient is significant for all brands, the quadratic discount can only be found for Motorola refurbished products. The utility of class QD for Motorola

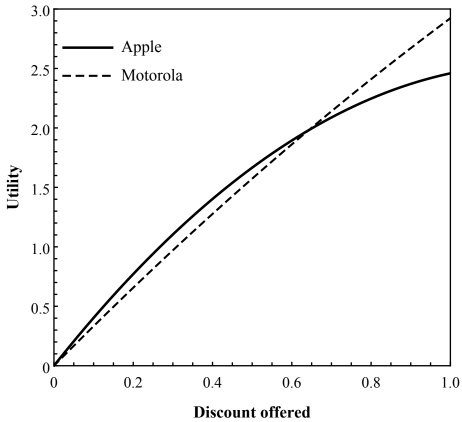
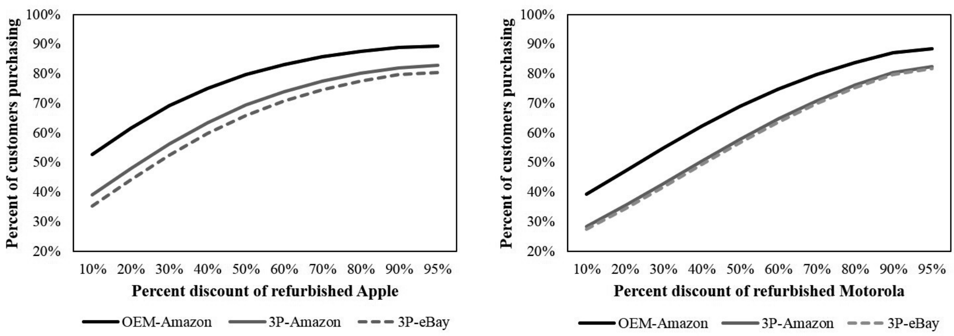


Figure 2.7: Utility functions of discount offered for refurbished products in the MNL model



(a) Apple

(b) Motorola

Figure 2.8: Percentage of customers purchasing refurbished products by price increase in the MNL model

increases for discounts up to about 20%. The larger the discount, the more willing the respondents are to purchase refurbished products. For discounts above 20%, the utility of respondents from the class QD declines. For the respondents, a discount increase for refurbished products above a certain level decreases the likelihood of purchase. For low-end brand refurbished products, there is a subset of respondents who perceive highly discounted products as low quality and prefer not to purchase them. However, the number of those respondents is relatively low, about 11.97% of all respondents. On the other hand, the utility of respondents from all classes increases with discounts for Apple refurbished products, because respondents trust a refurbished product from a high-end brand more, even when its price is too low.

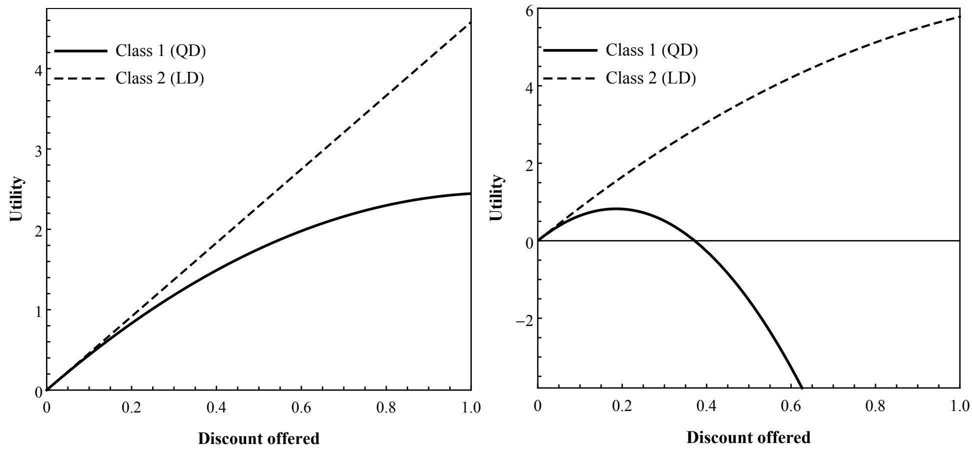
Table 2.8: Relative importance of attributes for the LC model

	Apple		Motorola	
Attributes	Class 1: QD (83.27%)	Class 2: LD (16.73%)	Class 1: QD (11.97%)	Class 2: LD (88.03%)
Discount	53.25%	34.76%	75.73%	65.77%
Product condition	5.42%	1.81%	1.40%	3.53%
Seller identity	30.80%	10.27%	8.99%	22.73%
Marketplace	2.28%	30.81%	01.79%	4.53%
Eco-friendly certification	08.25%	22.35%	12.09%	3.44%
Sum	100%	100%	100%	100%

Furthermore, Figures 2.10 and 2.11 illustrate the percentage of respondents that would purchase refurbished products, according to the discount increases for the products. For refurbished Apple products from two online marketplaces, respondents from the class LD indicate low purchase intentions for refurbished products sold on eBay. However, respondents from the class QD do not differentiate between Amazon.com and eBay. For refurbished Motorola products, the respondents are more concerned with the price of the products. As the discount for the product increases, the respondents from class QD express more doubts about the product quality. This result is different from respondents in class LD who do not believe in the price–quality relationship.

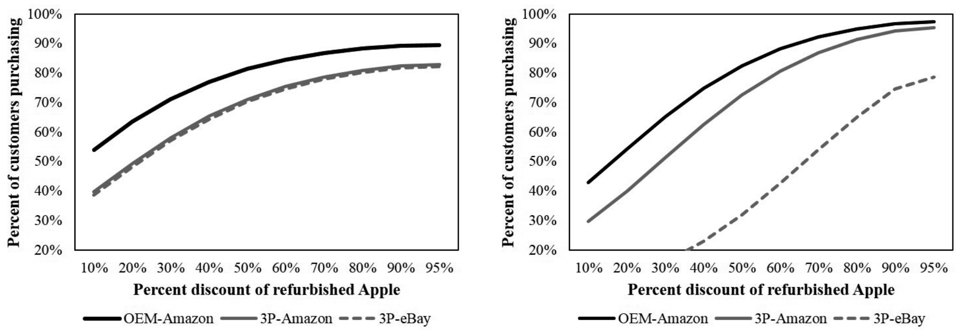
2.3.2 Study 2: Consumer Behavior in Choosing between New and Refurbished Products

In this subsection, we investigate the relationship between the perceived quality of the refurbished product and the discount offered when there is a new product in the same market. In line with Völckner and Hofmann (2007), Ovchinnikov (2011), and Abbey et al. (2015b), we fix the price of the new products, which enables us to view the cannibalization as a function of the discount offered. This effect could be nonlinear, implying an increased negative perception if the discount is too high. In this study, we manipulate the discount and brand combination to measure quality perceptions. Appendix A presents the complete DCE output. Table A.8 and Figure A.1 present some statistics of interest for the MNL model. All attributes for smartphone preferences are at a statistically significant level. We obtain similar



(a) Apple *(b)* Motorola

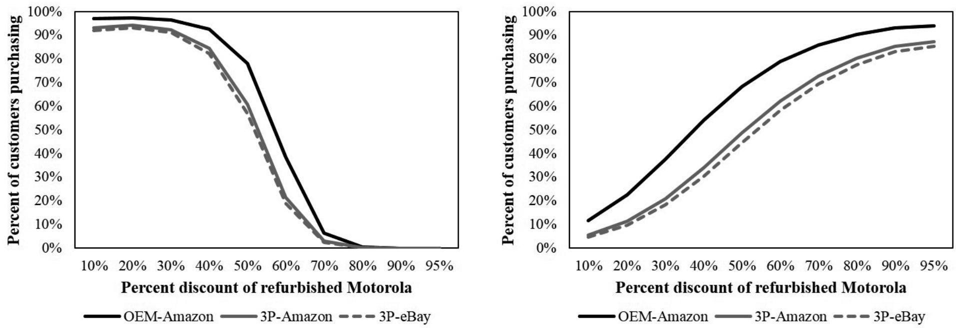
Figure 2.9: Utility functions of discount offered for refurbished products in the LC model



(a) Apple: Class 1 (QD) *(b)* Apple: Class 2 (LD)

Figure 2.10: Percentage of customers purchasing refurbished Apple products by discount increases for the products in the LC model

results to those gathered in Study 1. For both the high-end brand (Apple) and the low-end brand (Motorola) refurbished products, the impact of the discount is greater than the other product attributes, and the choice of seller identity is preferred over the product condition. Moreover, the average partworth utilities of the two brands increase based on the discount offered. We calculate the utility of both new and refurbished products by discount and condition. We then obtain

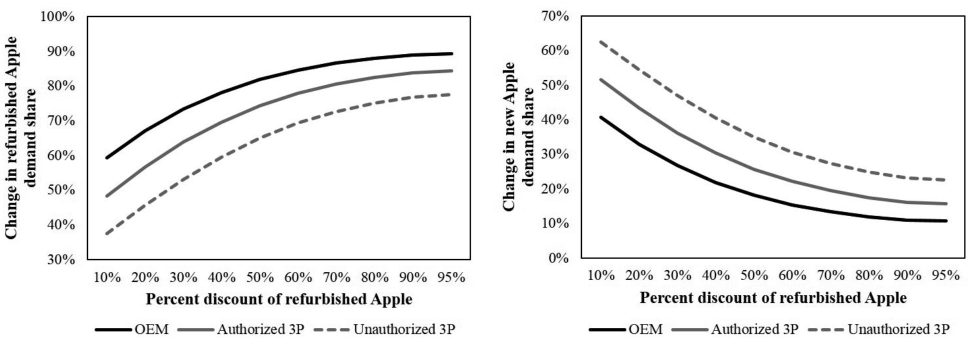


(a) Motorola: Class 1 (QD)

(b) Motorola: Class 2 (LD)

Figure 2.11: Percentage of customers purchasing refurbished Motorola products by discount increases for the products in the LC model

the purchase probability for a given product as a ratio of the exponent of its utility to the sum of exponents of utilities for all alternatives in the choice set. Figure 2.12 illustrates the change in demand share for Apple refurbished and new products based on discount increases of the refurbished product (Appendix A shows the demand share for the Motorola smartphone). The results obtained for Apple and Motorola are similar. For the three categories of refurbished products, we find that the greater the seller's reputation, the more respondents consider the refurbished products close substitutes for new products.

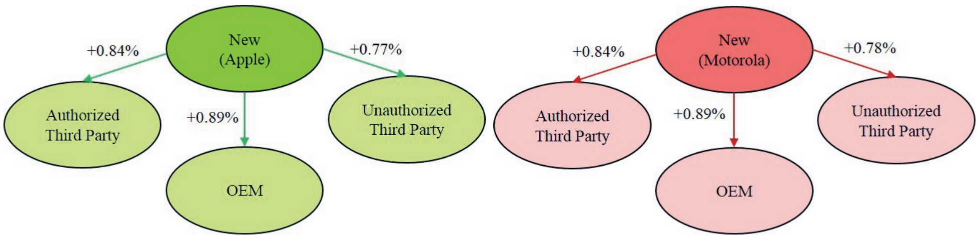


(a) Refurbished Apple

(b) New Apple

Figure 2.12: Change in demand share of refurbished and new Apple products by discount increases for refurbished products in the MNL model

Figure 2.13 shows the cross-discount elasticities of refurbished products. The values represent a 1% increase in the discount offered for the refurbished product on the cannibalization levels. For example, Figure 2.13a shows that a 1% increase in the discount of OEM refurbished Apple products increases its market share by .89%, a 1% increase in the discount of A3P refurbished products increases its market share by .84%, and a 1% increase in the discount of U3P refurbished products increases its market share by .77%. Thus, the OEM or A3P refurbished products pose a big threat of cannibalization to new products. Although refurbished products sold by the OEM and an A3P have the same quality and are authorized by the OEM, the reputation of the sellers seems to influence quality perceptions. The authorization strategy increases the cannibalization level of third-party refurbished products. The results obtained for Apple and Motorola are similar.



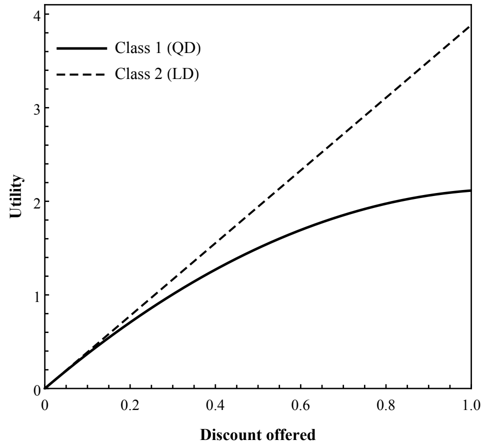
(a) Apple *(b)* Motorola

Figure 2.13: Discount elasticity between new and refurbished products for the MNL model for (a) Apple and (b) Motorola products

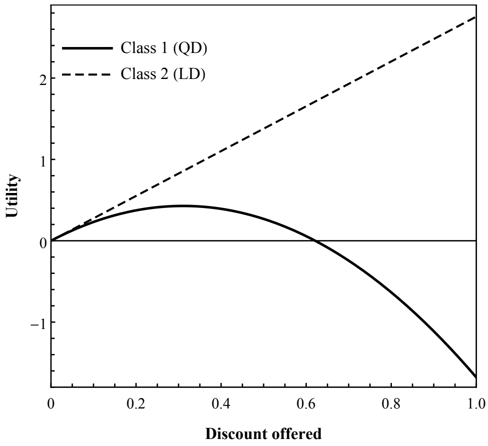
Table 2.9: Relative importance of attributes for the LC model

	Apple		Motorola	
Attributes	Class 1: QD (85.08%)	Class 2: LD (14.92%)	Class 1: QD (15.47%)	Class 2: LD (84.53%)
Discount	59.97%	74.17%	58.03%	64.11%
Product condition	8.55%	5.51%	12.96%	11.08%
Seller identity	31.48%	20.32%	29.01%	24.81%
Sum	100%	100%	100%	100%

We also present some statistics of interest for the LC model (see Table 2.9 and Figure 2.14); Appendix A presents the complete experiment output. The results align with our Study 1 findings. We observe that class QD offers lower discount sensitivity (or greater seller reputation and condition sensitivity) than class LD. In addition, the quadratic discount can only be found for low-end brand refurbished



(a) Apple

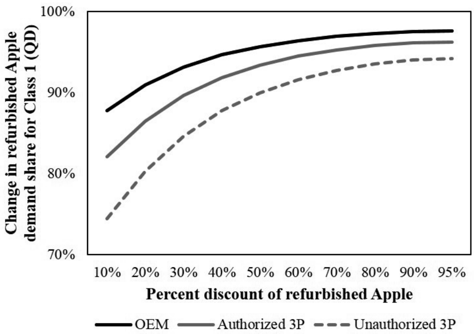


(b) Motorola

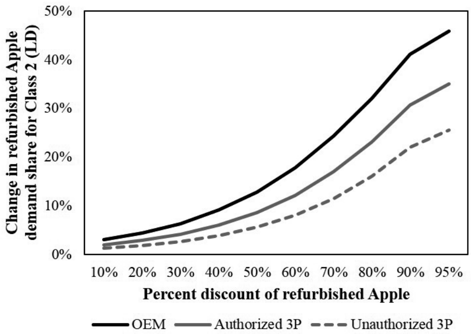
Figure 2.14: Utility functions of discount offered for refurbished products in the LC model for (a) Apple and (b) Motorola products

products. The partworth utilities for the discount offered start decreasing when the discount is around 30% of the full price of the new product. This discount-perceived quality threshold is a bit higher than what we found in Study 1 (20% discount), because the intention of respondents to purchase refurbished products is greater when there is a new version on the market. The percentage of respondents who doubt the product quality for highly discounted products is relatively low, around 15.47%. The partworth utilities for the discount offered for refurbished Apple products instead are linear in all classes.

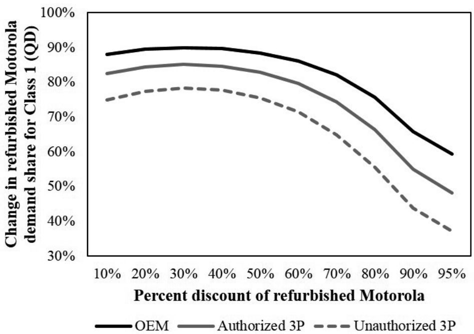
Figure 2.15 illustrates the change in demand share for new and refurbished products based on discount increases of the refurbished products for each brand by class. We observe that the greater the seller's reputation, the greater the demand share of the refurbished products. For the Motorola, class QD, though the refurbished products are authorized (i.e., sold by the OEM or an A3P), the demand share for the products decreases with the discount after around 30% of the new product price. For Apple, class QD, though a U3P sells the refurbished products, the demand share for the product always increases with increased discounts. Figure 2.16 illustrates the cross-discount elasticities for the LC model by brand and class. Figure 2.16c shows that, on average, a 1% increase in the discount of the OEM refurbished products decreases its market share by .25%. The lower the seller's



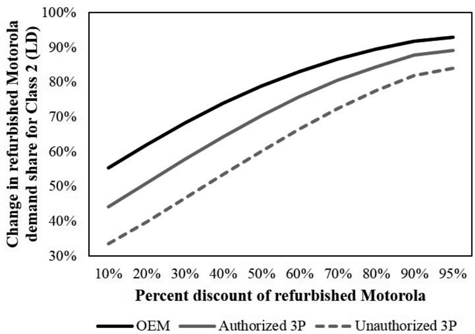
(a) Apple: Class 1 (QD)



(b) Apple: Class 2 (LD)



(c) Motorola: Class 1 (QD)



(d) Motorola: Class 2 (LD)

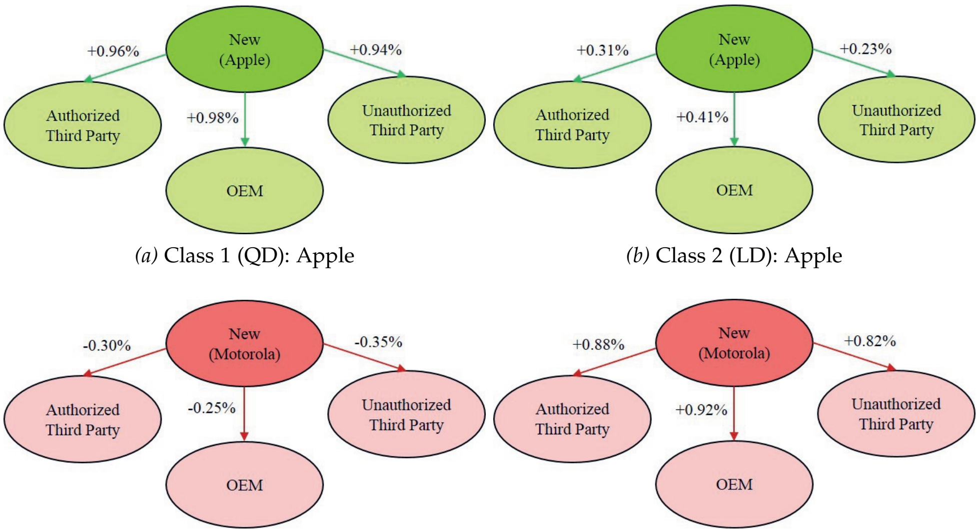
Figure 2.15: Change in demand share of refurbished products by discount increases for refurbished products in the LC model

reputation, the more the market share level decreases.

We incorporate the results of Study 2 into the analytical model in Chapter 4.

2.3.3 Study 3: Consumer Behavior in a Competitive Market

In this study, we estimate the sensitivity of consumer choice to the price differences between new and refurbished products and between two brands. We also investigate the relationship between price and perceived quality in a competitive setting. Table 2.10 and Figure 2.17 present some statistics of interest for the MNL model; Appendix A presents the complete DCE output. All attributes



(a) Class 1 (QD): Apple *(b)* Class 2 (LD): Apple

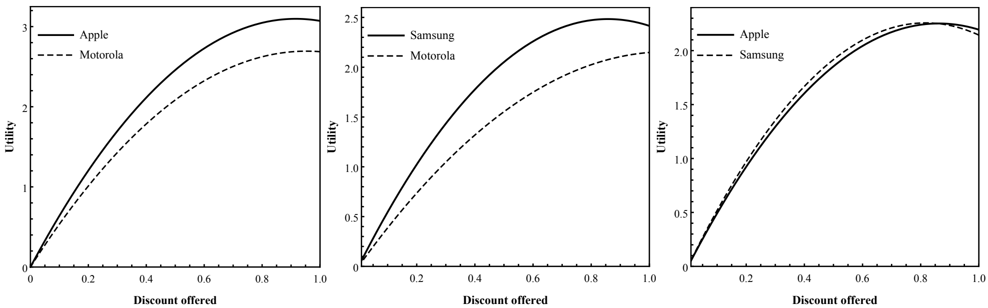
(c) Class 1 (QD): Motorola *(d)* Class 2 (LD): Motorola

Figure 2.16: Discount elasticity between new and refurbished products for the LC model

contribute to the preferences for smartphones at a statistically significant level. In all competitive models, the average partworth utilities increase based on the discount offered. We calculate the utility of each product alternative based on its discount and condition. We then obtain the purchase probability for a given product as a ratio of the exponent of its utility to the sum of exponents of utilities for all alternatives in the choice set. Figure 2.18 illustrates the demand function for the four products as a function of the price for a refurbished Motorola (Apple) product when the discounted price of a refurbished Apple (Motorola) product costs 40% less than a new product. The demand share for a new Apple product is always greater than that for a new Motorola product. Furthermore, the refurbished Motorola product needs to have a greater discount (or lower price) to have a greater demand share than the refurbished Apple product. For example, a refurbished Apple product with a 40% discount (or $360) has a lower demand share than a refurbished Motorola with a discount higher than around 65% or a price less than $168. Appendix A shows the demand share for other competitions. At the same discount level (and even at the same price), the refurbished product for a high-end brand has a greater demand share than its lower-end brand competitors. If the difference between the two brand levels is smaller, the market share difference at the same discount is also lower. This finding explains why the refurbished Apple and Samsung products have a similar demand share at the same discount.

Table 2.10: Attribute importance for the MNL model

	Attribute Importance					
	Apple versus Motorola		Samsung versus Motorola		Apple versus Samsung	
Attributes	Apple	Motorola	Samsung	Motorola	Apple	Samsung
Product condition	21.67%	19.35%	31.35%	33.44%	18.47%	16.28%
Discount	78.33%	80.65%	68.65%	66.56%	81.53%	83.72%



(a) Apple versus Motorola *(b)* Samsung versus Motorola *(c)* Apple versus Samsung

Figure 2.17: Average partworth utilities for discount in the MNL model

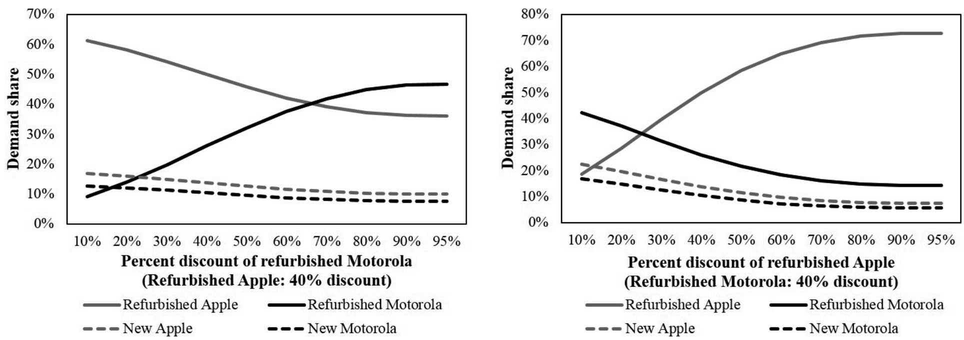
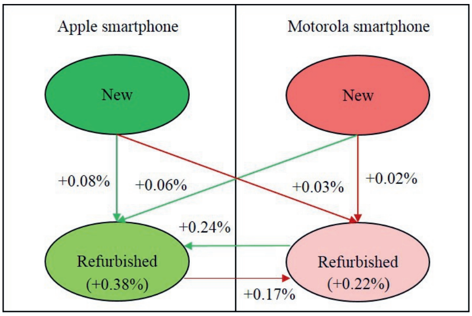
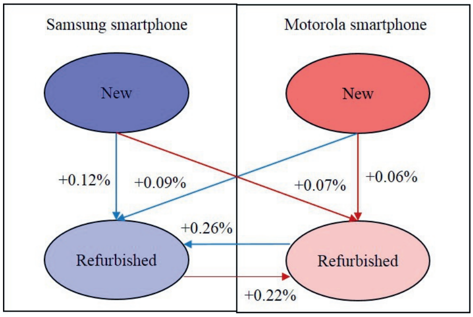


Figure 2.18: Demand share for Apple versus Motorola in the MNL model

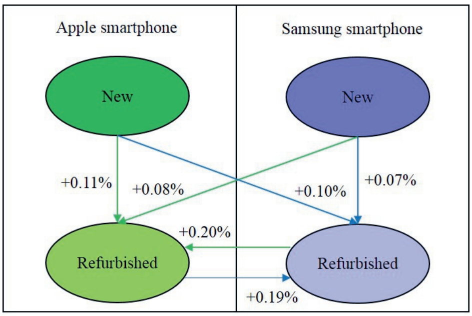
In Figure 2.19, we show the cross-discount elasticities. The values in the figures represent the effect of a 1% increase in the discount offered on the refurbished product on the internal and external cannibalization levels. For example, a 1% increase in a refurbished Apple product discount compared with the new price cannibalizes .08% market share of the new Apple smartphone, .06% market share of the new Motorola smartphone, and .24% market share of the refurbished Motorola smartphone. Thus, a 1% increase in the discount for the refurbished Apple smartphone increases its market share by .38%. We note significant differences in the cross-discount values across brands. In contrast, a 1% increase in the discount for a Motorola refurbished product cannibalizes market share for new Apple and Motorola smartphones by only .03% and .02%, respectively. We observe similar behavior in the competition between Samsung and Motorola. A possible explanation for this result is that consumers are more sensitive to changes in discounts for a refurbished product with higher brand value. In the case of Apple versus Samsung (i.e., both brands have high value), we observe similar increases in the market share with a 1% increase in discount.



(a) Apple versus Motorola



(b) Samsung versus Motorola



(c) Apple versus Samsung

Figure 2.19: Summary of cross-discount elasticities between product conditions and brands for the MNL model

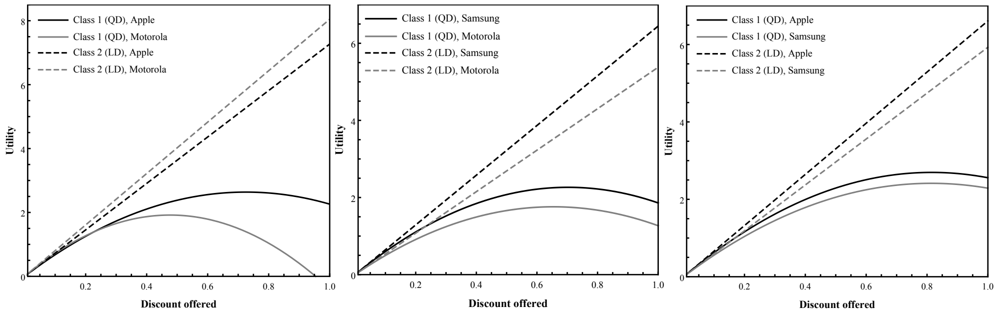
Motivated by the findings presented by Ovchinnikov (2011), we assess whether

U-shaped behavior exists in a competitive setting. Using the LC model, we can observe which class shows an inverted U-shaped utility for discount. Table 2.11 and Figure 2.20 illustrate some statistics of interest for the LC model; Appendix A presents the complete output. We also assess whether any classes have an inverted U-shaped utility in discount (price), using the model with two classes, that is, with a linear discount (LD) or a quadratic discount (QD). The two-class model has good interpretability, and by applying it, we can observe the differences among three competitive comparisons for the quadratic discount class. Table 2.11 shows that class QD has lower discount sensitivity than class LD in the first two competitions, whereas we see the opposite direction in the competition between Apple and Samsung products. Table A.20 in Appendix A shows that the partworth utilities of refurbished Apple and Samsung products in class LD are low compared with new products. This result indicates that the respondents in the class are only willing to purchase new products. The demand share of refurbished products is constant for discounts, in Figure A.11, Appendix A. Furthermore, Figure 2.20 shows that though the quadratic parameter is significant for all forms of competition, the quadratic discount can only be found in the competition between Apple and Motorola products, that is, the partworth utility of refurbished Motorola products. In this case, the difference between the two brands is much greater than in other competitions. We assume the partworth utilities for refurbished Apple products or refurbished products in other competitions are linear, because the utilities start decreasing when the discount is high enough. Figure A.7 in Appendix A shows the demand share for each class. In the quadratic discount class, the demand share of the refurbished Motorola product increases as the discount increases and then decreases when the discount exceeds 50%.

Table 2.11: Attribute importance for the LC model

	Attribute importance (%)											
	Apple (A) versus Motorola (M)				Samsung (S) versus Motorola (M)				Apple (A) versus Samsung (S)			
	Class 1: QD (59.64%)		Class 2: LD (40.36%)		Class 1: QD (73.96%)		Class 2: LD (27.04%)		Class 1: QD (79.50%)		Class 2: LD (20.50%)	
Attribute	A	M	A	M	S	M	S	M	A	S	A	S
Condition	29.36	23.64	11.63	7.80	37.94	39.64	14.18	24.85	16.12	21.22	50.34	48.83
Discount	70.64	76.51	88.37	92.20	62.06	60.36	85.82	75.15	83.88	78.78	49.66	51.17

We also calculate the total demand share by including all classes. Weighing the demand share for the two classes by the size of the class gives the product demand, as shown in Figure A.8. In this case, we cannot identify the quadratic discount



(a) Apple versus Motorola *(b)* Samsung versus Motorola *(c)* Apple versus Samsung

Figure 2.20: Average partworth utilities by discount for the LC model

for the Motorola utility. Although the utility starts decreasing after around a 70% discount, the decrease rate is very small. Appendix A shows the demand share for each class and the total demand share for other competitions. Figure A.13 illustrates the cross-discount elasticities for each competition; the results are similar to those in Figure 2.19. We observe the U-shaped behavior only in the competition among firms with high brand-level differences. Furthermore, it is apparent only when the discount levels are quite high. Such steep discounts (> 60 – 70%) are not common in reality. We also calculate the total demand share and report the results in Appendix A. Figure A.13 in Appendix A illustrates the cross-discount elasticities from the LC model. The results are similar to those from the MNL model.

We incorporate the results of Study 3 into the analytical model in Chapter 3.

2.4. Conclusion

Although it is generally true that the price and perceived quality of consumer products are highly related, a paucity of empirical evidence illustrates the existence of this relationship for refurbished products. To better understand this phenomenon, this chapter presents an empirical examination of three price–perceived quality models. The first model in Study 1 applies to a situation in which only a single refurbished product is presented to respondents. The second model in Study 2 expands the first model by considering the competition between a new product and its refurbished version in a market. The third model in Study 3 evaluates the price–perceived quality relationship by considering competition among brands.

The experimental results show that price and perceived quality are highly correlated in the first two models, represented by an inverted U-shaped price acceptability function. The results of the DCE indicate that for low-end brand products, there are consumers who perceive the low-priced refurbished product as low in quality and choose not to purchase it or prefer to purchase a new product. Firms with lower brand value experience the inverted U-shaped function, because consumers become suspicious of the quality as the discount increases. Firms with a high-end brand image or high-quality products experience linear cannibalization, because the consumers trust the refurbished version of the product. However, in Study 1, we obtained different results when using the price categorization approach. Inverted U-shaped purchasing behavior always exists for high- and low-end brand refurbished products. Moreover, refurbished products with a high-end brand image, in good condition, or sold by a seller with a good reputation tend to have lower discount perceived quality threshold; that is, respondents doubt the quality of the products more when the discounts are relatively high. In the price categorization method, respondents identify the range of acceptable prices for a single product with specific attributes, and this procedure may influence respondents to believe that there should be a price that is too expensive or too cheap. The underlying assumption of the DCE instead is that respondents perceive a product option as a combination of attributes and make purchases on the basis of those utilities. However, respondents are unaware of the utilities they attach to different attributes. They can only indicate their preferences for different attribute combinations.

In Study 3, we show that the inverted U-shaped cannibalization behavior demonstrated in previous studies is largely absent in a duopolistic setting. Our results further show that cross cannibalization is an effect to be reckoned with, especially for low-end brands facing competition from high-end brands offering refurbished products. Our extensive experiment also enables us to estimate the elasticity coefficients, specically for the smartphone industry. In a competitive environment, the high-brand refurbished products are always dominant over its low-brand competitor. This is because the mid low-end market for new products is being cannibalized by refurbished high-end products. Therefore, the high-brand valued firms can have huge potential gains in the secondary market.

3
Revenue Management in Refurbishing Duopoly with Cannibalization

3.1. Introduction

Global brands in many industry sectors have considered refurbishing as an important business strategy. Xerox has been recognized as a leader in circular economy for electronics for over 30 years. In 2017, they won the Green Electronics Council's Catalyst Award. They have been able to realize cost benefits of over $127 million and save over 115 million pounds of greenhouse gases (Drzewiecki, 2017; Xerox, 2018). Similar efforts and successes are reported by companies such as Caterpillar, Boeing, BMW, Ford, Nissan, Toyota and Honda (Caterpillar, 2020; Waldron, 2019; BMW, 2020; Ford, 2020; Nissan, 2020; Toyota, 2020; Honda, 2020). In the consumer electronics industry, companies such as Apple, Samsung, Lenovo, Motorola, Dell, HP have made product refurbishing a key part of their strategy (Apple, 2020; Samsung, 2020; Lenovo, 2020; Motorola, 2020; Dell, 2020; HP, 2020; Panasonic, 2020; IBM, 2020; Canon, 2020; Kodak, 2020; Epson, 2020).

Firms in the smartphone industry that engage in refurbishing face two major strategic considerations in their decisions on offering refurbished products in the market - competition and cannibalization. The decisions are further complicated by poorly understood consumer perceptions of brand and quality of the refurbished product. Some managers believe that for every four refurbished products sold, one new product is cannibalized since consumers can easily differentiate between new and refurbished product (Abbey et al., 2015a; Ferguson and Toktay, 2006). However, Atasu et al. (2010a) suggest that while cannibalization can lead to loss in new product sales, it also brings in additional revenue from refurbishing than can balance or even tip the scales in favor of refurbishing. Further, the presence of affordable refurbished products might also attract new consumers who would not normally purchase new products, thus creating a demand from these "low-end" consumers (Ovchinnikov, 2011). A company's strategic refurbishment decision is exacerbated by the presence of a competitor also selling a primary product and its refurbished version. Thus, the cannibalization effect depends not only on the quality of the refurbished product, but also the consumers' perception about the product's brand value versus that of its competitors.

Facing competition and the threat of cannibalization, firms now have to design their refurbishing strategy: whether to put the refurbished product in the market, and how to manage their quantities and prices. This strategy needs to be designed while taking the used product collection efforts into account. In such a competitive environment with cannibalization of new product sales, setting the product quantities and prices correctly will determine the profitability of the firm. If not done correctly, entering this market may reduce profitability altogether. A firm's refurbishing strategy also may depend on the relative strength of its brand. In fact, Guide and Li (2010) advice that OEM's with products that have high brand value or name recognition would better off selling refurbished versions of their products. This is because these refurbished versions reach a customer segment that desire to own a name brand product, but are unwilling to pay the premium pricefor a new product (these are the "low-end" consumers). This situation exists in practice - Apple, Samsung, Motorola among many smartphone manufacturers sell both new and refurbished versions of their premium smartphones. These firms have different brand recognition in the market. In this chapter, we provide insights into the design of a firm's refurbishment strategy, taking into account the effects of competition, cannibalization, and brand.

Our work contributes to the understanding of optimal refurbishment strategies in term of the novelty of the model which based on the experimental results in

Chapter 2. We introduce two types of cannibalization. Internal cannibalization of a new product is caused due to the refurbished product made available by the same firm as a function of discount; and external (or cross) cannibalization is caused by the presence of a competitors' refurbished product. The two refurbished products also compete with each other. Our subsequent model analysis allows us to obtain the optimal refurbishing strategy for the two competing firms under used product collection constraints. First, we find interesting results from the cross cannibalization and the used product constraint. The optimal price of the high-brand valued firms' refurbished product increases in the cross cannibalization from new customers of a low-brand valued firm to the refurbished product of a high-brand valued firm. Second, we show that a low brand valued firm faces a harder challenge due to its high cross cannibalization levels. However, it can achieve a higher profit if it is able to beat its competitor in collection and refurbishing efforts. Third, we find that the used product collection constraint has novel relationships with the pricing and profitability for both firms. We see that the higher brand valued firm will charge a higher refurbished product price than its competitor, but only when the amount of used products collected satisfies a certain condition. They will have to charge a lower price otherwise, which can result in the lower brand valued firm leading the market. Furthermore, profits are concave in collection efforts, implying that firms should identify their market position to either increase or decrease these efforts.

3.2. Literature Review

Our work fits into a well-established stream of research that studies closed-loop supply chains where remanufacturing and refurbishment play a critical role. Apart from the general positioning, product-line competition is of particular relevance to our work. Competition in refurbishing has been considered in the literature from various viewpoints. Different assumptions are made on who produces the refurbished product. Most papers analyze the impact of competition between an OEM selling a new product and a third party selling only a refurbished product (e.g., Majumder and Groenevelt, 2001; Debo et al., 2005; Ferrer and Swaminathan, 2006; Ferguson and Toktay, 2006; Webster and Mitra, 2007; Oraiopoulos et al., 2012; Subramanian and Subramanyam, 2012; Wu, 2012; Bulmus et al., 2014; Örsdemir et al., 2014; Abbey et al., 2015a; Agrawal et al., 2015b; Yan et al., 2015; Wu and Wu, 2016; Zou et al., 2016; Wu and Zhou, 2016; Agrawal et al., 2016; Esenduran et al., 2017; Hong et al., 2017; Liu et al., 2018; Chen and Chen, 2019; Fang et al., 2019; Zheng et al., 2019). A limited number of studies investigate the profitability of refurbishing under competition between original equipment manufacturer (OEMs) (e.g., Heese et al., 2005; Atasu et al., 2008b; Mitra, 2016). Three such studies consider direct OEM competition with one OEM engaged in refurbishing activities, while the other only sells new products. They find that refurbishing may be a better strategy if a firm can initiate product take-back (Heese et al., 2005) and if refurbishing costs are sufficiently low (Atasu et al., 2008b), and is almost always profitable even when it cannibalizes new product sales since the additional profits from refurbishing may be able to compensate for the loss of profits from new product sales (Mitra, 2016). In an alternative setting, Raz et al. (2017) consider two product + service firms where each firm offers products and services at a different product-lines: one firm sells new versions of high-end and low-end products; while the other offers an identical new high-end product plus its refurbished version. Their results show that refurbishing in a product + service context increases social welfare. These prior studies on competing OEMs all consider asymmetric firms. Our work differs from these in the sense that we consider symmetric firms with different brand recognition. Both of our firms offer a new product and its refurbished version, with similar features. This allows us to introduce both internal and external cannibalization into our model. In line with previous works, we analyze the steady state single period of an infinite horizon model, where the production of the refurbished product is constrained by the volume of used products collected (taking place in a previous period). However, the used product of a firm cannot be considered as a source of supply for another firm's refurbishing process. This is true for OEMs that have different manufacturing/refurbishing processes, and hence can refurbish only their own brands. Therefore, there is no substitutability of used products for refurbishing from the point of view of manufacturers.

3.3. Model

We consider two competing firms, M_h (high-brand firm) and M_l (low-brand firm), producing and selling both new and refurbished products in a single period. Figure

3.1 illustrates the model schematic. For example, a firm will sell units of the current generation for the period until the next is available after which only the new generation is sold and the previous one is discontinued. Figure 3.1 shows the two sub-periods when these generations are sold. In this chapter, we focus on the period where both firms are offering new and refurbished products from the same generation. A finite number of used products are collected in the previous period. We interpret this period to be where the product has reached maturity in its life-cycle and that the prices and refurbishing rates are steady (Zou et al., 2016; Esenduran et al., 2017). These single period models are common when studying strategic decisions like ours (e.g., Savaskan et al., 2004; Atasu et al., 2009; Ovchinnikov, 2011; Jacobs and Subramanian, 2012; Galbreth et al., 2013; Souza, 2013; Xiong et al., 2013; Ma et al., 2013; Örsdemir et al., 2014; Yan et al., 2015; Esenduran et al., 2017). Savaskan et al. (2004) and Ma et al. (2013) assume that the product previously existed in the market and was thus returnable to the manufacturer for reuse.

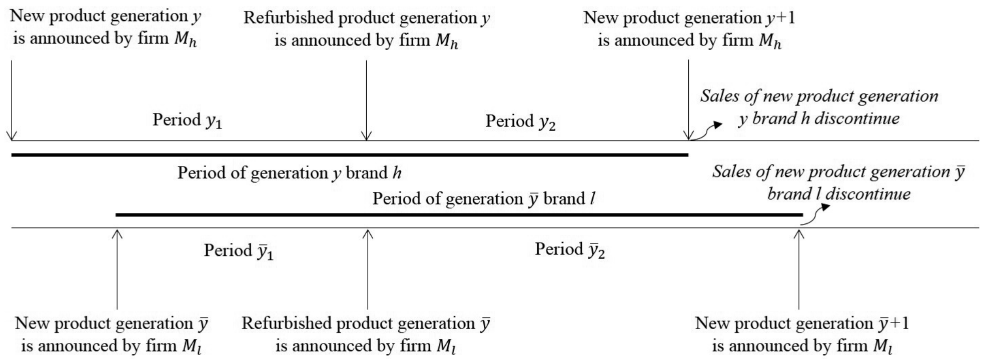


Figure 3.1: Model schematic

We distinguish two types of customers, i.e., high end and low end. High-end customers are willing to purchase new products, whereas low-end customers only purchase refurbished products (with lower price than new products). The notation that we use is presented in Table 3.1. The firm M_i, $i \in \{h, l\}$ sells two products: new and refurbished products at prices p_i^n and p_i^r, respectively. New product's prices p_h^n and p_l^n are fixed, as we discussed in Chapter 1; p_h^r and p_l^n are decision variables, where $p_i^r \leq p_i^n$, $\forall i \in \{h, l\}$.

Table 3.1: Notation and associated description

Symbol	Description
M_i	Firm who produces and sells both new and refurbished products of brand i, where $i \in \{h,l\}$
p_i^r	Unit selling price of refurbished product of brand i, where $i \in \{h,l\}$
c_i^r	Unit refurbishing cost of a refurbished product of brand i, where $i \in \{h,l\}$
p_i^n	Unit selling price of new product of brand i, where $i \in \{h,l\}$
c_i^n	Unit manufacturing cost of a new product of brand i, where $i \in \{h,l\}$
w_i^n	Unit margin of new product of brand i, where $i \in \{h,l\}$ and $w_i^n = p_i^n - c_i^n$
t_i	Cost saving of refurbishing, where $t_i = c_i^n - c_i$
q_i^n	Demand of new product of brand i when there is no refurbished unit available, where $i \in \{h,l\}$
α_i^j	Fraction of high-end customers of brand i who switch to purchase refurbished product of brand j, where $i,j \in \{h,l\}$
α_i	Total fraction of high-end customers of brand i who switch to purchase refurbished products i and j, where $i,j \in \{h,l\}$ and $\alpha_i = \alpha_i^i + \alpha_i^j$
q_{ia}^j	Number of high-end customers of brand i who switch to purchase refurbished product of brand j, where $i,j \in \{h,l\}$ and $q_{ia}^j = \alpha_i^j q_i^n$
q_{ib}^r	Number of low-end customers who purchase refurbished product of brand i, where $i \in \{h,l\}$
$D_i^n(D_i^r)$	Total demand of new (refurbished) product of brand i, where $i \in \{h,l\}$
b_i^j	Cannibalization coefficient from new product of brand i to refurbished product of brand j, where $i,j \in \{h,l\}$
k_i	Price elasticity on market demand of low-end customers brand i, where $i \in \{h,l\}$
m	Intensity of price competition
Π_i	Profit function of firm M_i, where $i \in \{h,l\}$
Symbols used for simplification of expressions:	
$r_h(r_l)$	Internal (external) cannibalization elasticity, where $r_h = b_h^h q_h^n$ and $r_l = b_l^h q_l^n$
a_i	Maximum demand of refurbished product of brand $i \in \{h,l\}$, where $a_h = (k_h + r_h)p_h^n + r_l p_l^n$ and $a_l = k_l p_l^n$
d_i	Overall effects on demand of refurbished product of brand i, where $d_h = k_h + r_h + r_l + m$ and $d_l = k_l + m$

The two firms take part in a competition where the prices of their refurbished products influence both the demand for their own new product and their competitor's refurbished product. The demand for new products (or the high-end demand) in the absence of refurbished products is q_h^n for M_h and q_l^n for M_l. In the presence of the refurbished product on the market, some high-end consumers of firm M_i, $i \in \{h,l\}$ switch to refurbished products - if they are available. This fraction is $\alpha_i(p_i^r, p_j^r) \in [0,1]$, $i,j \in \{h,l\}, i \neq j$. The switching fraction α_i is affected directly by both the refurbished product price of firm M_i and that of its competitor. Hence, there are $\alpha_i(p_i^r, p_j^r)q_i^n$ high-end customers of firm M_i who switch to the refurbished products of firm M_i and M_j. Let $\alpha_i(p_i^r, p_j^r) = \alpha_i^i(p_i^r) + \alpha_i^j(p_j^r)$, $i,j \in \{h,l\}$, where α_i^i and

α_i^j represent the internal and external cannibalization fractions, respectively. Thus, there are $q_{ia}^j = \alpha_i^j(p_j^r)q_i^n$ high-end customers of firm M_i, $i, j \in \{h, l\}$ who switch from new products of brand i to refurbished products of brand j. Moreover, a firm's refurbished product sold at price p_i^r also attracts $q_{ib}^r(p_i^r, p_j^r)$ low-end customers. The market demand of refurbished products is assumed to be price-dependent and these products are substitutes, i.e. some low-end customers will switch from firm M_i to M_j if $p_i^r > p_j^r$, $i, j \in \{h, l\}$.

The demand function of refurbished-product-only customers for each firm is continuous, deterministic and has the following form:

$$q_{ib}^r(p_i^r, p_j^r) = k_i(p_i^n - p_i^r) + m(p_j^r - p_i^r), \tag{3.1}$$

where $i, j \in \{h, l\}, i \neq j$ and demand parameters k_i and m are all positive. The function is a variation of the general class of linear demand functions utilized in various studies (Choi, 1991; Tsay and Agrawal, 2000; Majumder and Groenevelt, 2001; McGuire and Staelin, 2008; Lu et al., 2011; Ovchinnikov, 2011; Wu, 2012; Jena and Sarmah, 2014). Parameter $k_i p_i^n$ is the market size for the refurbished product of firm M_i. This represents the demand faced by the firm M_i for the refurbished product if their prices are 0. k_i represents the price sensitivity and m denotes the price competition between the refurbished products of M_i and of M_j. The degree m is included because competitor pricing has an impact on product demand of a firm in a price sensitive market. A higher m increases the influence of price competition. Thus, when the firm decreases the price of the refurbished product by one unit, the increase in low-end demand is $k_i + m$. The increase k_i is from the decrease in price and the increase m is from the customers that switch over from the competitor. Equation 3.1 illustrates that the demand for refurbished products decreases with increase in its own refurbished product price and increases with increase in the competitor's refurbished product price. The total demand of new and refurbished product of firm M_i, $i \in \{h, l\}$ is given by

$$\begin{aligned} D_i^n &= q_i^n - q_{ia}^i - q_{ia}^j \\ D_i^r &= q_i^r = q_{ia}^i + q_{ja}^i + q_{ib}^r. \end{aligned}$$

Currently, manufacturers are responsible in collection of end-of-use products and proper treatment due to take-back legislation even if they have not integrated refurbishing into their business (OECD, 2001; Directive, 2012; Atasu et al., 2010b; Esenduran et al., 2017). In our OEM-OEM competition model, a manufacturer may exercise the refurbishing profit opportunity from its mandatory collection efforts. Let s_h and s_l denote the number of used product collected for firms M_h and M_l, respectively, that can all be refurbished. The decisions that the firm M_i, $i \in \{h, l\}$ needs to make are the refurbished product quantity, $q_i^r \in [0, s_i]$, and the price of the product, p_i^r. Implicitly, we assume $\tau_i q_i^n \leq s_i \leq \eta_i q_i^n$, where τ_i denotes the collection target (take-back regulation) of firm M_i, and η_i represents the maximum possible fraction of used products the firm can collect. We would like to characterize the optimality conditions for two competing firms (brands) where the number of used products collected is limited and a firm cannot intercept the returning cores of its competitor. This is because the used product of a firm cannot be considered as a source of supply for another firm's refurbishing process. Further, we assume that firm M_i, $i \in \{h, l\}$ has unit manufacturing cost c_i^n and unit refurbishing cost c_i^r. The refurbishing costs include collection, testing, etc. We also assume that unit refurbishing costs are lower than unit new production costs, that is, $c_i^r < c_i^n, \forall i \in \{h, l\}$. Then, both firms face the optimization problem Θ to maximize their profit:

$$\begin{aligned} \Theta_i(p_i^r, q_i^r | p_j^r, s_i) : \max \Pi_i = \;& (p_i^n - c_i^n)(q_i^n - q_{ia}^i - q_{ia}^j) + (p_i^r - c_i^r) q_i^r \\ \text{s.t.} \;\; & 0 \leq q_i^r \leq s_i, \\ & c_i^r < p_i^r < p_i^n, \\ & q_i^r = q_{ia}^i + q_{ja}^i + q_{ib}^r, \end{aligned} \tag{P1}$$

where $i, j \in \{h, l\}$ and $i \neq j$. To find the optimal prices, we simultaneously solve for p_i^r and p_j^r.

Building on our experimental results in Chapter 2, and without loss of generality, we consider a situation where the presence of high brand refurbished products cannibalizes the new products of both high-end and low-end brands, and attracts low-end customers; further, the presence of low brand refurbished products only attracts low-end consumers and does not cannibalize new products. In our model, the high-end consumers may indirectly switch to purchase the low brand-valued firms' refurbished product if the price is relatively lower than the refurbished-competitor. Moreover, since in Chapter 2 we also show that the inverted U-shaped cannibalization behavior is largely absent in a duopolistic setting, we model the cannibalization for both firms M_h and M_l as a general linear switching function, that is, $\alpha_h^h(p_h^r) = b_h^h(p_h^n - p_h^r)$ and $\alpha_l^h(p_h^r) = b_l^h(p_l^n - p_h^r)$, for some coefficient b_h^h, b_l^h. We assume $b_h^l = b_l^l = 0$, thus $\alpha_h^l(p_l^r) = \alpha_l^l(p_l^r) = 0$. The cannibalization structure is illustrated at Figure 3.2. This is a simplification of the complete cannibalization case, where $b_h^l \neq 0$ and $b_l^l \neq 0$. While this helps in the clarity and simplification of the results, our insights and findings shown in this section still hold for the complete cannibalization case.

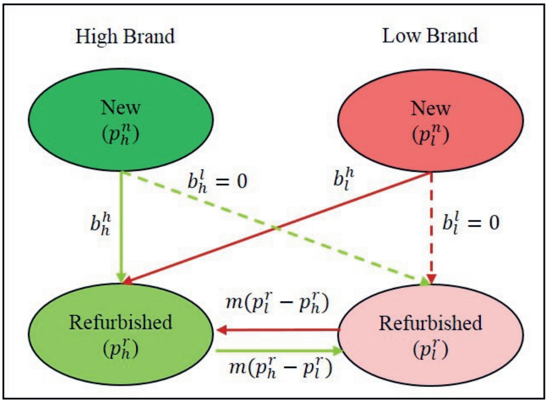


Figure 3.2: Cannibalization structure

3.3.1 Optimal policies

Assuming that the firms M_h and M_l make decisions independently and simultaneously, (Θ_h, Θ_l) constitutes a static game which can be solved to obtain a unique Nash equilibrium. To be able to solve the constrained problem, we use the Karush-Kuhn-Tucker (KKT) conditions to solve for optimality[1]. Solving this problem gives us the following lemma.

Lemma 3.1 *The optimal policy for the firm depends on certain critical values and the cost savings $t_i = c_i^n - c_i^r$, $i = h, l$ from its own production and that of its competitor. These policies are shown in Figure 3.3. The thresholds γ and μ and the optimal prices are given in Appendix B.1.*

[1] All proofs are included in Appendix B.1

A *If* $t_h < \mu_{AC} t_l + \gamma_{AC}$ *and* $t_l < \mu_{AB} t_h + \gamma_{AB}$*, both* M_h *and* M_l *refurbish and sell less than the used products they collect. If* $t_h < \mu_{AC} t_l + \gamma_{hA_0}$ *and/or* $t_l < \mu_{AB} t_h + \gamma_{lA_0}$*, firm* M_h *and/or* M_l *do not make any refurbished product.*

B *If* $t_h < \gamma_{BD}$ *and* $t_l > \mu_{AB} t_h + \gamma_{AB}$*,* M_l *refurbishes and sells all used products that it collects, while* M_h *does not. If* $t_h < \gamma_{BB_0}$*,* M_h *does not make any refurbished product.*

C *If* $t_l < \gamma_{CD}$ *and* $t_h > \mu_{AC} t_l + \gamma_{AC}$*,* M_h *refurbishes and sells all used products that it collects, while* M_l *does not. If* $t_l < \gamma_{CC_0}$*,* M_l *does not make any refurbished product.*

D *If* $t_h > \gamma_{BD}$ *and* $t_l > \gamma_{CD}$*, both* M_h *and* M_l *refurbish and sell all used products that they collect.*

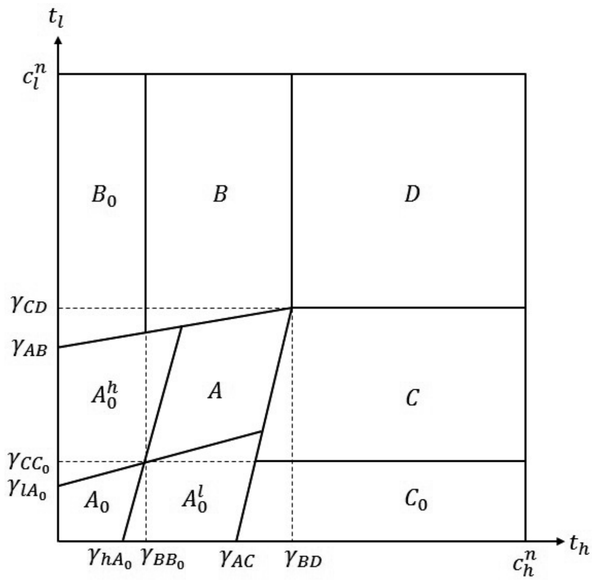


Figure 3.3: Optimal policy structure for refurbishing in duopoly, with all thresholds γ as in Lemma 3.1

The cost savings parameters t_h and t_l and total used products collected define these four cases. It is important for managers to note this result. Having high cost savings is not enough to refurbish all collected products, a somewhat intuitive but not optimal response. With respect to thresholds γ_{hA_0}, γ_{lA_0}, γ_{BB_0}, γ_{CC_0}, γ_{AB}, γ_{AC}, γ_{BD}, γ_{CD}, μ_{AB}, and μ_{AC} as in Lemma 3.1, with low values of t_i, $i = h, l$, both firms should not refurbish and sell all used products collected; for low values of

t_i and high values of t_j, M_i should not refurbish and sell all used products that it collects, while M_j should. Moreover, for high values of t_i, $i = h, l$, both M_h and M_l should refurbish and sell all used products that they collect. Here are two examples to illustrate Lemma 3.1.

Case 1. For firm M_h, $p_h^n = 100, c_h^n = 80$, $q_h^n = 1000$, $k_h = 3.5$, $b_h^h = .001$, $s_h = 300$. For firm M_l, $p_l^n = 90$, $c_l^n = 40$, $q_l^n = 1000$, $k_l = 3.5$, $b_l^h = .01$, $s_l = 200$. The price competition is $m = 12$. The new product profit margin and the internal cannibalization for M_h are low, whereas the new product profit margin and the external cannibalization coefficient for M_l are high. The used product collected by firm M_h is higher than that by M_l. The price competition between the two refurbished products are relatively high. In this case, $\mu_{AB} = .469$, $\mu_{AC} = .275$, $\gamma_{AB} = -17.909$, $\gamma_{AC} = 27.470$, $\gamma_{BD} = 25.890$, $\gamma_{CD} = -5.757$. Parameters γ_{AB} and γ_{CD} are less than 0. Hence, only scenarios B and D are present. The low-brand valued firm always refurbish and sell all used products that it collects. The high-brand valued firm does not refurbish all used product collected when $t_h < 25.890$.

Case 2. For firm M_h, $p_h^n = 100$, $c_h^n = 50$, $q_h^n = 1000$, $k_h = 3.5$, $b_h^h = .01$, $s_h = 300$. For firm M_l, $p_l^n = 90$, $c_l^n = 70$, $q_l^n = 1000$, $k_l = 3.5$, $b_l^h = .001$, $s_l = 300$. The price competition is $m = 2$. The new product profit margin and the internal cannibalization for firm M_h are high, whereas the new product profit margin and the external cannibalization coefficient for firm M_l are low. The price competition between the two refurbished products are relatively low. Both firm M_h and M_l have the same amount of used products collected. In this case, $\mu_{AB} = .186$, $\mu_{AC} = .062$, $\gamma_{AB} = 90.602$, $\gamma_{AC} = 19.950$, $\gamma_{BD} = 25.862$, $\gamma_{CD} = 95.41$. Parameters γ_{AB} and γ_{CD} are higher than c_l^n. Hence, only scenarios A and C are present. The low-brand valued firm always refurbish and sell less than the used products that it collects. The high-brand valued firm refurbish and sell all used product collected when $t_h > .062t_l + 19.950$.

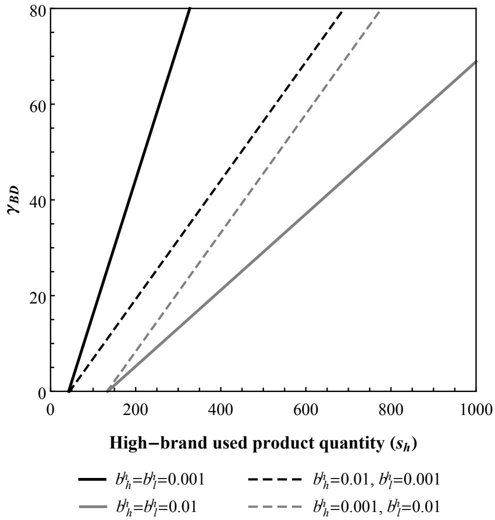
Corollary 3.1 *The following relationships hold between the thresholds γ_{BD} and γ_{CD} in Lemma 3.1 and costs and used products quantities.*

A *The thresholds γ_{BD} and γ_{CD} are constant in refurbishing costs c_h^r and c_l^n, but increasing in new product costs c_h^n and c_l^n.*

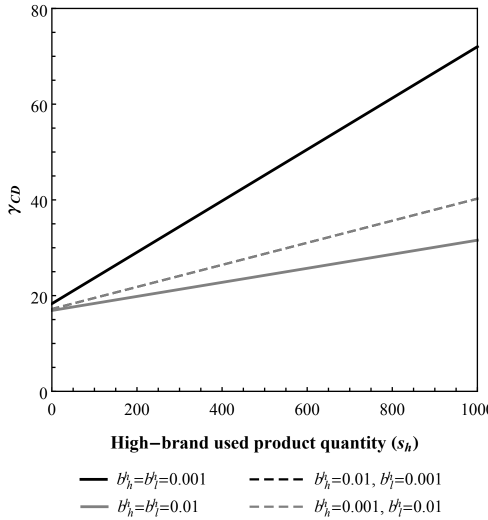
B *The thresholds γ_{BD} and γ_{CD} are increasing in both s_h and s_l, and the rate of increase is higher in s_l than in s_h.*

Corollary 3.1 gives us a relationship between the collection efforts, costs and cost savings, and the quantity of used products collected (available for refurbishing). In the broad sense, if a firm collects a large number of used products, it will require high cost savings to refurbish them all. For managers, this is very useful. If the current cost savings are higher than these thresholds, then the firm should increase its collection efforts. In particular, firm M_h will benefit more because its threshold increases slower than that of firm M_l. This will also attract more customers for the refurbished product of M_h due to the cross-cannibalization from the new product of M_l. Increased collection efforts will not have a large impact on firm M_l. When cost savings are low, firms are in the zone where it is optimal not to refurbish all collected products. In this region, the firms should focus on improving their refurbishing process to decrease the costs, rather than on used product collection.

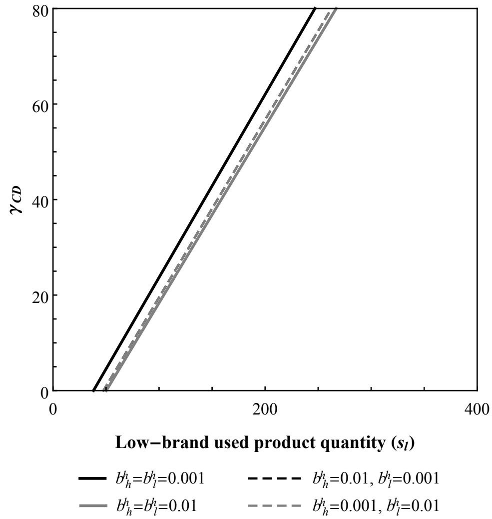
The higher the number of used products collected, the lower the firms' intention to refurbished and sell all those products. In other words, a firm with high collection rate does not need to increase the collection effort. The high-brand valued firm should invest more in collection effort than the low-brand valued firm. Such investment could be managed for instance, marketing take-back programs to increase end-of-use product return rates and building a more efficient collection system. For example, Figure 3.4 shows that if the both firms have the same saving costs, that is, $t_h = t_l = 50$, the high-brand valued firm will refurbish all used product collected whenever $s_h \leq 220$ for $b_h^h = b_l^h = .001$, $s_h \leq 448$ for $(b_h^h, b_l^h) = (.01, .001)$, $s_h \leq 536$ for $(b_h^h, b_l^h) = (.001, .01)$, and $s_h \leq 762$ for $b_h^h = b_l^h = .01$. On the other hand, the low-brand valued firm will refurbish all used product collected whenever $s_l \leq 168$ for $b_h^h = b_l^h = .001$, $s_l \leq 181$ for $(b_h^h, b_l^h) = (.01, .001)$ and $(b_h^h, b_l^h) = (.001, .01)$, and $s_l \leq 185$ for $b_h^h = b_l^h = .01$. It can also be seen that if the internal and external cannibalization levels are relatively high, the high-brand valued firm should invest to increase its collection efforts; while for the low-brand valued firm, such investment does not have a significant impact. This is because the cannibalization levels only increase the expected demand for high-brand refurbished products. In addition, the collection effort of a firm will influence its competitor. If the collection effort of a firm increases, it may decrease its competitor's intention to refurbish all used products collected. For example, if $b_h^h = b_l^h = .001$ and $s_l = 100$, the low-brand valued firm will refurbish all those 100 used products whenever $s_h \leq 590$, and does not otherwise.



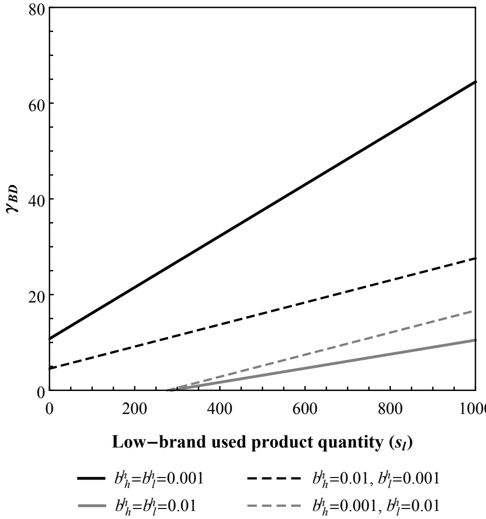
(a) $s_l = 100$



(b) $s_l = 100$



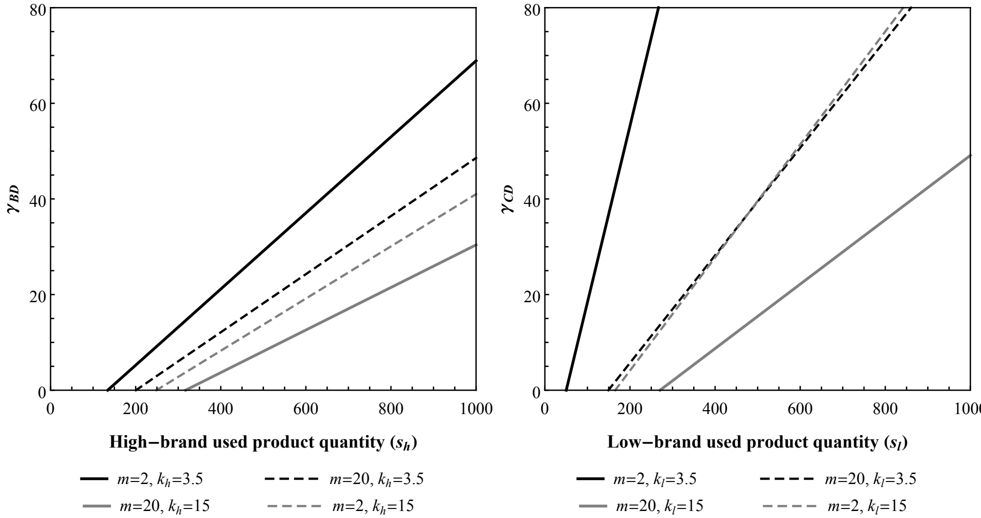
(c) $s_h = 100$



(d) $s_h = 100$

Figure 3.4: Values of γ_{BD} and γ_{CD} when M_h and M_l are alike (product demands, costs) with $p_h^n = p_l^n = 100$, $c_h^n = c_l^n = 80$, $q_h^n = q_l^n = 1000$, $k_h = k_l = 3.5$, and $m = 2$, with γ_{BD} and γ_{CD} as in Lemma 3.1

Further, Figure 3.5 shows that price competition (m) and low-end market base (k_h, k_l) have a significant impact in the firms' decision of refurbishing quantity. If the parameters' values are relatively high, the firms will likely invest in collection systems and take-back programs. The explanation for this result is that the firms tend to decrease the price when the price competition increase in order to keep their customers from switching to the competitor. Hence, it will increase the demand for refurbished products.



(a) $s_l = 100, k_l = 3.5$ *(b)* $s_h = 100, k_h = 3.5$

Figure 3.5: Values of γ_{BD} and γ_{CD} when $p_h^n = p_l^n = 100$, $c_h^n = c_l^n = 80$, and $q_h^n = q_l^n = 1000$, with γ_{BD} and γ_{CD} as in Lemma 3.1

If the firms are not competing with one another, that is, when $b_l^h = m = 0$, the problem reduced to a monopoly instead of a duopoly. In this case, each manufacturer would face internal cannibalization and does not face external cannibalization. Corollary 3.2 shows that firm M_i has a threshold γ_i, which determines whether all used products collected should be refurbished or not. Clearly, the threshold of M_i is not influenced by any parameter from the competitor.

Corollary 3.2 *Under no external cannibalization and price competition, firm M_i, $i \in \{h, l\}$ should only refurbish and sell all its used products when the cost saving t_i is sufficiently large (larger than $\gamma_i = \frac{2s_i + (r_i + k_i)c_i^n + r_i w_i^n - a_i}{r_i + k_i}$). The optimal policy is shown in Figure 3.6.*

A *When $t_i < \gamma_i$, M_i should not refurbish and sell all used products that they collect. If $t_i < \gamma_0 = \gamma_i - \frac{2s_i}{k_i + r_i}$, the firm does not make any refurbished product.*

B *When $t_i > \gamma_i$, M_i should refurbish and sell all used products that they collect.*

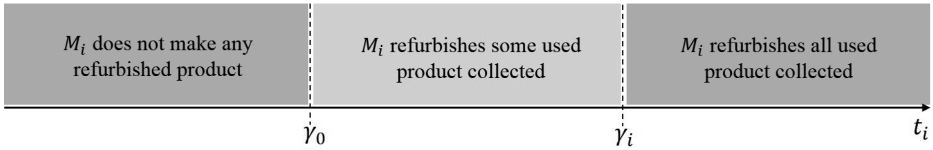


Figure 3.6: Optimal policy structure for refurbishing in monopoly, with threshold $\gamma_i, i \in \{h, l\}$ as in Corollary 3.2

In the next analysis, we assume the two firms decide to produce and sell refurbished products when they can gain benefit from the cost savings, that is, the thresholds γ_{BD} and γ_{CD} in Lemma 3.1 satisfy the following conditions: $\gamma_{BD} \le t_h \le c_h^n$ and $\gamma_{CD} \le t_l \le c_l^n$.

3.3.2 Effects of model parameters on equilibrium prices

The following proposition examines how sensitive the price is to changes in model parameters.

Proposition 3.1 *The following relationships hold between cost and demand parameters and the optimal prices of the refurbished products.*

(a) As the internal cannibalization increases, the optimal refurbished product prices also increase. The increase of p_h^{r*} in b_h^h is greater than the increase of p_l^{r*} in b_h^h.

(b) The optimal price p_h^{r*} is increasing in the external cannibalization coefficient b_l^h whenever $d_l s_h + m s_l > d_l (k_h + r_h)(p_h^n - p_l^n)$, and is decreasing otherwise. Similarly, when $m \neq 0$ the price p_l^{r*} is increasing in b_l^h whenever $d_l s_h + m s_l > d_l (k_h + r_h)(p_h^n - p_l^n)$, and is decreasing otherwise. The increase (decrease) of p_h^{r*} in b_l^h is greater than the increase (decrease) of p_l^{r*} in b_l^h.

Proposition 3.1.(a) shows that larger internal cannibalization will increase the high-brand refurbished product price. This leads to a higher refurbished product profit margin to keep the high-end customers from being cannibalized and to increase the profit from second-hand market. Proposition 3.1.(b) shows that if the two brands have the same new product price (the low-brand new product price is high), the larger low-brand external cannibalization level will always increase the high-brand refurbished product price in order to get benefit from the higher profit margin.

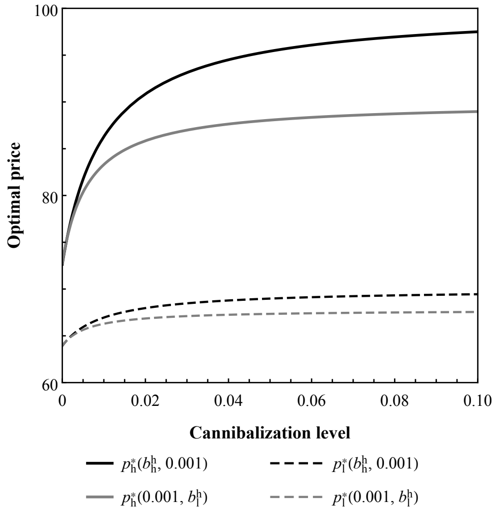
However, if the low-brand new product price is lower than its competitor and the number of refurbished products in the market is relatively low, the high-brand manufacturer sells refurbished products at high price relative to its competitor's new product price. Hence, the high-brand refurbished product price is decreasing in the external cannibalization level in order to get more high-end switching customers from its competitor. Further, we observe that with price competition ($m > 0$), the two cannibalization types have an indirect effect on the optimal price of the low-brand manufacturer. The low-brand valued firm will make a smaller increase in price in response to the price increase of the high-brand's refurbished product. This gives the low-brand manufacturer an advantage in the second-hand market replacing the profit lost from new product sales.

Proposition 3.2 *The following relationships hold between cost and demand parameters and the optimal prices of the refurbished products.*

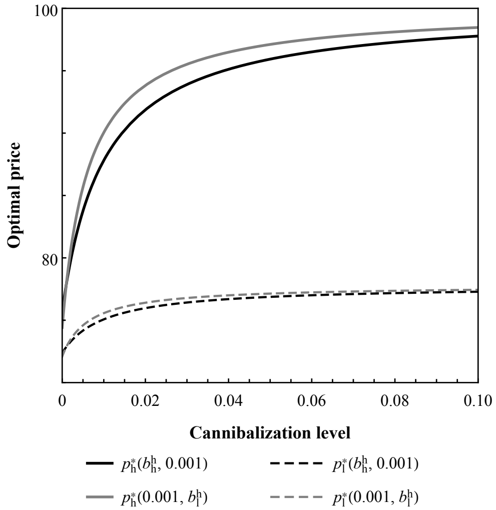
(a) If $p_l^n < p_h^n$, the sensitivity of the optimal prices p_h^{r*} and p_l^{r*} to b_h^h is higher than that to b_l^h. If $p_l^n = p_h^n$, the sensitivity of the optimal prices p_h^{r*} and p_l^{r*} to b_l^h is higher than that to b_h^h whenever $q_l^n > q_h^n$.

(b) The optimal refurbished product price p_i^{r*} is decreasing in the number of used product collected s_i, where $i \in \{h, l\}$. The decrease of p_l^{r*} in s_l is greater than the decrease of p_h^{r*} in s_h whenever $d_l \leq d_h$. When $m \neq 0$, the price p_j^{r*} is also decreasing in s_i, and the decrease of p_i^{r*} in s_i is greater than that of p_j^{r*} in s_i, where $i, j \in \{h, l\}$ and $i \neq j$.

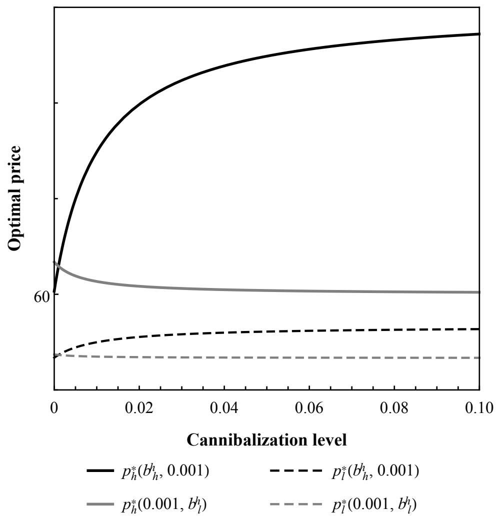
Proposition 3.2.(a) (see Figure 3.7a and 3.7b for illustration) show that if the low-brand new product price is lower than its competitor, the optimal refurbished product prices are more sensitive to the internal cannibalization than to its competitor's external cannibalization. This is because the potential number of high-end consumers who would switch from the low-brand product is relatively low and prefer to focus on the impact of the internal cannibalization. On the other hand, if the two firms have the same new product price (the low-brand new product price is high), the two internal and external cannibalization will have the same impact on the consumer switching level whenever the two firms have the same new products sales. Hence, if the low-brand new product quantity is larger than its competitor, the high-brand manufacturer should take this advantage to get more profit by increasing its refurbished product price. The different results are shown in Figure



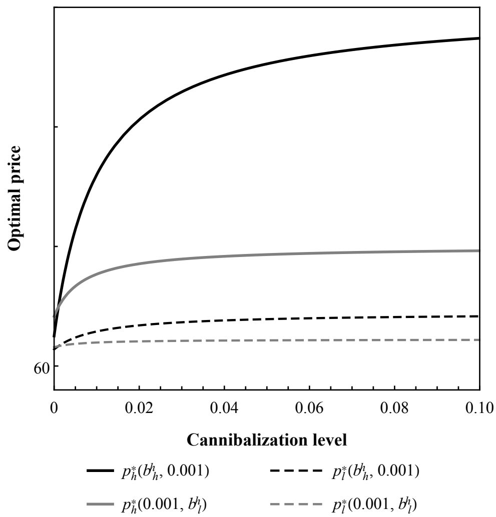
(a) C: $p_h^n = 100, p_l^n = 90$ and $c_h^n = 80, c_l^n = 70$



(b) C: $p_h^n = p_l^n = 100$ and $c_h^n = c_l^n = 80$



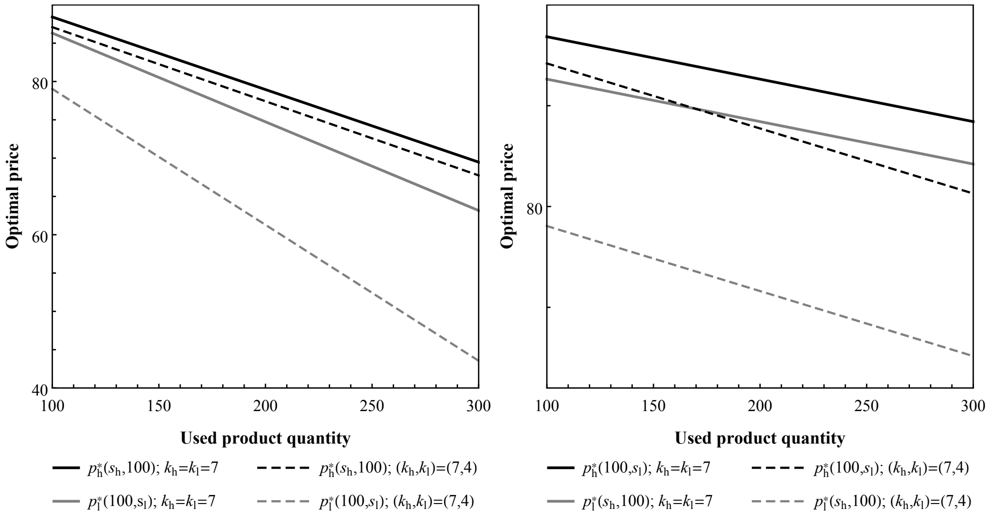
(c) UC: $p_h^n = 100, p_l^n = 90$ and $c_h^n = 80, c_l^n = 70$



(d) UC: $p_h^n = p_l^n = 100$ and $c_h^n = c_l^n = 80$

Figure 3.7: Optimal prices for M_h and M_l as a function of the cannibalization levels, b_h^h and b_l^h, for constrained (C) and unconstrained (UC) problems when $(q_h^n, q_l^n) = (1000, 1500)$, $k_h = k_l = 7$, $c_h^r = c_l^r = 30$, $m = 2$, and $s_h = s_l = 200$

3.7c and 3.7d when the firms can satisfy all demand. The high-brand manufacturer always focus on the internal cannibalization which has high impact on its total profit and just give smaller responses on the competitor's external cannibalization.



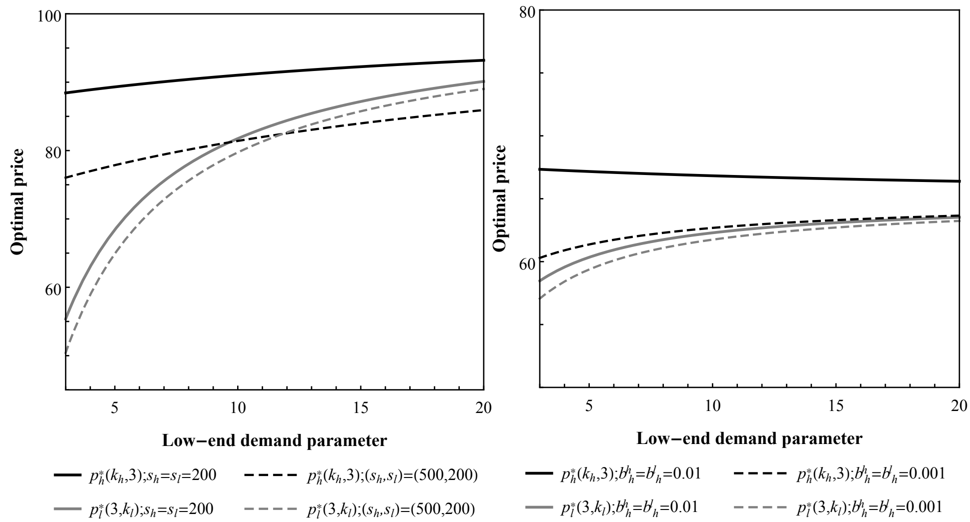
(a) $p_h^{r*}(s_h)$ and $p_l^{r*}(s_l)$ *(b)* $p_h^{r*}(s_l)$ and $p_l^{r*}(s_h)$

Figure 3.8: Optimal prices for M_h and M_l as a function of the used product quantities, s_h and s_l, when $p_h^n = p_l^n = 100$, $c_h^n = c_l^n = 80$, and $q_h^n = q_l^n = 1000$

With regard to used product collection, our analysis provides some important insights. Proposition 3.2.(b) shows that higher used product quantity leads the firms to decrease the refurbished product price in order to increase the product sales. The sensitivity of the low-brand refurbished product price to its used product quantity is higher than that of its competitor. This is because the expected demand for low-brand refurbished product is lower than that for high-brand refurbished product. Figure 3.8a illustrates the results. It can be seen from the figure that the slope of $p_l^{r*}(s_l)$ is greater than that of $p_h^{r*}(s_h)$. Moreover, we observe that due to price competition, the number of used product collected of a firm has an indirect effect on the optimal price of competitor. If used product quantity of a firm is higher, the firm will charge a lower price for the refurbished product, which in turn causes a smaller decrease in the optimal price of its competitor (see Figure 3.8b).

Proposition 3.3 *The optimal refurbished product price p_i^{r*} is increasing in low-end market base of refurbished product of brand i (i.e., parameter k_i is increasing), where $i \in \{h, l\}$. The increase of p_l^{r*} in k_l is greater than the increase of p_h^{r*} in k_h. When $m \neq 0$, the price p_i^{r*} is also increasing in k_j, and the increase of p_i^{r*} in k_i is greater than the increase of p_i^{r*} in k_j, where $i, j \in \{h, l\}$, $i \neq j$.*

The relationship between the optimal price and the low-end market base is as expected, due to the choice of our demand function. Proposition 3.3 shows that, the larger low-end demand market base leads to increase the price to get more profit margin. The low-brand valued firm can charge a low price without worries about cannibalization, whereas the high-brand valued firm sells refurbished products at a high price since the firm is afraid to cannibalize its new product's demand. Therefore, the low-brand valued firm gives more response to the changes of its low-end demand market base. Figure 3.9a illustrates this result. Further, if the firms can satisfy all their demand (see Figure 3.9b), the price of high-brand refurbished product could be decreasing in low-end demand market base when the internal cannibalization is high. This brings in some low-end customers and cannibalizes some new product demand, but it sells refurbished products at a high price.



(a) Constrained problem *(b)* Unconstrained problem

Figure 3.9: Optimal prices for M_h and M_l as a function of the low-end demand parameters, k_h and k_l, when $p_h^n = p_l^n = 100$, $c_h^n = c_l^n = 80$, $c_h^r = c_l^r = 30$, $q_h^n = q_l^n = 1000$, $m = 2$, and $b_h^h = b_l^h = .01$

3.3.3 Comparisons between the firms' equilibrium decisions

Many pricing decisions are based on costs and cost savings. In a competitive environment, a firm may charge a lower price if it costs less to refurbish their product compared to its competitor. However, it is not so straightforward as that due to the effect of cannibalization. Proposition 3.4 shows the relationship between equilibrium decisions p_h^{r*} and p_l^{r*}. The firm needs to take into account the number of used product collected s_i, the new product price $p_i^n, i = h, l$, and the potential expected demand for refurbished products. In case the two firms have the same new product price, if there are a few low-end consumers for low-brand products, i.e., parameter k_l is equal to $k_h + r_h + r_l$, the two firm will have the same price for their refurbished products when they have the same collection efforts. In this case, the low-brand manufacturer will charge a lower price when the firm increase its used product quantity or the competitor decrease its collection effort. If there are a few low-end consumers for high-brand products $\mu > 1$, the low-brand manufacturer has few possibilities to charge higher price, that is only when its used product collected is small enough such that $s_1 < s_h/\mu$. In case $p_l^n < p_h^n$, the higher the new products price difference, the higher possibilities for low-brand manufacturer to charge lower price for its refurbished products. For example, if the number of high-brand used product is relatively low ($s_h < \gamma$), the low-brand manufacturer will always charge lower price for any number of its used product collected. This is because the price of refurbished product should be lower than the new one in order to attract the low-end consumers.

Proposition 3.4 *Let $\mu = \frac{k_h + r_h + r_l}{k_l}$ and $\gamma = (k_h + r_h)\left(p_h^n - p_l^n\right)$. A high brand manufacturer will charge a higher refurbished product price than its competitor (a low brand manufacturer) if the number of used product collected s_h satisfies the condition $s_h < \mu s_l + \gamma$, and a lower price otherwise (see Figure 3.10).*

Corollary 3.3 *As the price competition m increases, the firms move in the opposite direction. When $s_h < \mu s_l + \gamma$, the high brand refurbished product price p_h^{r*} is decreasing in m, while low brand refurbished product price p_l^{r*} is increasing in m, where μ and γ are in Proposition 3.4. The sensitivity of low-brand refurbished product price to the price competition is higher than that for high-brand refurbished products. The higher the price competition, the smaller the difference between the refurbished product prices.*

Corollary 3.3 shows that higher price competition leads to aggressive pricing in the opposite direction. Given that the collection constraint is satisfied, the refurbished product prices of the firms will move closer to one another as the competition increases. The high-brand valued firm will decrease its refurbished product price

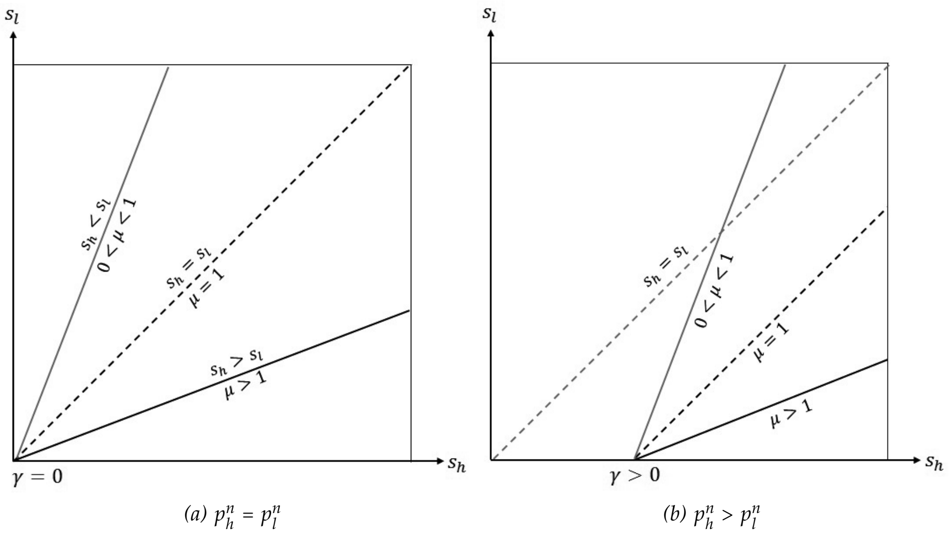
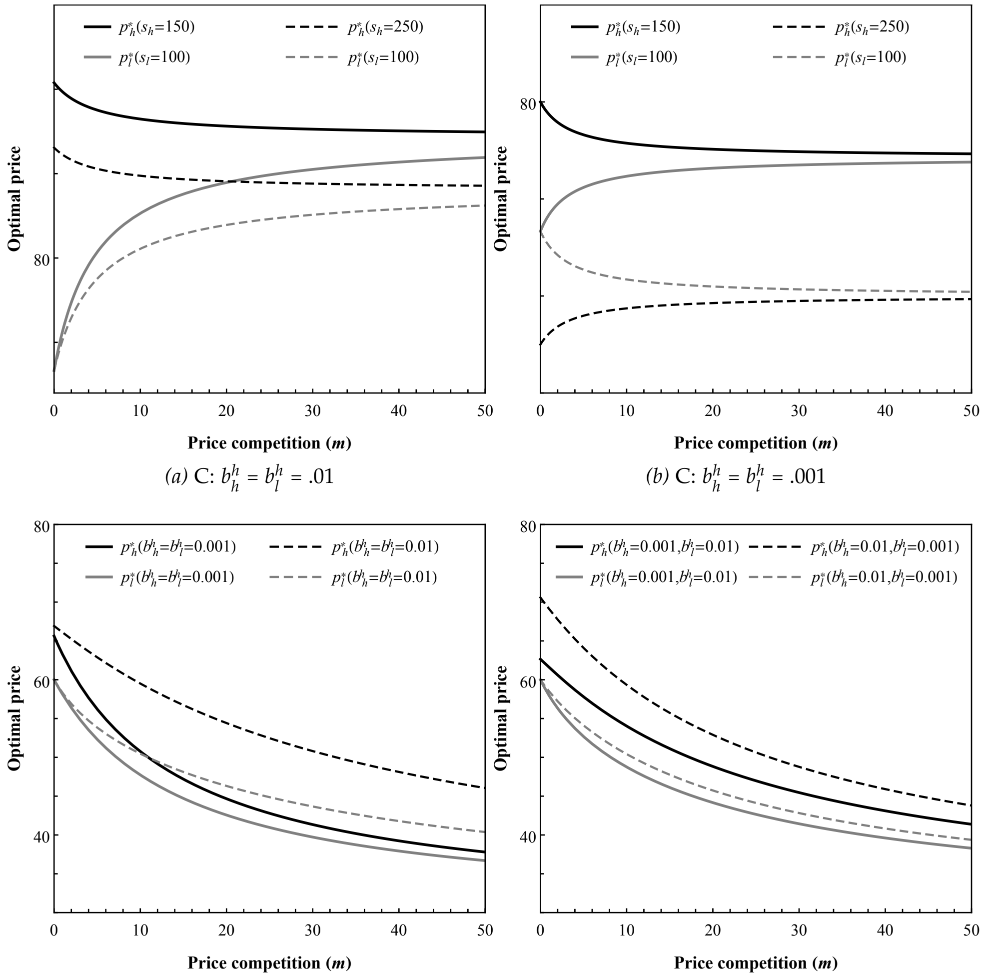


Figure 3.10: Threshold $s_h = \mu s_l + \gamma$ for price comparison for various μ and γ, with μ and γ as in Proposition 3.4

to keep its customers from switching and the low-brand valued firm will increase its price to increase its profit. This implies that when the demand from low-end customers for the low-brand valued firms' refurbished product is equal or lower than that of the high-brand valued firm, the low-brand valued firm will always charge a lower price for its refurbished product. These results are illustrated in Figure 3.11. In case the expected demand for high-brand refurbished product is high (see Figure 3.11a), $\mu = 4.333$ and $\gamma = 160$. In this case, $\gamma + \mu s_l = 593$ for $s_l = 100$. Since the threshold is relatively high, the high-brand manufacturer tend to charge the refurbished products at a higher price that its competitor. Hence, the price of high-brand (low-brand) refurbished products is decreasing (increasing) in price competition. In case the expected demand for high-brand refurbished products is low (see Figure 3.11b), $\mu = 1.333$ and $\gamma = 70$. In this case, the threshold value is low, i.e., $\gamma + \mu s_l = 203$ for $s_l = 100$. Hence, the high-brand (low-brand) refurbished product price is decreasing (increasing) in price competition only when the number of high-brand used product is lower than the threshold ($s_h = 150 < 203$). The opposite result is shown when $s_h = 250 > 203$. Further, in case the firms can satisfy all their demand (see Figure 3.11c and 3.11d), the high-brand refurbished product price is always higher than its competitor, and the optimal prices for both high-



(a) C: $b_h^h = b_l^h = .01$ *(b)* C: $b_h^h = b_l^h = .001$

(c) UC: $b_h^h = b_l^h$ *(d)* UC: $b_h^h \neq b_l^h$

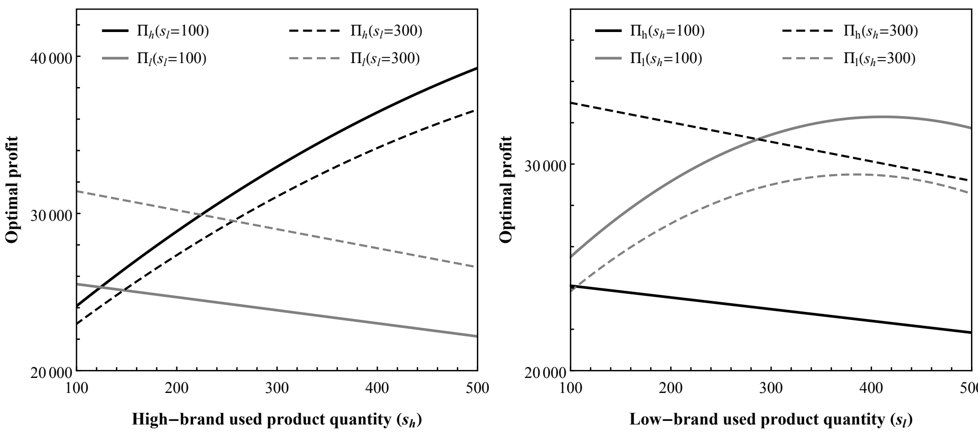
Figure 3.11: Optimal prices for M_h and M_l as a function of the price competition, m, for constrained problem (C) and unconstrained problem (UC) when $p_h^n = 100$, $p_l^n = 90$, $c_h^n = 80$, $c_l^n = 70$, $q_h^n = q_l^n = 1000$, and $k_h = k_l = 6$

brand and low-brand refurbished products are decreasing in price competition. This is because the prices difference between the two refurbished products is relatively small even when the price competition is low and the low-brand valued firm always keep the refurbished product price smaller than its competitor.

3.3.4 Effects of model parameters on equilibrium profits

Proposition 3.5 *Let* $\gamma_h^s = \frac{d_l(r_h w_h^n + s_h)}{d_h d_l - m^2}$ *and* $\gamma_l^s = \frac{d_h s_l + m r_l w_l^n}{d_h d_l - m^2}$. *The profit of firm* M_i *is decreasing in used product quantity* s_i *when the threshold* γ_i^s *is higher than the refurbished product profit margin* ($w_i^r = p_i^r - c_i^r$)*, i.e.,* $w_i^r < \gamma_i^s$*, and it is increasing otherwise, where* $i \in \{h, l\}$*. The profit of firm* M_i *is always decreasing in* s_j*, where* $i, j \in \{h, l\}$ *and* $i \neq j$*.*

Having more refurbished products to sell will increase profits for both firms. However, this increase is concave in nature and the maximum is achieved at the thresholds γ_i^s, $i \in \{h, l\}$. Thus, the firms need to stop their collection efforts whenever they surpass these thresholds. In general, the low-brand valued firm makes a lower profit than the high-brand valued firm (even with the same refurbishing costs, their profit margins are lower because the refurbished price is lower). However, it is possible for the low-brand valued firm to have a higher profit than its competitor if it manages its collection efforts efficiently.

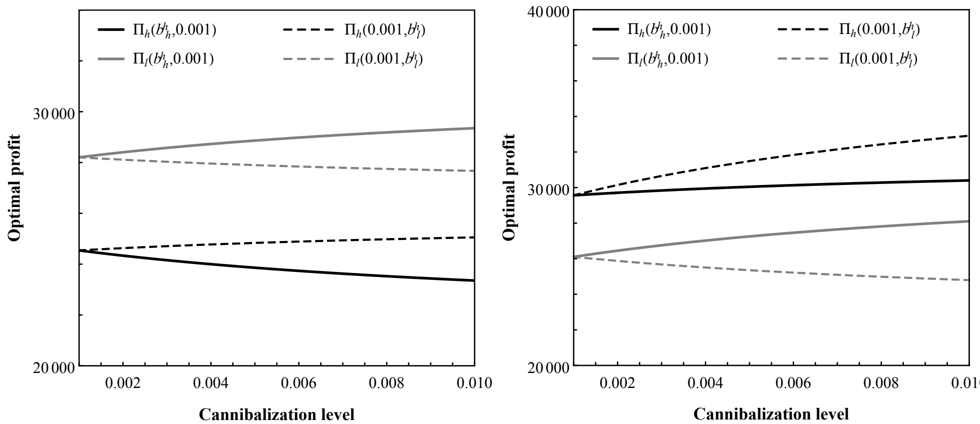


(a) Changes in s_h *(b)* Changes in s_l

Figure 3.12: Optimal profits for M_h and M_l as a function of the used product quantities, s_h and s_l, when $(p_h^n, p_l^n) = (100, 90)$, $(c_h^n, c_l^n) = (80, 70)$, $q_h^n = q_l^n = 1000$, $k_h = k_l = 7$, $m = 10$, and $b_h^h = b_l^h = .01$

Proposition 3.5 shows that higher used product quantity increase the profit of the related firm when the profit margin of refurbished product is sufficiently high. However, it will decrease the profit of the competitor. Figure 3.12a shows that the profit of high-brand manufacturer is increasing in its used product quantity in the range $100 \le s_h \le 500$. For a certain number of low-brand used product, the profit of high-brand manufacturer will surpass its competitor when its used product quantity is greater than a certain number. On the other hand, Figure 3.12b shows that the low-brand manufacturer's profit is increasing in its used product quantity until some number, and then it starts decreasing. This is because the potential market of low-brand refurbished product is lower than its competitor. Hence, taking excessive collection efforts could be not profitable for the firm. Moreover, if the number of high-brand used product is relatively high, the profit of low-brand manufacturer will always be lower than its competitor no matter how many used products it collects. However, if the number of high-brand used product is low, the low-brand valued firm has an opportunity to surpass the profit of its competitor.

Proposition 3.6 *Let* $\mu_h^h = \frac{(d_l(k_h+r_l)+k_l m)(p_h^n - c_h^n)}{d_l}$ *and* $\mu_l^h = \frac{(d_l(k_h+r_h)+k_l m)(p_l^n - c_l^n)}{m}$. *The optimal profit of firm* M_h *is increasing in internal cannibalization coefficient* b_h^h *whenever* $s_h > \mu_h^h$ *and is always increasing in external cannibalization coefficient of low brand product* b_l^h. *The profit of firm* M_l *is decreasing in* b_l^h *whenever* $s_l < \mu_l^h$ *and is increasing in* b_h^h.



(a) $s_h = 100, s_l = 200$ *(b)* $s_h = 300, s_l = 200$

Figure 3.13: Optimal profits for M_h and M_l as a function of the cannibalization levels, b_h^h and b_l^h, when $(p_h^n, p_l^n) = (100, 90)$, $(c_h^n, c_l^n) = (80, 70)$, $q_h^n = q_l^n = 1000$, $k_h = k_l = 7$, and $m = 10$

Proposition 3.6 shows that higher internal cannibalization leads to increase the profit of high-brand valued firm whenever its used product quantity is relatively high such that the firm advantage in the second-hand market replacing the profit lost from new product sales. Figure 3.13 shows that if the firm does not have enough refurbished products to be sold while the internal cannibalization is high, the profit lost from new product sales would be greater than the profit from second-hand market. Moreover, the high external cannibalization level always be profitable for the high-brand manufacturer. On the other hand, the low-brand valued firm always takes advantage of internal cannibalization since it could increase the potential market of refurbished products, which could be attracted through pricing strategy. Using the same strategy, high external cannibalization could also be profitable for the low-brand manufacturer if there are enough refurbished product could be used to replace the profit lost from new product sales. For example, with the given parameters values, the thresholds are $\mu_h^h = 242$ and $\mu_l^h = 412$. It can be seen from Figure 3.13 that the profit of high-brand valued firm is decreasing (increasing) in internal cannibalization level whenever $s_h = 100 < 242$ ($s_h = 300 > 242$). Moreover, since $s_l = 200 < 412$, the profit of low-brand valued firm is decreasing in external cannibalization level.

Proposition 3.7 *Let μ and γ in Proposition 3.4 and $\beta = \frac{r_l w_l^n}{\mu}$. The effects of price competition on equilibrium profits for the firm depends on thresholds μ, γ and β, and the used product quantity s_i from its own production and that of its competitor. These policies are shown in Figure 3.14.*

A If $s_l < \beta$ and $s_h < \mu s_l + \gamma$, profits of both M_h and M_l are decreasing in m.

B If $s_l < \beta$ and $s_h > \mu s_l + \gamma$, profits of both M_h and M_l are increasing in m.

C If $s_l > \beta$ and $s_h < \mu s_l + \gamma$, profit of M_h is decreasing in m, while profit of M_l is increasing in m.

D If $s_l > \beta$ and $s_h > \mu s_l + \gamma$, profit of M_h is increasing in m, while profit of M_l is decreasing in m.

Proposition 3.7 shows that at a certain condition, the increase of price competition m could be profitable for either high- or low-brand valued firm. It can be seen that the higher price competition leads to increase the profit of high-brand manufacturer when the firm has enough refurbished products such that the refurbished product price is lower than its competitor, i.e., $s_h > \mu s_l + \gamma$. On the other hand, having lower price than its competitor, i.e., when $s_h < \mu s_l + \gamma$, is not enough for the low-brand

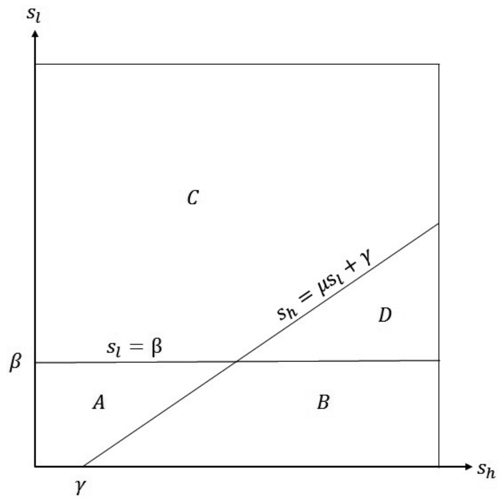
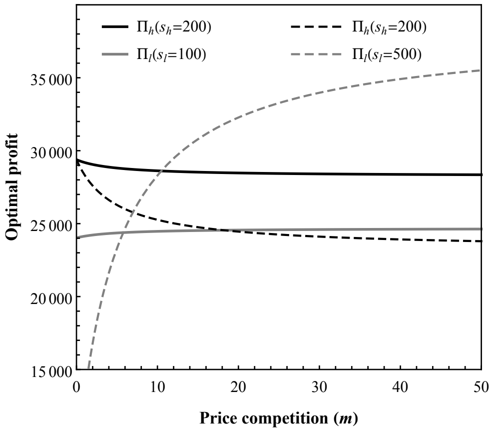


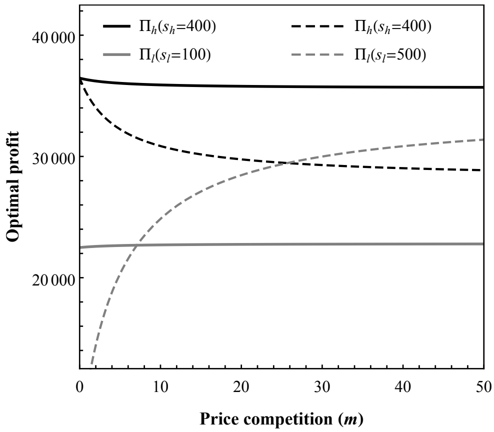
Figure 3.14: Effect of price competition on equilibrium profits, with γ, μ, and β as in Proposition 3.7

manufacturer to get benefit from price competition. The firm also needs to have enough used product quantity ($s_l > \beta$) to satisfy the low-end customers switching from its competitor.

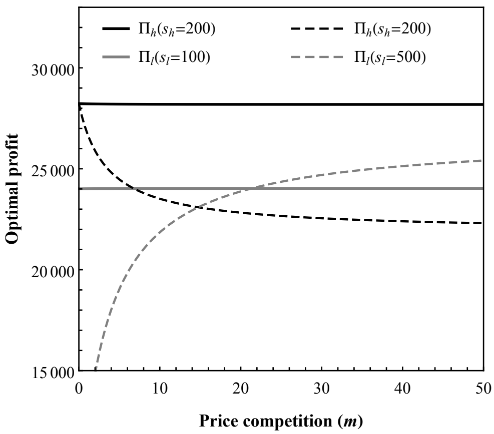
Figure 3.15 illustrates the effects of price competition on the equilibrium profits. In case the expected demand for high-brand refurbished products is relatively high (see Figure 3.15a and 3.15b), we have $\mu = 4.333, \gamma = 160$, and $\beta = 46.154$, where $\gamma + \mu s_l = 593$ and 2326 for $s_l = 100$ and 500, respectively. The threshold values $\gamma + \mu s_l$ are higher than the number of high-brand refurbished products ($s_h = 200$ and 400). Hence, the profit of high-brand valued firm is most likely decreasing in price competition. However, the firm can still gain more profit by increasing its collection effort, especially when the low-brand valued firm only have few number of refurbished products or price competition is low. In this case, the low-brand manufacturer cannot attract more low-end consumers from the competitor due to the limited number of refurbished products or the low-end consumers is more sensitive to brand than to price. On the other hand, the number of low-brand used products ($s_l = 100$ and 500) is higher than β. Hence, the higher the price competition, the higher the profit of low-brand manufacturer. Further, since the expected demand for the high-brand refurbished products is high, the low-brand manufacturer should see both the competitor's collection effort and the price



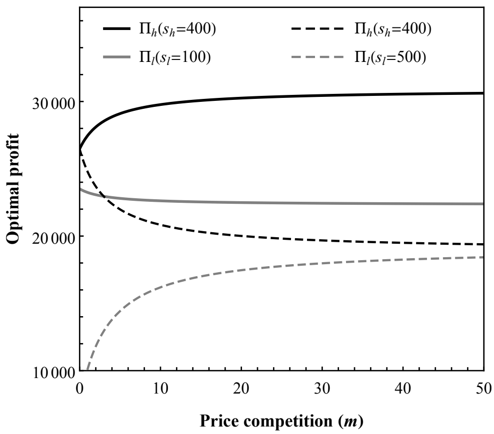
(a) $b_h^h = b_l^h = 0.01, s_h = 200$



(b) $b_h^h = b_l^h = 0.01, s_h = 400$



(c) $b_h^h = b_l^h = 0.001, s_h = 200$



(d) $b_h^h = b_l^h = 0.001, s_h = 400$

Figure 3.15: Average profits for M_h and M_l as a function of the price competition, m, when $(p_h^n, p_l^n) = (100, 90)$, $(c_h^n, c_l^n) = (80, 70)$, $q_h^n = q_l^n = 1000$, $c_h^r = c_l^r = 30$, and $k_h = k_l = 6$

competition. For example, if the high-brand manufacturer has more refurbished products sold in the market ($s_h = 400$) and price competition is relatively low ($m \leq 8$), it would be more profitable for the low-brand valued firm to not invest much in collection, i.e., take $s_l = 100$ instead of $s_l = 500$. Otherwise, if the price competition is relatively high ($m > 8$), the low-brand manufacturer should produce and sell more refurbished products, i.e., take $s_l = 500$, in order to increase its profit by attracting some competitor's low-end consumers. In this case, the profit of low-brand manufacturer could be higher than its competitor for some price competition values. In case the expected demand for the high-brand refurbished products is relatively low (see Figure 3.15c and 3.15d), we have $\mu = 1.333$, $\gamma = 70$, and $\beta = 15$, where $\gamma + \mu s_l = 203$ and 736 for $s_l = 100$ and 500, respectively. Therefore, the profit of high-brand valued firm is increasing in price competition when $s_h = 400$ and $s_l = 100$. In this case, $s_h > \gamma + \mu s_l$.

3.4. Conclusion

Refurbishing has shown good economic potential, but firms remain wary due to the (within-firm) cannibalization effect on new product sales. The presence of competitors selling both the new product and its refurbished version adds an additional (cross-firm) dimension to this effect. Moreover, competitors may have similar brand strength or may be positioned differently in the market. Further, in practice, such firms are increasingly confronted by collection constraints, such as those imposed by national or supranational regulations. In this chapter, we shed light onto how such firms would need to make their strategic choices.

Our analytical results show that manufacturers with a strong brand should increase the prices of their refurbished products if the cross-cannibalization coefficients of the low-brand consumers are higher. For low-brand firms, competing on price is challenging; instead, such firms should focus on beating the high-brand competitors in collection and refurbishing efforts. Finally, we show that the collection constraints have an effect on the pricing strategy of both the high-brand and the low-brand manufacturers. As a consequence, such constraints that are typically set exogenously by public authorities will impact the actual pricing and market equilibria.

All in all, our study contributes to a richer understanding of the economics, pricing, and strategic behavior of firms offering refurbished products. As refurbishing is becoming more commonplace in more and more industries, our results can inform managers and public policy decisions makers about the right path to follow.

4

Authorization Strategy in Refurbishing with Consumer Behavior

4.1. Introduction

Although refurbishing has great economic potential, not all OEMs choose to refurbish their products. According to Ferguson and Toktay (2006), cost and internal cannibalization are the two main reasons some OEMs do not refurbish. For them, refurbishing costs, including cost of collecting used products, are too high. Some OEMs that are capable of refurbishing used products worry about the cannibalization threat to the sales of their new products (Guide and Li, 2010; Agrawal et al., 2016). The firms assume cannibalization will occur, because refurbished product versions are sold at lower prices than new products. In an empirical study, Agrawal et al. (2015b) note that the presence of OEM-refurbished products has a negative impact on the perceived value of new products. Consequently, refurbishing sectors have been dominated by third party (3P) refurbishing firms that offer refurbished versions of new products from OEMs (Ferguson, 2010). Hauser and Lund (2008) determine that 94% of approximately $2,000$ refurbishing firms are third parties, usually small to medium in size, with revenue expectations ranging from \$500,000 to \$5,000,000. According to Liu et al.

(2018), OEMs cannot control the existence of 3Ps, especially those that sell electrical and electronic products. Third party-refurbished products cannibalize OEMs' new products, resulting in competition between refurbished and new products (Atasu et al., 2008b; Agrawal et al., 2015b; Liu et al., 2018). However, from OEMs' perspective, the presence of 3Ps may be preferable to adding refurbishing to their own business models, because it may increase the perceived value of new products (Agrawal et al., 2015b).

With the rapid growth of refurbished products in the secondary market, it may be ideal for OEMs to cooperate with 3Ps (Yan et al., 2015; Xiong et al., 2016; Liu et al., 2018; Ma et al., 2018). Some OEMs have adopted refurbishing-authorization scenarios as forms of cooperation. In such scenarios, third-parties obtain proprietary rights from OEMs to refurbish used products and remarket them using OEM-authorized signage, without the participation of the OEMs (Zou et al., 2016). For instance, Cat Reman remanufactures for multiple OEMs from several industries, such as Perkins and Alcoa (industrial), Ford (automotive), and Honeywell (components) (Caterpilar, 2019). Telrepco, Mooringtech, and Rugged Notebooks are among the authorized service centers that sell refurbished Panasonic Toughbook laptops (Telrepco, 2019; Tech, 2019; Notebooks, 2019). However, many other third parties refurbish used products and market them without authorization from manufacturers, labeling them as "seller refurbished" and listing them on eBay; according to eBay, a "seller refurbished" item is one that has been restored to working order by the seller or a third party that is not authorized by an OEM (eBay, 2019).

From the perspective of OEMs, the entry of unauthorized 3Ps is problematic; it risks cannibalization from underpricing and reputation degradation from low quality. Accordingly, some OEMs try to eliminate or minimize these impacts. For example, Apple recently established an agreement with Amazon to allow listings of Apple's product line on Amazon's online store (Business, 2018; Check, 2018), such that any Apple products obtained directly from Apple or its authorized third parties (A3Ps) can be sold and shipped by Amazon. In return, Amazon agrees to remove from its sits all unauthorized third parties (U3Ps) that sell new or refurbished Apple products. To sell refurbished Apple products in the Amazon online store, firms must apply to become authorized Apple third parties, agree to meet certainty requirements (e.g., assurance of product quality), and pay fees to Apple. Although

U3Ps can continue to sell their refurbished products on other platforms such as or on their own sites, the Apple-Amazon agreement may decrease their product acceptance and sales volumes significantly, considering that Amazon still ranks first in terms of popularity, revenue, valuation metrics from investors, and seller ratings from customers (Investopedia, 2018).

These examples suggest an authorization strategy provides OEMs with an advantage in maintaining the positive market reputations of their brands and enlarging their market share. Cooperation scenarios allow OEMs to inspect and review their A3Ps to ensure they meet OEM standards. For example, through its product recycling program, Lenovo strongly encourages A3Ps to achieve recycling standards, including Responsible Recycling (R2) and e-Stewards, and to meet other environmental, safety, health, business control, and security standards (Lenovo, 2019). Apple typically audits and reviews its A3Ps to ensure they meet Apple's standards with regard to service levels, certification of technicians, and availability of service to customers (Apple, 2019).

The authorization strategy also allows OEMs to increase their revenues from authorization fees and royalties. For 3Ps, cooperating with OEMs through authorization scenarios can increase their sales volumes and improve consumer acceptance of refurbished products. Authorized third party status enhances firm reputations and gives customers confidence. In terms of refurbished Apple products, Apple authorized 3Ps are allowed to sell their products in online megastores such as Amazon. Moreover, authorization scenarios may decrease refurbishing costs as a result of technical support provided by OEMs. For example, Apple gives its A3Ps access to comprehensive product, service, repair, troubleshooting, take-apart, upgrading, and technical support (Apple, 2019).

However, an authorization strategy also may be risky for OEMs. Because it leads to an increase in customers' perceptions of the quality of authorized refurbished products, it may cause cannibalization. For customer, buying authorized refurbished products is a way to find reliable products at bargain prices. The risks could be greatest for OEMs that have premium name brand, because customers may prefer to have good-quality refurbished products from name brands that are available lower prices and have the same warranty periods as new versions. Although authorization scenarios seem to benefit 3Ps, the parties may not accept the authorization contracts offered by OEMs. In most cases, the 3Ps are concerned about the costs of new developments related to contracts, certification, inspection, and royalty fees (Oraiopoulos et al., 2012; Zou et al., 2016; Liu et al., 2018).

Much literature on refurbishing addresses the competition between OEMs and 3Ps. Majumder and Groenevelt (2001) were the first to propose a model to investigate the interactions between OEMs and 3Ps. According to prior literature, OEMs compete with 3Ps, the existence of refurbished products influences OEM decisions, and consumer behavior affects OEM and 3P decisions. But no studies address how these effects manifest, especially with regard to refurbished products' influence on price, quantity, and refurbishing authorization. Because consumers' behaviors toward new and refurbished products differ, due to varying perceptions of product quality, it is important to consider consumer behavior when solving the pricing problem, which directly affects demand for refurbished products. Most research assumes that willingness to pay (WTP) drives consumer behavior, such that demand for refurbished products decreases as prices of products increase. In Chapter 2, in a study of consumer behavior related to refurbished products though, we identify an inverted U-shaped switching function, such that consumers appear to doubt the quality of refurbished products that are discounted excessively.

Some recent operations management studies note technology licensing or authorization related to refurbishing. Oraiopoulos et al. (2012) propose a model in which OEMs charge relicensing fees to consumers who purchase their refurbished products. Zou et al. (2016) compare outsourcing with authorization, and Hong et al. (2017) compare royalty licensing and fixed-fee licensing in the refurbishing mode. Both papers assume that relicensing/authorization is mandatory for 3Ps and that 3Ps cannot engage in refurbishing products without a license to refurbish. Huang and Wang (2017) consider information sharing in technology-licensed refurbishing scenarios. Liu et al. (2018) study the conditions in which it is optimal for OEMs to use the authorization strategy; however, they do not consider real-market consumer behavior and used-product availability. Our study addresses these gaps and thereby addresses our central research question: How do these factors affect 3Ps' decision making, including whether to participate in authorizations offered by OEMs? To the best our knowledge, our research is the first to seek an answer.

4.2. Model

We consider a supply chain that consists of two members, a manufacturer (OEM) that produces a new product with a cost c_n per unit and a 3P that collects and refurbishes used products with a cost c_r per unit. The unit production cost of all refurbished products is the same and lower than the unit production cost of the new product $c_r < c_n$. We assume the new product's price p_n is fixed, as we discussed in Chapter 1. In our model, the 3P needs to choose whether to accept the authorization program offered by the OEM, and the OEM needs to determine the authorization fee and whether to authorize the 3P. In the first stage, the OEM sets an authorization fee. In the second stage, the 3P decides on price of refurbished product, and whether to accept the authorization. Thus, for the authorization problem, the 3P has two choices: to be authorized or to remain unauthorized. We discuss the acceptable authorization fee for both the OEM and the 3P. The 3P is willing to accept authorization whenever its profit increases after being authorized. Likewise, the OEM is willing to authorize the 3P if the authorization strategy benefits the OEM. We summarize the notations used in this chapter in Table 4.1. Let superscripts "U" and "A" denote the unauthorized and authorized refurbishing scenarios, respectively.

The market is divided into two segments: high end and low end. Customers at the high end are willing to purchase new products, whereas customers at the low end purchase only refurbished products at lower prices. In the absence of refurbished products, the demand for new products (i.e., high-end demand) is Q_n. In the presence of the refurbished product market, a fraction $\alpha^U(p_r^U) \in [0,1]$ of customers at the high end switch to refurbished products - if they are available. By offering a refurbished product at price p_r^U, a 3P also attracts $k^U(p_n - p_r^U)$ low-end customers who will not purchase new products. The numbers of consumers who purchase new and refurbished products for unauthorized scenario are as follows:

$$q_n^U = Q_n(1 - \alpha^U(p_r^U)), \tag{4.1}$$

$$q_r^U = k^U(p_n - p_r) + \alpha^U(p_r^U)Q_n. \tag{4.2}$$

We study the impact of consumer behavior on the refurbishing authorization strategy. According to Oraiopoulos et al. (2012) and Souza (2013), some manufacturers

Table 4.1: Notation and associated description

Symbol	Description
$M_o(M_t)$	OEM (3P)
p_n	Price of new product
p_r^j	Price of refurbished product for scenario j, where $j \in \{U, A\}$
p_r^m	Price-perceived quality threshold, i.e., the price of refurbished products such that the fraction of customers switching reach a maximum level
c_n	Unit manufacturing cost of a new product
w_n	Unit margin of new product, where $w_n = p_n - c_n$
c_r^j	Unit refurbishing cost a refurbished product for scenario j, where $j \in \{U, A\}$
g	Authorization fee
c_g^A	Marginal refurbishing cost of 3P after being authorized, where $c_g^A = c_r^A + g$
Q_n	Demand for new products when there is no refurbished unit available
$q_n^j(q_r^j)$	Number of consumers purchasing new (refurbished) product for scenario j, where $j \in \{U, A\}$
α^j	Fraction of high-end customers who switch to purchase refurbished product for scenario j, where $j \in \{U, A\}$
δ	Fraction of the cores available to the third party
k^j	price elasticity on market demand of low-end customers for scenario j, where $j \in \{U, A\}$
b^j	Cannibalization coefficient for scenario j, where $j \in \{U, A\}$ and $b^A = b^U + \tau_b$
τ_c	Average reduction of refurbishing cost, where $\tau_c = c_r^U - c_r^A$
τ_k	Average increment of price elasticity on low-end market demand, where $\tau_k = k^A - k^U$
τ_b	Average increase of cannibalization coefficient, where $\tau_b = b^A - b^U$
$\Pi_o^j(\Pi_t^j)$	Profit function of the OEM (3P) for scenario j, where $j \in \{U, A\}$
Symbols used for simplification of expressions:	
r^j	cannibalization elasticity for scenario j, where $j \in \{U, A\}$, $r^U = b^U Q_n$ and $r^A = b^A Q_n$
d^j	Composite effect of the refurbished product's price in price-sensitive area $(p_r^m, p_n]$ for scenario j, where $j \in \{U, A\}$, $d^U = k^U + r^U$ and $d^A = k^A + r^A$
d_u^j	Composite effect of the refurbished product's price in quality-sensitive area $(0, p_r^m]$ for scenario j, where $j \in \{U, A\}$, $d_u^U = k^U - \rho r^U$, $d_u^A = k^A - \rho r^A$ and $\rho = (p_n - p_r^m)/p_r^m$

conduct refurbishing by themselves, and others decide not to participate directly in the secondary market. In our model, we consider only the scenario in which a manufacturer does not participate directly in the secondary market and instead enters the market by authorizing a 3P. In such a business model, the manufacturer focuses on new products but also fulfills its environmental responsibility and obtains shared profits from the secondary market. For example, Hewlett-Packard and IBM already receive many benefits from the secondary market by charging authorization fees, and Huawei collaborates with a 3P, Aihuishou, to collect, refurbish, and sell its used products (Ding et al., 2018). We consider a case in which the 3P does not produce its own products but instead collects and refurbishes used products of the manufacturer. In the refurbishing authorization program, the manufacturer sets the authorization fee. The manufacturer can set the fee as high as necessary, so it is costless. The 3P chooses whether to take the authorization. In the unauthorized scenario, the profit of OEM is formulated as:

$$\Pi_o^U = (p_n - c_n)q_n^U, \tag{4.3}$$

with q_n^U as defined in Equation 4.1, and the optimization problem for the U3P is:

$$\begin{aligned} &\max_{p_r^U} \Pi_t^U(p_r^U) = (p_r^U - c_r^U)q_r^U \\ &\text{s.t.} \quad 0 \le q_r^U \le \delta q_n^U, \end{aligned} \tag{4.4}$$

with q_r^U as defined in Equation 4.2, and the 3P has access to 100δ percent of the cores for collection. We also assume that collection cost is linear in the quantity collected and is included in c_r^U (see Ferrer and Swaminathan (2006) and Atasu et al. (2008b)).

In the authorized scenario, the 3P can refurbish products at a lower cost because of the technical support provided by the OEM. Also, because the authorized refurbished product is of higher quality than the unauthorized product, customers have more trust in the A3P. Therefore, the authorization program can increase customers' acceptance and improve the attractiveness of the refurbished product (Erdem et al., 2002; Subramanian and Subramanyam, 2012; Hamzaoui-Essoussi and Linton, 2014; Abbey et al., 2015b). The A3P also can expand its market by putting its products into marketplaces such as Amazon to increase the product's visibility. The mid–low-end market for new smartphones is being cannibalized by refurbished high-end smartphones. In our study setting, the program can increase the cannibalization level of customers at the high end and increase the market base of customers at the low end. Let $\alpha^A(p_r^A)$ be the new fraction of customers who switch after the 3P chooses the authorization scenario. The numbers of consumers who purchase new and refurbished products for authorized scenario are as follows:

$$q_n^A = Q_n(1 - \alpha^A(p_r^A)), \tag{4.5}$$

$$q_r^A = k^A(p_n - p_r^A) + \alpha^A(p_r^A)Q_n, \tag{4.6}$$

where $k^A = k^U + \tau_k$ is the price elasticity on low-end market demand in the authorization scenario for some constant $\tau_k \geq 0$. We assume the 3P pays the OEM an authorization fee g for each unit refurbished product, according to a royalty licensing contract. Since the fraction of high-end customers switching after the 3P being authorized is higher than that before the firm take the authorization program, the OEM always set $g \geq 0$. In this case, the total marginal refurbishing cost of the 3P is $c_g^A = c_r^A + g$, where $c_r^A = c_r^U - \tau_c$ is the refurbishing cost in the authorization scenario for some constant $\tau_c \geq 0$. The profit of OEM is as follows:

$$\Pi_o^A = (p_n - c_n)q_n^A + gq_r^A, \tag{4.7}$$

with q_n^A as defined in Equation 4.5, and the optimization problem for the A3P is:

$$\max_{p_r^A} \Pi_t^A(p_r^A) = (p_r^A - c_g^A)q_r^A \tag{4.8}$$
$$\text{s.t.} \quad 0 \leq q_r^A \leq \delta q_n^A,$$

with q_r^A as defined in Equation 4.6.

4.3. Refurbishing Authorization Strategy

Building on our experimental results in Chapter 2, we assume that the fraction of customers switching from new to refurbished products could be either linear or inverted U in shape. In the U-shaped switching function, the switching fraction increases with discount up to a certain point, and then decreases, because customers become suspicious of the product quality when the price is too low.

$$\alpha^U(p_r^U) = \begin{cases} b^U p_r^U (p_n - p_r^m)/p_r^m, & 0 < p_r^U \leq p_r^m, \\ b^U(p_n - p_r^U), & p_r^m \leq p_r^U \leq p_n. \end{cases} \tag{4.9}$$

Equation 4.9 formulates the switching function for coefficient b^U, where p_r^m is the price-perceived quality threshold. It is the price of refurbished products, such that the fraction of customers switching reaches a maximum value. We can represent both the linear and inverted U-shaped switching functions using this equation, by changing the value of p_r^m.

Figure 4.1 shows the increase in the cannibalization fraction that results from the

the authorization of the 3P, represented by τ_b, where $b^A = b^U + \tau_b$. The switching function for authorized scenario is formulated in Equation 4.10. For both high- and low-end brands, the fraction of switching customers always increases if the 3P is an authorized refurbisher. However, in line with our experimental results, the price–perceived quality threshold does not change with or without authorization.

$$\alpha^A(p_r^A) = \begin{cases} b^A p_r^A (p_n - p_r^m)/p_r^m, & 0 < p_r^A \le p_r^m, \\ b^A(p_n - p_r^A), & p_r^m \le p_r^A \le p_n. \end{cases} \tag{4.10}$$

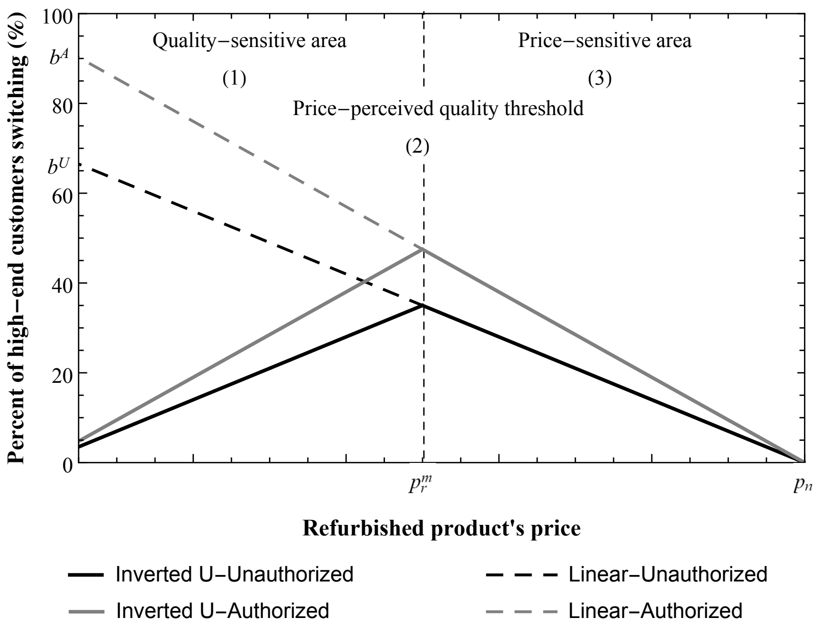


Figure 4.1: Relationship between refurbished product's price and percent of high-end customers switching for unauthorized and authorized scenarios

4.3.1 Unconstrained remanufacturable product supply

We start our analysis with unconstrained remanufacturable product supply throughout the product life cycle. The 3P can collect enough used products to satisfy refurbished product demand. In reality, households keep huge amounts of used products. Saphores et al. (2009) conducted a national survey of U.S. households and found that on average, each household had 4.1 small and 2.4 large electronic waste (e-waste) items in storage, more than estimates by the United States Environmental Protection Agency (US EPA), suggesting that the backlog of e-waste in the United States is larger than generally believed. Sabbaghi et al. (2015) observe that compared with household consumers, commercial consumers have more stored computers, regardless of brand and capacity factors. Sabbaghi et al. (2016) point out that it is empirically proven that consumers tend to store their unwanted electronic devices after the last time of usage. According to the US EPA, e-waste has increased by 120% in the past decade, and only 25% of it is collected for recycling or reuse (PMR, 2017). Therefore, the volume of used products that could be collected is huge.

In the basic model, there is no refurbishing authorization, or there is an authorization program that the 3P does not accept. The model consists of one OEM selling new products and one U3P selling refurbished products. In this unauthorized scenario, the 3P needs to solve Problem 4.4. Under an authorization strategy, the 3P needs to solve Problem 4.8. The third party will pay a royalty fee to the OEM to participate in the authorization program.

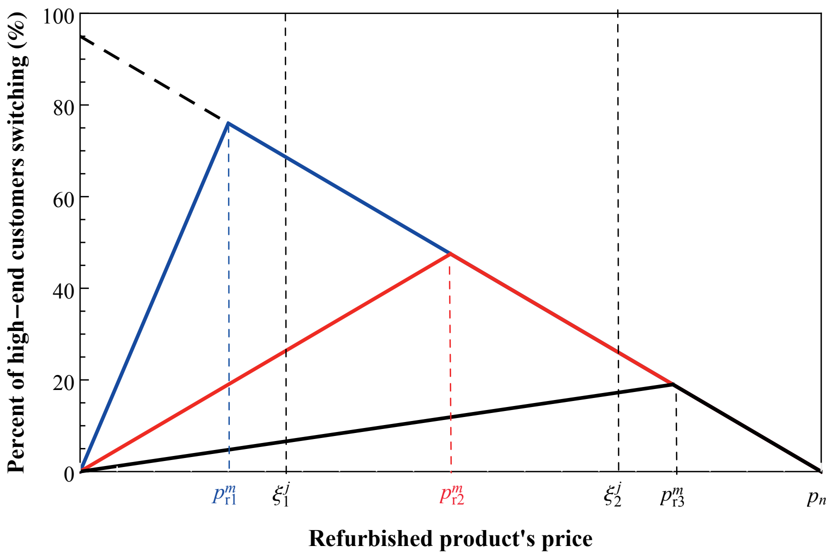
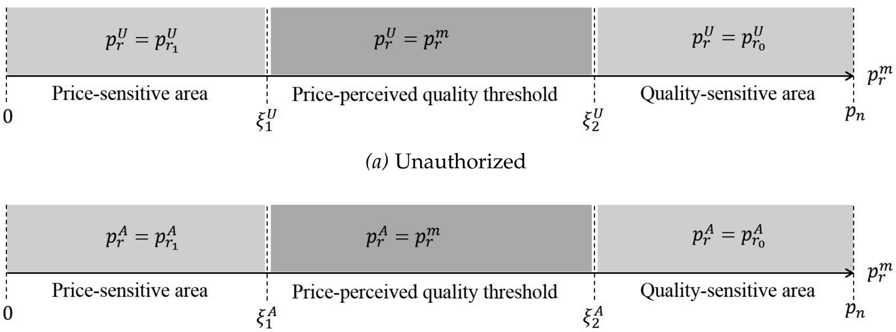


Figure 4.2: Relationship between refurbished product's price and percent of high-end customers switching for various price-perceive quality threshold values

Figure 4.2 shows that if the price-perceived quality threshold is close to zero ($p^m_r \approx 0$), the U-shaped switching function is close to the linear switching function.

On the other hand, if the price-perceived quality threshold is close to the new product's price, i.e., $p_r^m \approx p_n$, cannibalization would be very low. It is obvious that if the switching function is linear, the optimal solution of the 3P is always in the price-sensitive area; whereas if the price-perceived quality threshold is close to the new product's price, the optimal solution is always in the quality-sensitive area. In Lemma 4.1 we will show that in both unauthorized (U) and authorized (A) scenarios, there exist thresholds ξ_1^j and ξ_2^j, $j \in \{U, A\}$, such that the optimal solution is always in the price-sensitive area whenever $p_r^m \leq \xi_1^j$ and always in the quality sensitive area whenever $p_r^m \geq \xi_2^j$.

Lemma 4.1 *The optimal price for the 3P is determined by the price-perceived quality threshold p_r^m and its relationship with the constants ξ_1^U and ξ_2^U for the unauthorized scenario (N), and ξ_1^A and ξ_2^A for authorized scenario (A), where $\xi_i^U \leq \xi_i^A$, $i = 1, 2$. Three distinct cases exist for each scenario (see Figure 4.3). Appendix C.1 (Tables B.1 and B.2) provides the complete optimal solutions.*



(a) Unauthorized

(b) Authorized

Figure 4.3: Optimal solution for the third party in unconstrained problem

Lemma 4.1 shows that the optimal solution for the 3P in both unauthorized and authorized scenarios depends on the value p_r^m (price at which the percentage of switching customers is maximum) in comparison with two constants ξ_1^j and ξ_2^j, $j \in \{U, A\}$. There are three regions for 3P's optimal price: the price-sensitive area, the quality-sensitive area, and the price-perceived quality threshold itself. If the price-perceived quality threshold is relatively low, the 3P charges the refurbished product price in the price-sensitive area. Otherwise, the optimal price lies in the quality-sensitive area. The two constants ξ_1^j and ξ_2^j are be higher in authorized scenario, that is, $\xi_i^U \leq \xi_i^A$, $i = 1,2$. In this case, the price-sensitive area in the authorized scenario is larger than that in the unauthorized scenario, but the quality-sensitive area in the authorized scenario is smaller than that in the unauthorized scenario; the authorization program increases the marginal cost of refurbished product and, as a consequence, increases the optimal price.

Proposition 4.1 *The thresholds ξ_1^A and ξ_2^A are increasing with the authorization fee g. The authorization fee thresholds g_1 and g_2 ($g_1 \leq g_2$) determine the 3P's optimal decisions (see Figure 4.4). Appendix C.1 provides the values g_1 and g_2.*

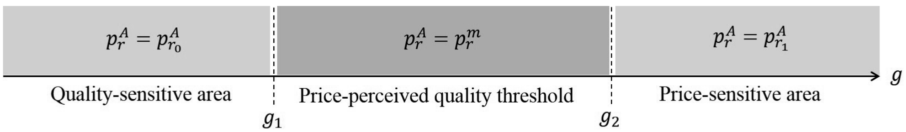


Figure 4.4: Unconstrained solution of the third party of authorization model

Proposition 4.1 predicts the higher authorization fee drives the 3P to focus on the price-perceived quality threshold and the price-sensitive area in determining the optimal solution. Lemma 4.1 and Proposition 4.1 also show that if the U3P charges the refurbished product price in the price-sensitive area, the new price is still in the same area after the U3P takes the authorization program. However, if the price of the previously unauthorized refurbished product is in the price–perceived quality threshold or quality-sensitive areas, the new price for the now-authorized product may move to another area, depending on the authorization fee. The optimal refurbished product price is increasing in the authorization fee for $g < g_1$ and $g > g_2$, and is constant for $g_1 \leq g \leq g_2$.

Example to illustrate Proposition 4.1. *For scenario U, we set $Q_n = 1000$, $p_n = 100$, $c_n = 70$, $k^U = 3$, $b^U = .001$, and $c_r^U = 20$. For scenario A, we set $\tau_b = .0005$, $\tau_k = .5$, $\tau_c = 2.5$, and $g = 5$. First, we consider the case where $p_r^m = 40$. The price-perceived quality threshold is low, i.e., the customers become suspicious of the product quality above a 60% discount. In this case, $\xi_1^U = 60$, $\xi_2^U = 68.87$, $\xi_1^A = 61.25$, $\xi_2^A = 71.53$, $g_1 = -217.5$, and $g_2 = -37.5$. Parameters g_1 and g_2 are less than 0. Hence, $p_r^m < \xi_1^U$, $p_r^m < \xi_1^A$, and $g > 0 > g_2 > g_1$. The 3P always charges the refurbished product price in the price-sensitive area, i.e., $p_r^{U*}, p_r^{A*} \in [30, 100)$. Now, we consider the case where $p_r^m = 70$. The price-perceived quality threshold is high, i.e., the customers become suspicious of the product quality after a 30% discount. In this case, $g_1 = 0$ and $g_2 = 22.5$. Hence, $p_r^m > \xi_2^U$,*

$p_r^m < \xi_2^A$, and $g_1 = 0 < g < g_2$. The U3P charges the price in the quality-sensitive area, i.e., $p_r^{U*} \in (0, 70)$. With the authorization fee $g = 5$, the optimal price of the A3P is at the price-perceived quality threshold, i.e., $p_r^{A*} = 70$. The A3P will keep the price even though the authorization fee increases as long as it is below $g = 22.5$. If the fee is higher than 22.5, the optimal price moves to the price-sensitive area, i.e., $p_r^{A*} \in (70, 100)$.

By comparing the results of unauthorized (U) and authorized (A) scenarios, we determine whether the 3P should participate in the authorization program and whether the OEM should accept the 3P as an authorized refurbisher. Proposition 4.2 indicates the 3P will accept the authorization fee when it is relatively low, such that the firm's profit increases following authorization. The OEM will obtain a higher profit from refurbishing authorization if the fee is relatively high. However, we observe that the profit of OEM is a concave curve with respect to authorization fee. Hence, the OEM does not always benefit from a higher authorization fee. The higher the fee, the more the 3P increases the price and decreases the number of refurbished products put in the market. The OEM should be aware of this effect: Authorization can be a win-win strategy for both the OEM and the 3P as long as the fees are acceptable for both firms.

Corollary 4.1 shows that for quality- and price-sensitive area under the authorization scenario, ${g_{oi}^j}^*$ is the optimal authorization fee for OEM in area (i, j) whenever it is available in the area. In the area, the OEM's profit is a concave function of the authorization fee. If the authorization fee increases too much, that is, $g > {g_{oi}^j}^*$, the OEM's profit drops. Moreover, if the price-quality threshold is the pricing area of the 3P under authorization scenario, the OEM's profit is an increasing function of the authorization fee, because the 3P does not change the price in that area. Hence, g_2 is the optimal authorization fee for the OEM in the price-quality threshold area. The OEM also should note though that the 3P will move to the price-sensitive area whenever $g > g_2$.

Proposition 4.2 *The condition for the 3P to engage in refurbishing authorization is $\Pi_t^A \geq \Pi_t^U$. Table 4.2 shows the acceptable authorization fee for the 3P. The condition for the OEM to be profitable from the authorization scenario is $\Pi_o^A \geq \Pi_o^U$. The profit of the OEM is a concave curve with respect to authorization fee and Table 4.3 shows the acceptable authorization fee for the OEM. Appendix C.1 provides the values g_i^j, $\bar{g}_i^j$, and $\tilde{g}_i^j$.*

Table 4.2: Acceptable authorization fee for 3P

Pricing area of U3P		Pricing area of A3P		
		(1) $p_r^m \geq \xi_2^A$ $(g \leq g_1)$	(2) $p_r^m \in (\xi_1^A, \xi_2^A)$ $(g_1 \leq g \leq g_2)$	(3) $p_r^m \leq \xi_1^A$ $(g \geq g_2)$
(1)	$p_r^m \geq \xi_2^U$	$0 \leq g \leq \min\{g_1^1, g_1\}$	$g_1 \leq g \leq \min\{g_1^2, g_2\}$	$g_2 \leq g \leq g_1^3$
(2)	$p_r^m \in (\xi_1^U, \xi_2^U)$	–	$0 \leq g \leq \min\{g_2^2, g_2\}$	$g_2 \leq g \leq g_2^3$
(3)	$p_r^m \leq \xi_1^U$	–	–	$0 \leq g \leq g_3^3$

Table 4.3: Acceptable authorization fee for OEM

Pricing area of U3P		Pricing area of A3P		
		(1) $p_r^m \geq \xi_2^A$ $(g \leq g_1)$	(2) $p_r^m \in (\xi_1^A, \xi_2^A)$ $(g_1 \leq g \leq g_2)$	(3) $p_r^m \leq \xi_1^A$ $(g \geq g_2)$
(1)	$p_r^m \geq \xi_2^U$	$\bar{g}_1^1 \leq g \leq \min\{\tilde{g}_1^1, g_1\}$	$\max\{\bar{g}_1^2, g_1\} \leq g \leq g_2$	$\max\{\bar{g}_1^3, g_2\} \leq g \leq \tilde{g}_1^3$
(2)	$p_r^m \in (\xi_1^U, \xi_2^U)$	–	$\max\{\bar{g}_2^2, g_1\} \leq g \leq g_2$	$\max\{\bar{g}_2^3, g_2\} \leq g \leq \tilde{g}_2^3$
(3)	$p_r^m \leq \xi_1^U$	–	–	$\max\{\bar{g}_3^3, g_2\} \leq g \leq \tilde{g}_3^3$

Corollary 4.1 *The most acceptable authorization fee for the OEM in area (i, j), $i = 1, 2, 3$, $j = 1, 3$ is $g_{oi}^{j*} = \frac{1}{2}(\bar{g}_i^j + \tilde{g}_i^j)$, whenever $g_{oi}^{j*} \in [0, g_1]$ for $i = j = 1$ and $g_{oi}^{j*} \geq g_2$ for $i = 1, 2, 3$, $j = 1$, whereas the optimal fee for the OEM in (i, j), $i = 1, 2, j = 2$ is g_2 whenever $\bar{g}_i^j \leq g_2$. Table 4.4 shows the optimal authorization fee for the OEM, for every pricing area of the 3P under the unauthorized scenario.*

Table 4.4: Optimal authorization fee for OEM

Pricing area of U3P		Optimal authorization fee for OEM	
		Condition	Solution
Quality-sensitive area	$p_r^m \geq \xi_2^U$	$g_{o1}^{1*} \geq g_1, g_{o1}^{3*} \geq g_2$	g_{o1}^{3*}
		$g_{o1}^{1*} \geq g_1, g_{o1}^{3*} \leq g_2$	g_2
		$g_{o1}^{1*} \leq g_1, g_{o1}^{3*} \geq g_2$	g_{o1}^{1*} or g_{o1}^{3*}
		$g_{o1}^{1*} \leq g_1, g_{o1}^{3*} \leq g_2$	g_{o1}^{1*} or g_2
Price-perceived quality threshold	$p_r^m \in (\xi_1^U, \xi_2^U)$	$g_{o2}^{3*} \leq g_2$	g_2
		$g_{o2}^{3*} > g_2$	g_{o2}^{3*}
Price-sensitive area	$p_r^m \leq \xi_1^U$	$g_{o3}^{3*} \geq g_2$	g_{o3}^{3*}

For example, if we let the U3P charge the refurbished product price at the price-perceived quality threshold ($p_r^{U*} = p_r^m$); $g_2^2, g_2^3 \geq g_2$, and $\max\{g_2^2, g_2^3\} = g_2^3$, and if the authorization fee is $g \in [0, g_2^2]$, the 3P will accept it without changing the price. If the fee is higher than g_2, the firm still engage in the refurbishing authorization whenever the fee is lower than g_2^3, but the optimal price will increase. If we let

$g_1 \leq \bar{g}_2^2 \leq g_2$ and $\bar{g}_2^3 \leq g_2$, the OEM could benefit from the authorization strategy by setting the fee to $\bar{g}_2^2 \leq g \leq \tilde{g}_2^3$. However. the OEM should note that if $g \geq g_2$, the 3P will move its price to the price-sensitive area. Both the OEM and the 3P will benefit from the refurbishing authorization if $\bar{g}_2^2 \leq g \leq g_2^3 \leq \tilde{g}_2^3$. When $g_2 \leq g_{o2}^{3\ *} \leq g_2^3$, the optimal authorization fee for the OEM is $g_{o2}^{3\ *}$. When $g_{o2}^{3\ *} > g_2^3$, the optimal fee is g_2^3. The OEM's profit may decrease, but the 3P will accept authorization.

4.3.2 Constrained remanufacturable product supply

So far, we have ignored the limitation of the remanufacturable product supply. In this subsection, we assume the 3P has access to $100\delta\%$ of the cores for collection. In the steady-state model, we assume products have a useful life of one period, with all units available thereafter for collection. Every item collected is assumed to be suitable for refurbishing. Lemma 4.2 shows that for each pricing area $i \in \{1,2,3\}$ and scenario $j \in \{U, A\}$, refurbishing is unconstrained whenever the reusability rate is relatively high ($\delta \geq \delta_i^j$) or low-end market base is relatively low ($k \leq k_i^j$). Therefore, there is a market level at which refurbishing is unconstrained. In this case, Lemma 4.1 and Proposition 4.2 apply. However, when the reusability rate is relatively low ($\delta < \delta_i^j$) or the low-end demand parameter is relatively high ($k^j \geq k_i^j$), the supply of used products is constrained. In this case, the pricing rules in Lemma 4.1 and Proposition 4.2 do not apply. Furthermore, the reusability threshold δ_i^j is increasing in low-end market base k^j and cannibalization level b^j, $i \in \{1,2,3\}$, $j \in \{U, A\}$, and δ_1^A and δ_3^A are decreasing in the authorization fee g. Therefore, lower market growth levels of refurbished products and higher authorization fees may lead the problem to the unconstrained condition (Corollary 4.2).

Lemma 4.2 *Let $i \in \{1,2,3\}$ represent the pricing area of the 3P, that is, the quality-sensitive area (1), the price-perceived quality threshold (2), and the price-sensitive area (3), and $j \in \{U, A\}$ represent the scenarios, that is, unauthorized (U) and authorized (A). For each i and j, the constraint $q_r^j \leq \delta q_n^j$ is binding if $\delta < \delta_i^j$ or, equivalently, if $k^j > k_i^j$. Figure 4.5 illustrates the optimal solutions, and Appendix C.1 provides the values δ_i^j, k_i^j, $p_{c_1}^j$, $p_{c_0}^j$.*

Corollary 4.2 *Let g_1 and g_2 from Proposition 4.1 and δ_2^A from Lemma 4.2. There are thresholds $g_1^A = \frac{2\left(p_n k^A - \delta Q_n\right)}{d_u^A - \delta \rho r^A} - \frac{p_n k^A}{d_u^A} - c_r^A$ and $g_3^A = p_n - c_r^A - \frac{2\delta Q_n}{d^A + \delta r^A}$ in the authorization fee that determine the 3P's optimal solutions (see Figure 4.6).*

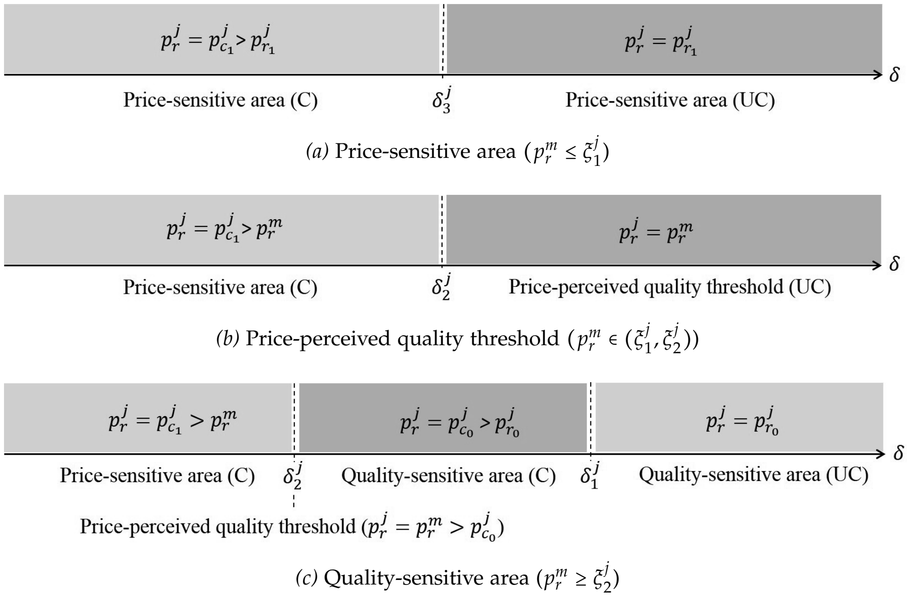
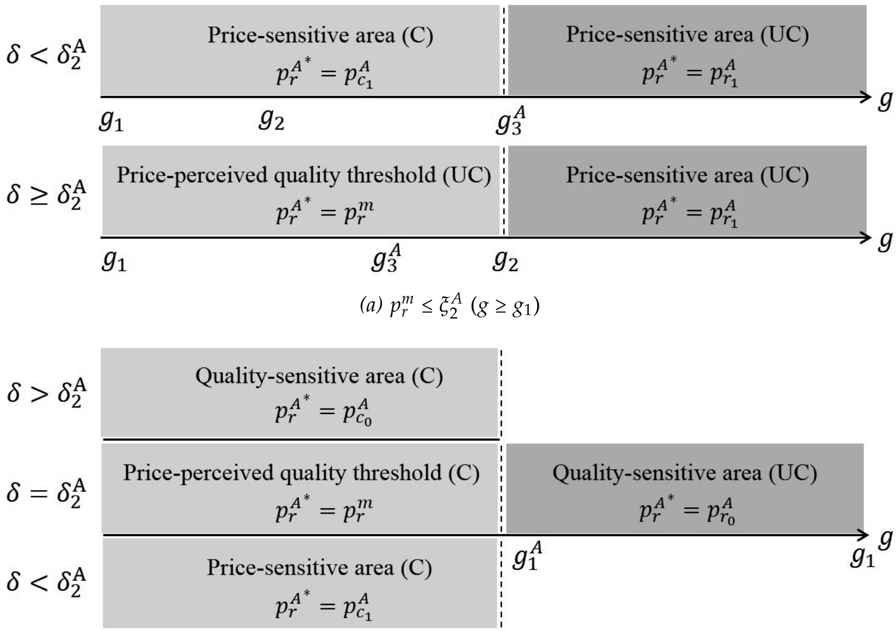


Figure 4.5: Optimal solutions of the 3P for constrained (C) and unconstrained (UC) problems for each pricing area $i \in \{1,2,3\}$ and each scenario $j \in \{U, A\}$ with regard to authorization fee threshold δ_i^j, with δ_i^j as in Lemma 4.2

According to Lemma 4.2, the lower reusability rate leads the 3P to focus on the price-sensitive area in determining the optimal solution. Therefore, without loss of generality, for the refurbishing authorization analysis in a constrained problem, we consider only the problem that occurs when the price-sensitive area and price-perceived quality threshold are the pricing areas in the unauthorized scenario, such that they are the pricing areas in the authorized scenario (Figure 4.5, where $\delta < \min\{\delta_3^U, \delta_3^A\}$ or Figure 4.6a, where $\delta < \delta_2^A$ and $g \leq g_3^A$). In this case, we assume the price-perceived quality threshold is relatively low, such that $p_r^m \leq \xi_2^j$, $\forall j \in \{U, A\}$.

Table 4.5, according to Lemma 4.2, identifies the 3P's optimal decision for each scenario. When there is a limited supply of remanufacturable product, the authorization fee does not influence the optimal price of the refurbished products. In this case, the 3P collects and refurbishes all available used products. That is, the 3P does not change the price and the quantity of refurbished products if the authorization fee is in the range $g \in [0, \bar{g}]$. In the range of authorization fees, if the supply of used products is not limited, the 3P has more used products and charges lower prices. However, if the authorization fee is relatively high, such that



(b) $p_r^m > \xi_2^A$ $(g < g_1)$

Figure 4.6: Optimal solutions of the 3P for constrained (C) and unconstrained (UC) problems with regard to authorization fee g

$g > \bar{g}$, the 3P decreases the number of refurbished products sold in the market and increases the price. In this case, the firm does not need to collect and refurbish all available used products. Moreover, a lower reusability rate (δ) leads the 3P to increase the refurbished product price for profitable refurbishing, generated by high profit margins.

Table 4.5: Optimal solutions for constrained problem

Third party	Unauthorized (U)	Authorized (A)
p_r^j	$\frac{p_n d^U - \delta(Q_n - p_n r^U)}{d^U + \delta r^U}$	$\frac{p_n d^A - \delta(Q_n - p_n r^A)}{d^A + \delta r^A}$
q_r^j	$\frac{\delta Q_n d^U}{d^U + \delta r^U}$	$\frac{\delta Q_n d^A}{d^A + \delta r^A}$
Π_t^j	$\frac{\delta Q_n d^U((d^U + \delta r^U)(p_n - c_r^U) - \delta Q_n)}{(d^U + \delta r^U)^2}$	$\frac{\delta Q_n d^A((d^A + \delta r^A)(p_n - c_g^A) - \delta Q_n)}{(d^A + \delta r^A)^2}$
OEM		
q_n^j	$\frac{Q_n d^U}{d^U + \delta r^U}$	$\frac{Q_n d^A}{d^A + \delta r^A}$
Π_o^j	$\frac{Q_n w_n d^U}{d^U + \delta r^U}$	$\frac{(\delta g + w_n) Q_n d^A}{d^A + \delta r^A}$

Table 4.5 shows that if the two scenarios, U and A, use the same reusability rate δ, the quantity of refurbished products or the supply of used-products could be different, that is, $\delta q_n^U \neq \delta q_n^A$, because the new product quantity $q_n^j, j \in \{U, A\}$ is influenced by the refurbished product price and the cannibalization level, whereas the price is affected by potential market growth. To compare scenarios U and A, we assume the scenarios have the same upper boundary on the used product supply. Let $\delta_j, j \in \{U, A\}$ be the reusability rate of scenario j, and $\delta_A = \frac{\delta_U d^U d^A}{(d^U + \delta_U r^U) d^A - \delta_U d^U r^U}$, such that $\delta_U q_n^U = \delta_A q_n^A$. By comparing no authorization with authorization, we obtain an acceptable fee for the 3P and the OEM.

Proposition 4.3 *Let* $\delta_j < \delta_3^j$, $\forall j \in \{U, A\}$, $g_{c3}^3 = p_r^A - p_r^U + \tau_c$, *and* $\bar{g}_{c3}^3 = \frac{Q_n w_n \left(\tau_b k^U - \tau_k b^U\right)}{d^U d^A}$. *The acceptable authorization fees for the 3P and the OEM are* $g \leq g_{c3}^3$ *and* $g \geq \bar{g}_{c3}^3$, *respectively.*

Proposition 4.3 shows that in the constrained problem, authorization can be a win-win strategy for the OEM and the 3P, as long as there are some authorization fees such that $\bar{g}_{c3}^3 \leq g \leq g_{c3}^3$. Because the two scenarios, U and A, have the same refurbished product quantity, the 3P engages in refurbishing authorization if the total benefits from the price differences and lower refurbishing cost are higher than the authorization fee. Therefore, higher potential market growth and lower refurbishing cost, which result from the 3P being authorized, increases the firm's intention to engage in refurbishing authorization. However, the OEM may not offer refurbishing authorization if it increases cannibalization. When the used products supply is constrained, the OEM's profit is an increasing linear function of the authorization fee. However, according to Figure 4.6a and Proposition 4.2, it becomes a concave function when the fee is relatively high. The average increment of the low-end market base has a positive effect for the 3P, as well as for the OEM. Therefore, the higher the low-end market base, the higher the possibility firms can find win-win solutions.

Figure 4.7 illustrates the acceptable authorization fee for both the OEM and the 3P for differing rates of market growth, cannibalization, refurbishing cost, and reusability. In Figure 4.7a, for both the constrained and unconstrained problems, the range of acceptable authorization fees is wider, because more low-end consumers purchase refurbished products. The authorization fee threshold for the 3P (maximum acceptable fee) and the OEM (minimum acceptable fee)

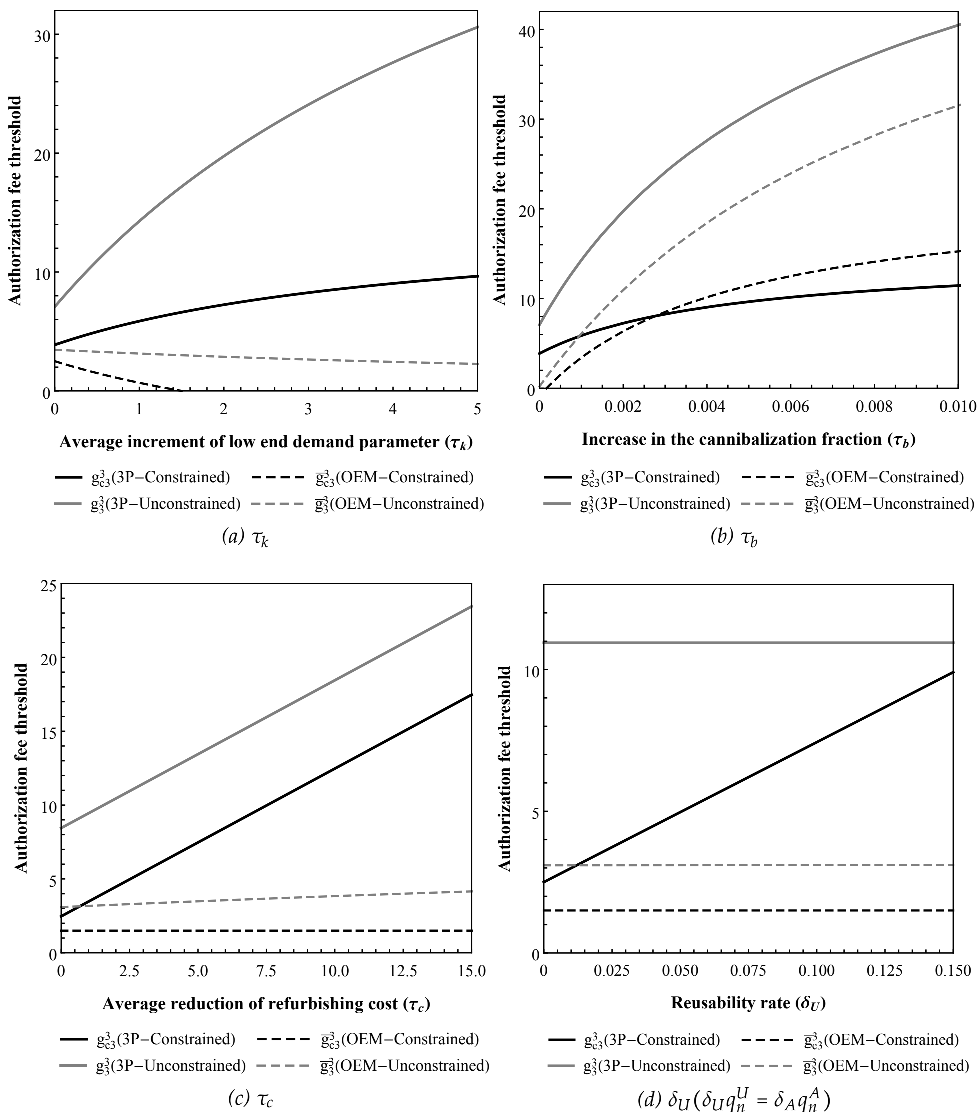


Figure 4.7: Authorization fee thresholds for different parameters τ_k, τ_b, τ_c, and δ_U when $Q_n = 1000$, $p_n = 100$, $c_n = 70$, $c_r^U = 20$, $b^U = .001$, $k^U = 3$, and $p_r^m = 30$

in the constrained problem always is lower than in the unconstrained case, i.e., $g^3_{c3} < g^3_3$ and $\bar{g}^3_{c3} < \bar{g}^3_3$. That is, the 3P prefers to accept authorization fees when the remanufacturable supply is large (see also Figures 4.7d and 4.7b). If the supply is constrained, the potential market growth that could be profitable for the 3P following authorization cannot be fully utilized. However, due to cannibalization, the OEM prefers to offer the refurbishing authorization to the 3P that has fewer refurbished products for sale or has high potential market growth from low-end customers. Yet the OEM also has great concerns about the increase in cannibalization following refurbishing authorization. Figure 4.7b shows that if the remanufacturable supply is constrained, there may not be a win-win solution when cannibalization is relatively high; the OEM will charge a high authorization fee, and the 3P cannot increase its minimum acceptable fee very much, because the firm can benefit only from the profit margin of its limited products. Figure 4.7c shows that the higher the average reduction of refurbishing cost, the higher the minimum acceptable fee of the 3P; it does not have a significant impact on the acceptable fee of the OEM. This result could be useful information for OEMs, because it widens the ranges of win-win solutions. Thus, the OEM can leverage this advantage by increasing the authorization fee.

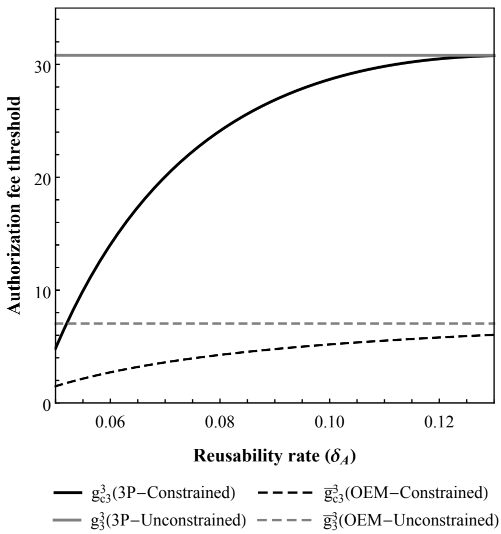


Figure 4.8: Authorization fee thresholds for different δ_A when $Q_n = 1000$, $p_n = 100$, $c_n = 70$, $c_r^U = 20$, $b^U = .001$, $k^U = 3$, $p_r^m = 30$, $\delta_U = .05$ ($\delta_U q_n^U \leq \delta_A q_n^A$)

Figure 4.8 illustrates the acceptable authorization fee for both the OEM and the 3P for differing reusability rates under the authorization scenario. In this case, the remanufacturable supply is constrained by $\delta_U q_n^U$. After being authorized, the 3P can access more used product supply, so the supply is still constrained with $\delta_U q_n^U \leq \delta_A q_n^A$ (parameter δ_A increases), or else the supply becomes unlimited. Figure 4.8 shows that as the reusability rate increases, the 3P increases its maximum acceptable fee. The increase is higher than the case of $\delta_U q_n^U = \delta_A q_n^A$ (see Figure 4.7d), in which the firm cannot sell more refurbished products even after being authorized. The OEM also increases its minimum acceptable authorization fee, because it faces an increased threat of cannibalization.

4.4. Conclusion

In this study, we focus on unauthorized and authorized refurbishing strategies of an OEM and a 3P. With the rapid growth of the refurbished market for electronic products, it is beneficial for OEMs to cooperate with 3Ps via authorization scenarios; such scenarios can boost OEMs' brand reputations, increase their sales, and strengthen consumer acceptance of A3P's refurbished products. We empirically characterize consumer behavior in complex settings in Chapter 2, then use these insights to model and analyze optimal pricing policies in Chapter 4. The higher the sellers' reputations, the higher the demand share for refurbished products. For low-brand refurbished products that are sold by A3Ps, the demand share of the products decreases with the discount, after a certain discount off of the new product price. For high-brand refurbished products that are sold by U3Ps, the demand share always increases with the discount.

Our analytical results show that if the remanufacturable supplies are not constrained, optimal solutions for 3Ps are driven by price-perceived quality thresholds. There are three regions of solutions: the price-sensitive area, the quality-sensitive area, and the threshold. Two thresholds of authorization fees determine 3P's decision. Higher authorization fees lead 3Ps to focus on price-perceived quality thresholds or price-sensitive areas in determining optimal solution. In these areas, 3Ps can benefit from high profit margins and potential market growth. By comparing the results of having no authorization scenario with having an authorization scenario, we find that authorization fees that are acceptable to 3Ps and OEMs are influenced by the pricing areas of the 3Ps before and after authorization; 3Ps accept authorization fees when the fees are relatively low, such that firms' profits increase following authorization, and OEMs obtain higher profits from refurbishing authorization if fees are relatively high. However, OEMs do not always benefit from higher authorization fees, because higher fees lead 3Ps to increase their prices, thereby decreasing the number of refurbished products they place on the market. Moreover, to reach authorization agreements, OEMs do not need to offer their optimal fees.

If remanufacturable supplies are constrained, optimal solutions for 3Ps are driven by price-perceived quality thresholds and reusability rates. We find that lower reusability rates lead 3Ps to focus on price-sensitive areas in determining optimal solutions. When there is a limited supply of remanufacturable products, authorization fees do not influence optimal prices of refurbished products. In this case, 3Ps collect and refurbish all available used products. However, if authorization fees are relatively high, 3Ps do not need to collect and refurbish all available used products. The authorization fee threshold for 3Ps (i.e., maximum acceptable fee) and OEMs (i.e., minimum acceptable fee) in the constrained problem always is lower than in the unconstrained problem; 3Ps prefer to accept authorization fees when remanufacturable supplies are relatively large; OEMs prefer to offer refurbishing authorization to 3Ps with fewer refurbished products for sale. Finally, the larger the low-end market base, the greater the possibility that OEMs and 3Ps will reach win–win solutions.

5

Strategic Decision Making for Refurbishing Across New Product Generations

5.1. Introduction

Many manufacturers intend to reduce the potential cannibalization by differentiating the quality level of new product from refurbished ones by upgrading. Manufacturers usually invest to release new generations (upgraded products) at an intensive rate to cater for consumer demands. For example, Apple annually releases new iPhone models. Frequent introduction of new generation has been recognized as an important strategy in order to survive in a rapidly changing business environment. Intuitively, if a newer generation is introduced to the market, the previous generation becomes unattractive. The propensity of consumers to purchase the refurbished products will be smaller since the new technology development is not included. The refurbished product does not contain the latest innovation, and in turn, makes the product less attractive to customers compared to the new generation. Thus, if a manufacturer releases the refurbished products after the introduction of new generation, the firm may not need to worry about cannibalization. However, the refurbished product demand will be lower and may reduce the refurbishing profitability. Moreover, if the newer generation has been launched, the price of the older generation will drop and thus influence the price of refurbished products. This is because there is a significant difference in pricing between the new product and its refurbished version because of consumers' perception. At the same time, increasingly stringent regulations on manufacturers regarding collecting of end-of-use products and re-use (OECD, 2001; Directive, 2012) will impact on strategic decision making in refurbishing. Particularly, if refurbishing is considered as an important business strategy and has larger economic margin, a manufacturer may find it beneficial to introduce refurbished products before the new generation introduction. In this case, the refurbished products can be sold at a higher price to get higher margins.

An important question is: How should a manufacturer integrate refurbished products in its product line of new products? Specifically, we consider a manufacturer facing the refurbishing decision across multiple new product generations. The manufacturer could decide to launch the refurbished products before or after the introduction of new generations. One of the central issues in the economic assessment of refurbishing is demand cannibalization, i.e., the sales of refurbished products may reduce the market share of new product. Manufacturers often believe refurbished product cannibalizes the sales of new product because it is a low-price alternative. Within the operations management literature for refurbishing, cannibalization has been estimated by many authors using behavioral experiment (e.g., Guide and Li, 2010; Ovchinnikov, 2011; Ovchinnikov et al., 2014; Agrawal et al., 2015b; Raz et al., 2017; Abbey et al., 2019). If a newer generation has been introduced to the market, the refurbished version of the old generation is naturally less desirable to consumers. On the other hand, higher price of the new generation may reduce this effect. Therefore, it could capture more new ("low-end") customers who do not want to purchase new products. However, the manufacturer may also need to consider the pricing decision of the refurbished products. The older generation usually falls sharply in price after the launch of newer generation and will impact the refurbished product price. For example, in November 2017, the iPhone X was introduced to the market by Apple Inc. In September 2018, the product was discontinued, and at the same time, iPhone XS was released. As reported by Iphonehacks (2019), although iPhone X was discontinued by the firm, the price dropped across the web. When iPhone XS was launched, the price of iPhone X was $899 down from Apple's original pricing of $999, and then Apple sold the 64GB refurbished iPhone X for $769, which is a savings of $130 from the original $899 price tag.

Besides demand cannibalization, another fundamental issue in refurbishing is the supply of refurbished products, which depends on new product sales. The management of the refurbished product supply significantly influences the refurbishing profitability (Atasu et al., 2010a). When a manufacturer maximizes profit by offering new and refurbished products, the return flows of the refurbished version will have impact on the firm's decision. The firm must have sufficient quantities of remanufacturable products available before refurbishing can start. However, there is some lag between the sales of new and refurbished products (Ovchinnikov et al., 2014; Raz et al., 2017). The firm must acquire a unit of new product previously sold in order to sell a unit of refurbished product. Thus the cannibalization level of new product sales will influence the refurbished product supply in the future. To capture the lag, the selling horizon of both the new and refurbished products is assumed to consist of two periods (see Figure 5.1). For example, in period 0, the firm that sells new product generation 1 may also sell refurbished product generation 0. In period 1, the firm can sell new product generation 1 and its refurbished version, where the product supply is taken from the new product sold in period 0. In period 2, the firm launch new product generation 2 and sell refurbished product generation 1, where the new products sold in period 0 and 1 become the potential supply for refurbished products sold in period 2. There will be few used products available for refurbishing in the early new product life cycle. However, the used product supply may exceed the refurbished product demand in the end of new product life cycle.

The primary goal of this chapter is to deepen our understanding of the interaction between refurbishing and the new product generation life cycle using an analytical model that incorporates the used product supply. Specifically, we want to understand the consequences of launching the refurbished product in different periods to find the optimal distribution of the refurbished product supply across the new product line. It is important in practice that a manufacturer needs to decide whether to make an immediate launch of refurbished products or wait for better future opportunities. For this purpose, we develop a two-period model, i.e., period 1 and 2, in which a firm sells two generations of a product in a market. The manufacturer sells the first- and second-generation product in period 1 and 2, respectively. The manufacturer can start refurbishing and sell refurbished products at the beginning of period 1. Besides, in both periods, the manufacturer decides the price and quantity of refurbished products and sells them to the market.

Numerous papers have studied the upgrading or quality of refurbished products (e.g., Debo et al., 2005; Ferguson et al., 2009; Atasu and Souza, 2013). However, these works did not capture the relationship between refurbished products and the upgraded new products. To the best our knowledge, although refurbishing has been studied extensively in the literature, the interaction between refurbishing and product innovation is rarely investigated. Limited research only focuses on the problem where a product innovation rate is affected by the refurbishing decision. For example, Xiong et al. (2016) study the conditions under which it is optimal for a manufacturer to introduce an upgraded product and for a third party to enter a secondary market. Li et al. (2018) investigate the optimal timing decisions for new product introduction where a manufacturer facing the decision of investing either in refurbishing or in product quality improvement. They find that the decision is affected by overall manufacturing efficiency. Using a two-period decision problem, our research focuses more on the impact of new product generation life cycle on refurbishing decision. We consider several factors in our model: cannibalization, low-end demand, remanufacturable product supply, and the drop in new product price; many of which have been addressed individually but not simultaneously in existing literature.

5.2. Model Formulation

We consider a manufacturer selling a product that experiences technological innovation over time. Because of technological progress, newer generations with newest design and latest technology become available periodically. We model a firm selling new products from a specific generation until the next generation becomes available, at which point the sales of such next generation of products begin and the sales of the previous generation of products discontinue. Our model is consistent with the selling policy of Apple Inc. depicted in Figure 5.1 and the extant literature such as Ovchinnikov et al. (2014) and Li et al. (2018). In addition to the new products from a specific generation, the firm also offers a refurbished version of the products. To offer the refurbished products, the manufacturer must acquire the previously sold new products. Hence, there is some lag between the new product sales and the sales of the refurbished version. We assume that the selling horizon of new products from a generation consists of two periods to capture the lag. For example, new products generation 1 are sold in period 0 and 1. In period 1, the firm can collect, refurbish, and sell a fraction of new product generation 1 sold in period 0. In period 2, the firm also can collect, refurbish, and sell products of generation 1 sold in period 0 and 1.

The major decision in this chapter is whether the manufacturer should release the refurbished products before the introduction of the new product generation or wait for it, as well as the optimal price it should be sold at. Therefore, for new product generation 1, the firm could decide to release the refurbished version in period 1 and to sell some of these refurbished products in period 1 and 2, or release and sell them only in period 2. Figure 5.2 illustrates the example of the product line of Apple, where Apple Inc. sold refurbished iPhone X after the sales of its new version was discontinued and released new generation products (iPhone XS). Moreover, there is almost always a single launch event per year for refurbished iPhone. Due to mathematical simplicity in solving steady state models, we assume that refurbished products from a generation would never overlap with those from other generations. Our model is a two-period model, where we include period 1 and 2 (as illustrated in Figure 5.1), new product generation 1 and 2, and the refurbished products of generation 1. This is illustrated with the greyed boxes in the figure.

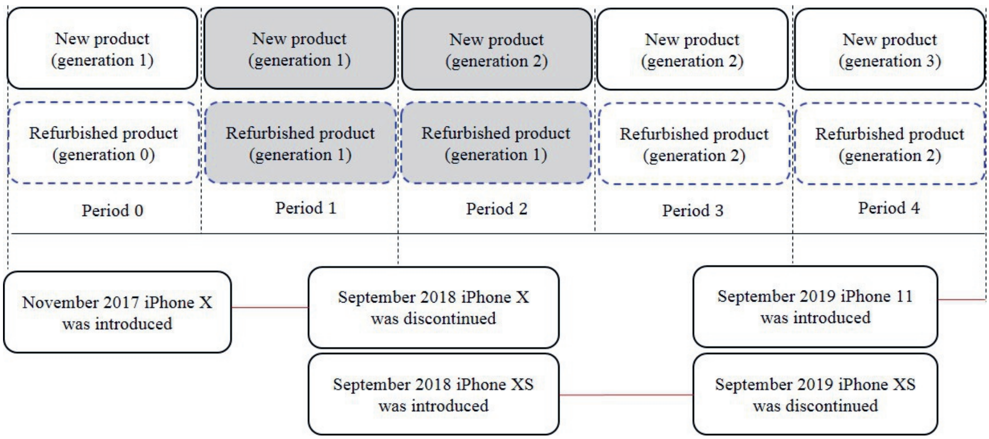


Figure 5.1: Model schematic

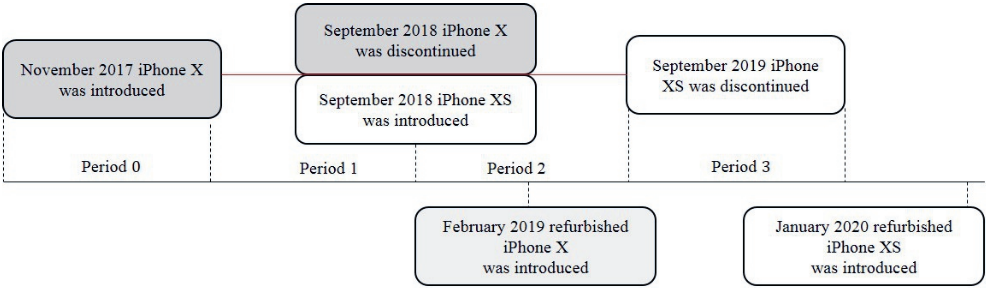


Figure 5.2: Apple begins selling refurbished iPhone X Model

Table 5.1: Notation and associated description

Symbol	Description
p_i^n	Price of new product generation i, where $i \in \{1,2\}$
p_t^r	Price of refurbished product generation 1 sold in period t, with $t \in \{1,2\}$
c_i^n	Unit cost of new product generation i, where $i \in \{1,2\}$
c^n	Upgrade cost of new product generation 2, where $c^n = c_2^n - c_1^n$
c^r	Unit cost of refurbished product generation 1
w^n	New product profit margin for both generation 1 and 2, where $w^n = p_1^n - c_1^n = p_2^n - c_2^n$
Q^n	Demand for new products when the refurbished version is not available, constant every period
b_t	Cannibalization coefficient in period t, with $t \in \{1,2\}$
θ	Price-drop coefficient, i.e., the discount factor of the price of new product generation 1 in period 2
α_i	Fraction of high-end customers of generation i who switch to purchase refurbished product generation 1, where $i \in \{1,2\}$
k_t	Price elasticity on market demand of low-end customers in period t, with $t \in \{1,2\}$
q_i^n	Number of consumers purchasing new product generation i, where $i \in \{1,2\}$
q_t^r	Number of consumers purchasing refurbished product generation 1 in period t, with $t \in \{1,2\}$
ρ_t	Recovery fraction in period t, with $t \in \{1,2\}$
Symbols used for simplification of expressions:	
ϕ	Degree of change in cannibalization coefficient, with $\phi = b_2/b_1$
ψ	Degree of change in price elasticity, with $\psi = k_2/k_1$
r_t	Cannibalization elasticity of refurbished products of generation 1 on the offered new generation products in period t, where $t \in \{1,2\}$, $r_1 = b_1 Q^n$ and $r_2 = b_2 Q^n$
d_t	Composite effect of refurbished product's price on its demand in period t, where $t \in \{1,2\}$, $d_t = k_t + r_t$
a_t	Maximum demand of refurbished products in period t, where $t \in \{1,2\}$, $a_1 = d_1 p_1^n$ and $a_2 = d_2 \theta p_1^n$
v_t	Minimum production of new products in period t, where $t \in \{1,2\}$, $v_1 = Q^n - r_1 p_1^n$ and $v_2 = Q^n - r_2 \theta p_1^n$
q_ρ	Total number of used products that could be collected in periods 1 and 2, where $q_\rho = \rho_1 q_2^n + \rho_2 q_1^n$

We summarize the notations used in this chapter in Table 5.1. Let p_i^n and c_i^n be the price and manufacturing cost for new product generation $i = 1, 2$, where $p_2^n \geq p_1^n$ and $c_2^n \geq c_1^n$. We assume the two new product generations have the same profit margin. Let c^n be the upgrade cost of generation 2. Hence, the price and cost of new product generation 2 would be $p_2^n = p_1^n + c^n$ and $c_2^n = c_1^n + c^n$. Note that our model considers the situation in which, when the firm decides to introduce the refurbished product, it would not influence the new products' prices. Hence, it is assumed that new product prices p_1^n and p_2^n are fixed, as we discussed in Chapter 1. The new product prices could be viewed as the optimal prices of new products generation 1 and 2 for the case without refurbishing and then uses the prices to determine the refurbished product prices that maximize the firm's profit. Let p_1^r and p_2^r are the prices charged for refurbished product generation 1 sold in period 1 and 2, respectively.

The market is divided into two segments: high end and low end. Customers at the high end are willing to purchase new products, whereas customers at the low end purchase only refurbished products at lower prices. Let Q^n be the demand for new products when the refurbished version is not available, constant every period. The presence of refurbished products generation 1 in period 1 will cannibalize the sales of new product generation 1 with linear switching fraction that is formulated as:

$$\alpha_1(p_1^r) = b_1(p_1^n - p_1^r) \tag{5.1}$$

for some coefficient b_1, with $\alpha_1(p_1^r) \in [0, 1]$. In addition, it could attract $k_1(p_1^n - p_1^r)$ low-end customers who would not purchase the new product. The numbers of consumers who purchase new and refurbished products generation 1 are as follows:

$$q_1^n = Q^n - b_1(p_1^n - p_1^r)Q^n, \tag{5.2}$$

$$q_1^r = k_1(p_1^n - p_1^r) + b_1(p_1^n - p_1^r)Q^n. \tag{5.3}$$

If a newer generation is introduced, the previous one becomes unattractive, and thus the refurbished version of the old generation naturally is less desirable to consumers. As a consequence, the presence of a refurbished version of the old generation may have lower negative effect on the new product sales of the new generation, and the low-end demand could be smaller. However, the low-end market could also be larger due to the higher price of the new generation. Thus in period 2, we introduce parameters $0 \leq \phi \leq 1$ and $\psi \geq 0$ that adjust the cannibalization level and low-end demand market base, respectively. Such adjustments have two effects: (1) the cannibalization level of new products in period 2 is lower than in period 1, with $b_2 = \phi b_1$, and (2) the low-end demand for refurbished products in period 2 could be either lower or larger than in period 1, with $k_2 = \psi k_1$. Moreover, even when the new product generation 1 has been discontinued by the firm, it will still be available for purchase at a lower price. This will influence the refurbished product's price since it should be lower than the price of the original product. Hence, the switching fraction in period 2 is formulated as:

$$\alpha_2(p_2^r) = \begin{cases} b_2(\theta p_1^n - p_2^r), & 0 \le p_2^r \le \theta p_1^n < p_2^n, \\ 0, & \theta p_1^n \le p_2^r \le p_2^n, \end{cases} \tag{5.4}$$

where $\theta \in (0, 1]$ is a price-drop coefficient, i.e., the discount factor of the new product price of generation 1 sold in period 2. The numbers of consumers who purchase new product generation 2 and refurbished product generation 1 are as follows:

$$q_2^n = Q^n - b_2(\theta p_1^n - p_2^r)Q^n, \tag{5.5}$$

$$q_2^r = k_2(\theta p_1^n - p_2^r) + b_2(\theta p_1^n - P_2^r)Q^n. \tag{5.6}$$

The fundamental feature of refurbishing is that the supply of used products that could be collected and refurbished is limited and constrained by the previous sales of the new products. Specifically, from Figure 5.1, the supply of refurbished products generation 1 in period 1 is constrained by the sales of new product in period 0, while in period 2, the supply of refurbished products is constrained by the total sales of new products generation 1 in the previous periods (period 0 and 1) net the quantity of refurbished products in period 1. Let the manufacturer has access to $100\rho_t$ percent of the cores for collection and refurbishing in period $t = 1, 2$. On the other hand, because refurbished product generation 1 overlaps with new product generation 2, the introduction of refurbished products in one generation influences the sales of new products of the next generation. Here, we assume that the technological innovations will impact consumer preferences for refurbished products generation 0 when it is offered with new products generation 1 in the same way as when refurbished product generation 1 is offered with new products generation 2. Hence, in our model terms, it is plausible to assume that

$$q_t^n = q_{t+2}^n \text{ and } q_t^r = q_{t+2}^r.$$

Hence, the problem of the manufacturer becomes separable across generations. In other words, the demand for new products generation 1 that refurbished products generation 0 cannibalizes in period 0, is the same as that from generation 2 that is cannibalized by refurbished products generation 1. Hence, to assess the economic impact of refurbishing across generations, the manufacturer only needs to consider two periods: period 1 and 2. Thus, the sales of refurbished products in period 1 is constrained by $q_1^r \leq \rho_1 q_2^n$, while in period 2 we have $q_1^r + q_2^r \leq \rho_1 q_2^n + \rho_2 q_1^n$. The manufacturer tries to maximize the total profit by setting the prices (and also the quantities) of refurbished products in period 1 and 2, constrained by the number of cores available for refurbishing. Formally, the problem is as follows:

$$\begin{aligned} \max_{p_1^r}\{\Pi = \; & (p_1^n - c_1^n)q_1^n + (p_1^r - c^r)q_1^r + \max_{p_2^r}\{(p_1^n - c_1^n)q_2^n + (p_2^r - c^r)q_2^r\}\} \\ \text{s.t.} \quad & q_1^r \leq \rho_1 q_2^n, \; q_1^r + q_2^r \leq \rho_1 q_2^n + \rho_2 q_1^n, \\ & p_1^r \leq p_1^n, \; p_2^r \leq \theta p_1^n, \end{aligned} \tag{P1}$$

with q_1^n, q_2^n, q_1^r, and q_2^r as defined in Equations 5.2, 5.3, 5.5, and 5.6, respectively.

5.3. Optimal Solution

Under refurbishing strategy, the refurbished products could be sold in both period 1 and 2. As the manufacturer's decision-making in period 2 is dependent on that in period 1, we solve this optimization problem in two stages. The decision-making sequence is presented as follows: (1) the manufacturer first determines the production decisions in period 1; and, (2) the manufacturer determines production decisions in period 2. The mathematical optimization involves one manufacturer (monopolist), who chooses what to do at each point of time. Thus, backward induction is used to solving the mathematical optimization of dynamic programming. The solving order is presented as follows: we begin with the second stage where the optimal price and quantity of refurbished products are determined, and then solve for the manufacturer's optimal production decisions in period 1.

According to backward induction, we start with period 2.

5.3.1 Period 2 Analysis

The quantities of refurbished products that could be sold in period 1 and 2 are restricted by the cores available for refurbishing. The function of the manufacturer's profit maximization in period 2 is:

$$\begin{aligned} \max_{p_2^r} \Pi_2 = \ & (p_1^n - c_1^n)q_2^n + (p_2^r - c^r)q_2^r \\ \text{s.t.} \quad & q_1^r + q_2^r \leq \rho_1 q_2^n + \rho_2 q_1^n, \end{aligned} \tag{P2}$$

where q_1^n, q_1^r, q_2^n, and q_2^r are stated in Equations 5.2, 5.3, 5.5, and 5.6, respectively. Let $q_\rho = \rho_1 q_2^n + \rho_2 q_1^n$ be the total number of used products that could be collected in periods 1 and 2.

Proposition 5.1 *Let $\bar{q}_\rho = \frac{1}{2}\left(2q_1^r + a_2 - d_2 c^r - r_2 w^n\right)$ denote the threshold amount of used products that can be collected. The optimal solution of manufacturer in period 2 is summarized in Table 5.2.*

Table 5.2: The optimal solution of manufacturer in period 2

Case	p_2^{r*}	q_2^{r*}	$q_1^r + q_2^r$
$q_\rho \leq \bar{q}_\rho$	$\frac{a_1+a_2-d_1p_1^r-\rho_2(r_1p_1^r+v_1)-\rho_1 v_2}{d_2+\rho_1 r_2}$	$a_2 - d_2 p_2^{r*} (= q_\rho - q_1^r)$	q_ρ
$q_\rho > \bar{q}_\rho$	$\frac{a_2+d_2c^r+r_2w^n}{2d_2}$	$\frac{1}{2}\left(a_2 - d_2c^r - r_2w^n\right) (< q_\rho - q_1^r)$	$\bar{q}_\rho$

Proposition 5.1 shows that when the supply of used products is limited by the threshold $\bar{q}_\rho$, the manufacturer prefer to collect all available used products q_ρ to refurbish. In this case, the firm decides to collect all used products that are available in period 2, including those that have not been collected in period 1. When the supply of used products is not limited by $\bar{q}_\rho$, the manufacturer can collect and refurbish the threshold amount of used products. In other words, the firm should only collect some used products. In this case, if the firm collects and sells all used products that are available in period 1, the number of refurbished products sold in period 2 is less than $\rho_2 q_1^n$. The threshold $\bar{q}_\rho$ is the function of q_1^r, c^r, ϕ, ψ, and θ. It is increasing in q_1^r, θ, and ψ; and is decreasing in c^r and ϕ. Intuitively, in period 2,

the manufacturer should invest to increase the reusability rate when refurbishing cost and cannibalization level are low or when the expected low-end demand is high. Moreover, the lower the number of refurbished products sold in period 1, the manufacturer should not invest in the reusability rate. This is because the supply of used products in period 2 increases as the decrease of refurbished products sold in period 1. The effect of the price of the new product generation 1 is also interesting. If the price drops too much (parameter θ is low), the firm should not invest to increase the reusability rate because the refurbished products cannot be sold at a high price.

5.3.2 Period 1 Analysis

Based on the optimal decision in period 2, we can maximize the total two-period profit as follows:

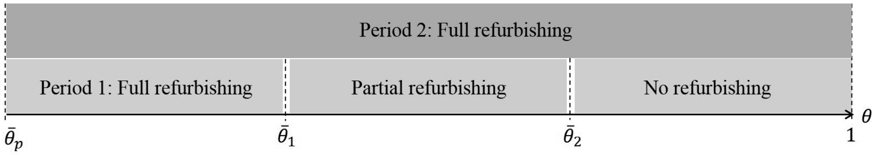
$$\begin{aligned} \max_{p_1^r} \Pi = \ & (p_1^n - c_1^n)q_1^n + (p_1^r - c^r)q_1^r + \Pi_2^* \\ \text{s.t.} \ & q_1^r \le \rho_1 q_2^n. \end{aligned} \tag{P3}$$

Proposition 5.2 *There exists $\bar{\theta}_1$, $\bar{\theta}_2$, $\bar{\theta}_\rho$, $\hat{\rho}_1$ (detailed in Appendix D) such that the production decision of refurbished products is summarized in Table 5.3 and is illustrated in Figure 5.3.*

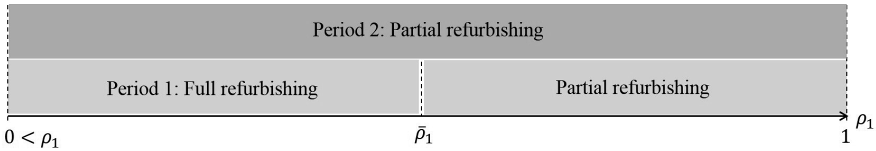
Table 5.3: The optimal solution of manufacturer in period 1 and 2

	Condition 1	Condition 2	q_1^{r*}	q_2^{r*}	$q_1^{r*} + q_2^{r*}$
1	$q_\rho \le \bar{q}_\rho$	$\bar{\theta}_\rho \le \theta \le \bar{\theta}_1$	$\rho_1 q_2^n$	$\rho_2 q_1^n$	q_ρ
2	$(\bar{\theta}_\rho \le \theta \le 1)$	$\bar{\theta}_1 < \theta < \bar{\theta}_2$	$\rho_1 q_2^n - \bar{q}_2^r$	$\bar{q}_2^r + \rho_2 q_1^n$	
3		$\bar{\theta}_2 \le \theta \le 1$	0	$\rho_1 q_2^n + \rho_2 q_1^n$	
4	$q_\rho > \bar{q}_\rho$	$0 < \rho_1 \le \bar{\rho}_1$	$\rho_1 q_2^n$	$\frac{a_2 - d_2 c^r - r_2 w^n}{2} (< \rho_2 q_1^n)$	$\bar{q}_\rho$
5	$(0 < \theta \le \bar{\theta}_\rho)$	$\bar{\rho}_1 < \rho_1 \le 1$	$\frac{a_1 - d_1 c^r - r_1 w^n}{2} (< \rho_1 q_2^n)$	$\frac{a_2 - d_2 c^r - r_2 w^n}{2} (< q_\rho - q_1^{r*})$	

Propositions 5.1 and 5.2 demonstrate that when the total supply of used products in two periods is not limited by the threshold $\bar{q}_\rho$, i.e., $q_\rho > \bar{q}_\rho$, the decision-makings in period 1 and 2 are completely independent. In this case, the optimal production in period 2 is not affected by that in period 1 (see Table 5.3 for solutions 4 and 5). We observe that in period 1, the firm collects all available used products $\rho_1 q_2^n$ whenever



(a) $q_\rho \leq \bar{q}_\rho$ or $\bar{\theta}_\rho \leq \theta \leq 1$



(b) $q_\rho > \bar{q}_\rho$ or $0 < \theta \leq \bar{\theta}_\rho$

Figure 5.3: Optimal policy structure for refurbishing

the recovery fraction ρ_1 is relatively low, i.e., $\rho_1 \leq \bar{\rho}_1$. Further, if the total supply of used products is limited by the threshold $\bar{q}$, i.e., $q_\rho \leq \bar{q}_\rho$, the decision-making in period 2 is dependent on the solutions in period 1. We observe that the higher the refurbished product price in period 1, the firm tends to decrease the price in period 2. This is because the lower the number of refurbished products sold in period 1, the higher the number of refurbished products sold in period 2. As Table 5.3 shows for solutions 1, 2, and 3, the price-drop coefficient θ determine the production decision of refurbished products in both period 1 and 2. With respect to $\bar{\theta}_1$ and $\bar{\theta}_2$, it is more beneficial for the firm to sell more refurbished products in period 2 when the price of new product generation 1 in the market is still relatively high. Otherwise, the firm should release and sell more refurbished products in period 1 before the new products price is dropped. This is because if the new product price is dropped, the firm cannot charge the refurbished product at a high price and thus decrease the refurbishing profit margin. In addition, when the price-drop coefficient is low enough such that $0 < \theta \leq \bar{\theta}_\rho$, the total supply of used products is not a constraint anymore, and the firm find it profitable to collect some used products in period 2.

Corollary 5.1 *For a given recovery fraction ρ_t, there exists a threshold $\hat{\rho}_j$, with $t, j \in \{1, 2\}$, $j \neq t$, such that when $\rho_j \leq \hat{\rho}_j$, $q_\rho \leq \bar{q}_\rho$, otherwise $q_\rho > \bar{q}_\rho$.*

Corollary 5.1 shows that if recovery fraction ρ_t, $t = 1, 2$ becomes large enough, the total sales of new products are no longer a constraint on the firm's refurbishing operations. Based on Proposition 5.2 and Corollary 5.1, when the recovery fraction

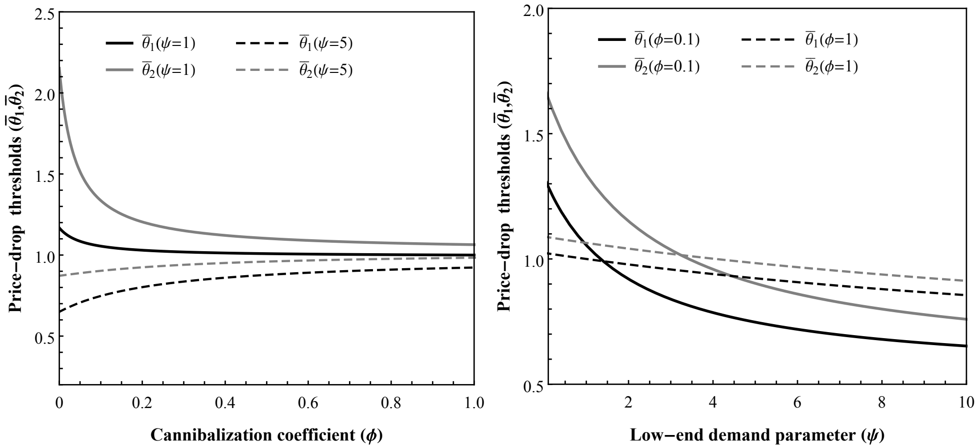
ρ_1 is relatively high such that $\hat{\rho}_1 < \bar{\rho}_1 < \rho_1$, the firm should not collect all available used products in period 1 and also in period 2. Hence, the firm should invest to increase the reusability rate in period 1 whenever $\rho_1 < \hat{\rho}_1$ and $\bar{\theta}_\rho \leq \theta \leq \bar{\theta}_1$, or $\hat{\rho}_1 \leq \rho_1 < \bar{\rho}_1$ and $0 < \theta < \bar{\theta}_\rho$. While the firm should invest more in increasing the reusability rate in period 2 whenever it is relatively low such that $\rho_2 < \hat{\rho}_2$.

5.4. Numerical Study

We provide two numerical examples to illustrate Proposition 5.2. *Case* 1. For new product generation 1, $p_1^n = 100$, $c_1^n = 60$, $Q^n = 1000$, $b_1 = .01$, $k_1 = 5$. For new product generation 2, $p_2^n = 120$, $c_2^n = 80$, $\phi = .8$, $\psi = .5$. For refurbished product, $c^r = 20$, $\rho_1 = \rho_2 = .2$. In period 2, $\theta = .9$, i.e., the price of the new product generation 1 drops 10% to 90. In period 2, the cannibalization level is high, although it is lower than that in period 1, and the low-end demand market base is low. In this case, $\bar{\theta}_1 = 1.15$, $\bar{\theta}_2 = 1.71$, $q_\rho = 350$, and $\bar{q}_\rho = 380$. The parameters $\bar{\theta}_1$ and $\bar{\theta}_2$ are higher than 1 and $q_\rho < \bar{q}_\rho$. Hence, the firm should introduce the refurbished products in period 1 and collect all available used products from the previous period. Moreover, $p_r^1 = 88$, $q_1^r = \rho_1 q_2^n = 173$, $p_r^2 = \rho_2 q_1^n = 73$, and $q_r^2 = 177$. The price of refurbished products in period 2 is lower than that in period 1, while the quantities are almost the same.

Case 2. For new product generation 1, $p_1^n = 100$, $c_1^n = 60$, $Q^n = 1000$, $b_1 = .01$, $k_1 = 7$. For new product generation 2, $p_2^n = 120$, $c_2^n = 80$, $\phi = .1$, $\psi = 5$. For refurbished product, $c^r = 20$, $\rho_1 = \rho_2 = .2$. In period 2, the cannibalization level is low and the low-end demand market base is high. We relax the parameter ψ such that it could be higher than 1. This means the potential market for refurbished products in period 2 could be higher than that in period 1. In this case, $\bar{\theta}_1 = .61$ and $\bar{\theta}_2 = .94$. The parameters $\bar{\theta}_1$ and $\bar{\theta}_2$ are lower than 1. First, let $\theta = .8$ such that $\bar{\theta}_1 < \theta < \bar{\theta}_2$. We obtain $p_r^1 = 95$, $p_r^2 = 72$, $q_1^r = 84 < \rho_1 q_2^n = 198$ and $q_2^r = \rho_1 q_2^n + \rho_1 q_2^n - q_1^r = 305$. Hence, the firm should release the refurbished products in period 1. However, it is more profitable for the firm to sell some refurbished products in that period and sell the remaining products in the next period. Further, let $\theta = 1 > \bar{\theta}_2$. We have $q_1^r = 0$, $q_2^r = \rho_1 q_2^n + \rho_1 q_2^n = 398$, and $p_r^2 = 83$. Hence, the firm should introduce the refurbished products in period 2.

Figure 5.4 gives us a relationship between price-drop thresholds, cannibalization

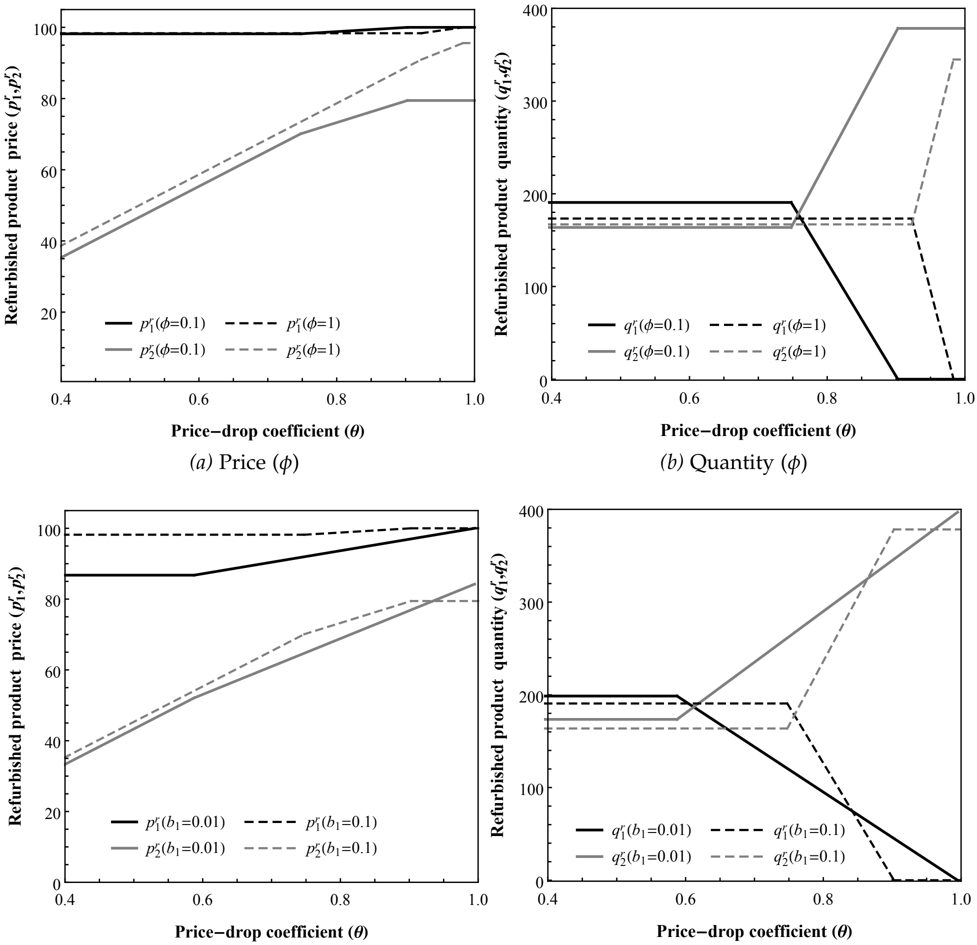


(a) ϕ *(b)* ψ

Figure 5.4: Values of price-drop thresholds $\bar{\theta}_1$ and $\bar{\theta}_2$ when $p_1^n = 100$, $c_1^n = 60$, $Q^n = 1000$, $k_1 = 5$, $p_2^n = 120$, $c_2^n = 80$, $c^r = 20$, $b_1 = .1$, $\rho_1 = \rho_2 = .2$, with $\bar{\theta}_1$ and $\bar{\theta}_2$ as in Proposition 5.2

level, and low-end market demand. It can be seen from the figure that having low cannibalization level in period 2 (parameter ϕ is low) is not enough to introduce or sell more refurbished products in that period. The firm also needs to take into account the low-end demand market base and the new price of the new product. If the low-end demand parameter (ψ) is small, it would be more beneficial for the firm to introduce refurbished products in period 1, although the cannibalization level in period 2 is low and the price-drop coefficient (θ) is high. The firm can release the refurbished products in period 2 whenever ϕ is small, and ψ and θ are high.

Figure 5.5 illustrates the refurbished product prices and quantities in both period 1 and 2 with respect to cannibalization parameters ϕ and b_1. We observe that the refurbished product price in period 2 is increasing in price-drop coefficient. However, it remains the same after a certain value of the coefficient since the firm decides not to sell refurbished products in period 1 and introduces them in period 2. Moreover, if ψ is relatively high, the higher cannibalization factor ϕ, the higher both $\bar{\theta}_1$ and $\bar{\theta}_2$. This means higher ϕ leads the firm to increase the refurbished product price in period 2 and sell all available refurbished products in period 1 if price-drop coefficient is low in order to decrease the impact of cannibalization on sales of new product generation 2. This is because it would be more detrimental to the firm if the cannibalization level is high, but the refurbished product price cannot

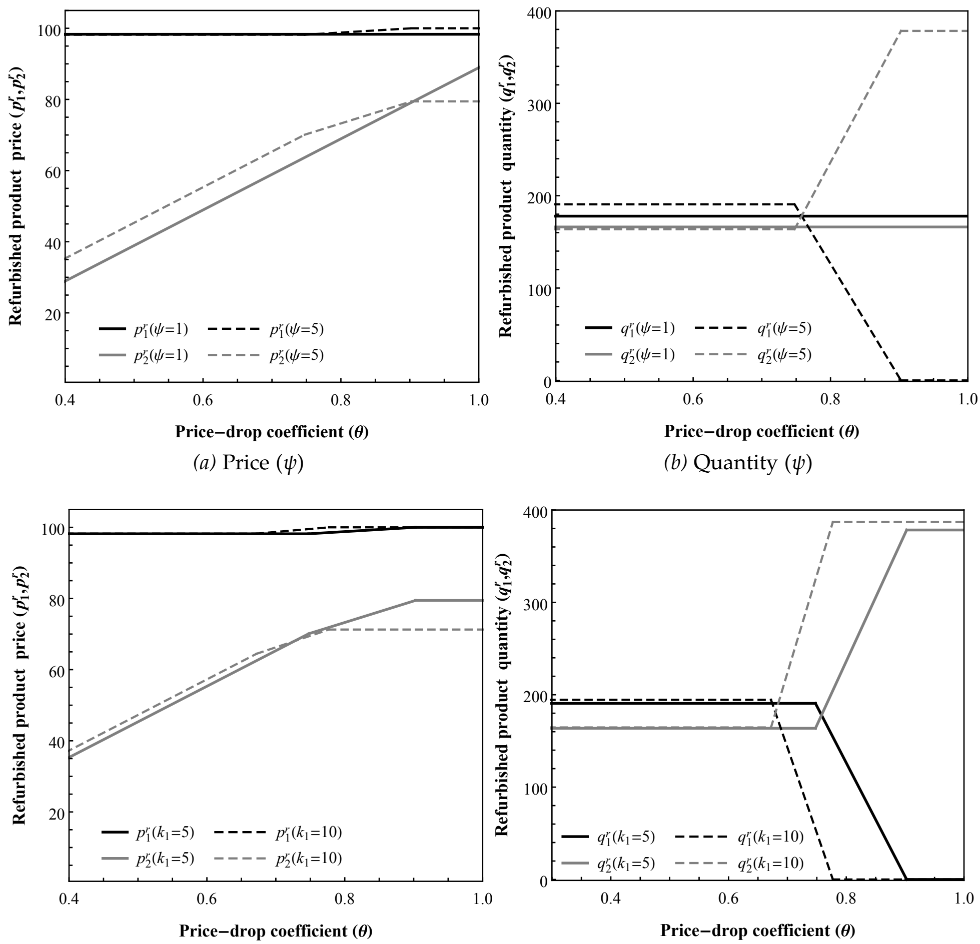


(a) Price (ϕ) *(b)* Quantity (ϕ)

(c) Price (b_1) *(d)* Quantity (b_1)

Figure 5.5: Refurbished product prices and quantities in period 1 and 2 when p_1^n = 100, c_1^n = 60, Q^n = 1000, k_1 = 5, p_2^n = 120, c_2^n = 80, ϕ = .1, ψ = 5, c^r = 20, $\rho_1 = \rho_2$ = .2, and b_1 = .1

be charged at a high price due to the low price-drop coefficient. While the lower price, the higher cannibalization's impact on the new product sales. In addition, we observe that the higher the cannibalization coefficient b in both period 1 and 2, the higher $\bar{\theta}_1$ and the lower $\bar{\theta}_2$. In other words, if the drop-price coefficient θ is relatively high, higher cannibalization coefficient b_1 will reduce the firm's intention to sell refurbished products in period 1. For example, it can be seen from Figure 5.5 that with θ = .9 and b_1 = .1, the firm introduces the refurbished products in period 2. While the firm still sells refurbished products in period 1 when $b_1 = .01$. Further, our observation indicates that the lower cannibalization level (parameters ϕ and b_1 are low), the firm should produce and sell more refurbished products in the market at a fairly high price, where the price in period 2 should be lower than that in period 1. With low cannibalization level, the firm sells more new products, and consequently, there is more supply of cores that could be collected.



(a) Price (ψ) *(b)* Quantity (ψ)

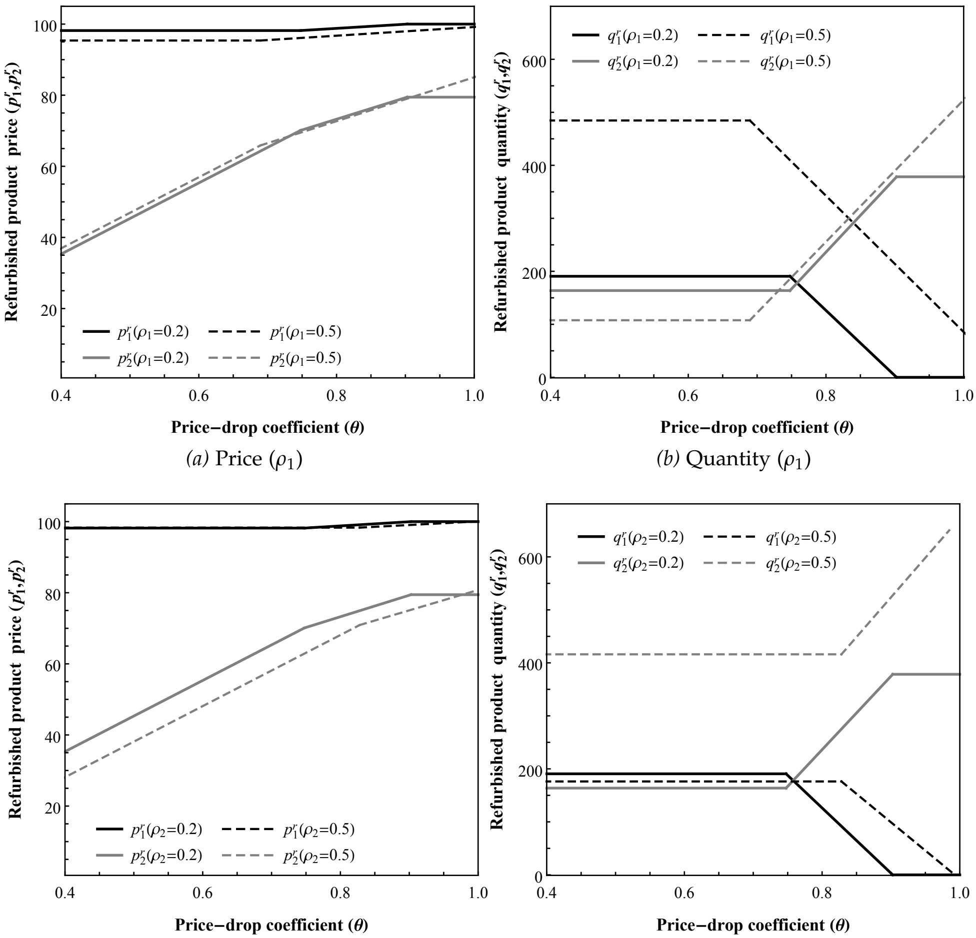
(c) Price (k_1) *(d)* Quantity (k_1)

Figure 5.6: Refurbished product prices and quantities in period 1 and 2 when $p_1^n = 100$, $c_1^n = 60$, $Q^n = 1000$, $k_1 = 5$, $p_2^n = 120$, $c_2^n = 80$, $\phi = .1$, $\psi = 5$, $c^r = 20$, $\rho_1 = \rho_2 = .2$, and $b_1 = .1$

Further, Figure 5.6 illustrates the refurbished product prices and quantities in both period 1 and 2 with respect to low-end demand parameters ψ and k_1. We observe that the low-end demand market base plays an important role in the production decision of refurbished products. The price-drop thresholds $\bar{\theta}_1$ and $\bar{\theta}_2$ decrease as the increase of low-end demand parameters ψ and k_1. Hence, it would be profitable for the firm to move the selling of refurbished products to period 2 when there is a huge low-end demand in the period compared to that in period 1. In this case, the firm increases the refurbished product price in period 2 in order to increase the profit margin and at the same time decrease the number of high-end consumers who switch to purchase the products. As a consequence, the total supply of refurbished products increases as the increase of low-end demand market base. Hence, when the price-drop coefficient is high and all available refurbished products are sold in one period, i.e., period 2, the firm decreases the product price as the low-end demand rises in order to increase the product sales.

Figure 5.7 illustrates the refurbished product prices and quantities in period 1 and 2 with respect to recovery fractions ρ_1 and ρ_2. It is obvious that the higher recovery fractions, the higher refurbished product quantity sold in the market as long as the firm finds it profitable to collect all available used products. If the firm invests to increase the recovery fraction in period 1 and sells all available refurbished products, more new product sales would be cannibalized. Hence, the number of new products sold in period 1 decreases and, as a consequence, will decrease the supply of cores for period 2. In this case, the firm should decrease the refurbished product price in period 1 to increase the product sales and increase it in period 2 to increase the profit margin. In addition, our observation indicates that the higher ρ_1, the lower $\bar{\theta}_1$ and the higher $\bar{\theta}_2$. A (huge) number of refurbished products sold in period 1 can be a threat to new product sales. Hence, the firm should move some of them to period 2 at some fairly low price-drop coefficient. However, although the price-drop coefficient is high, the firm may find it is not profitable to sell a huge number of refurbished products at one period (period 2) due to cannibalization and low-end demand in each period. On the other hand, the increase of recovery fraction ρ_2 will increase $\bar{\theta}_1$ and $\bar{\theta}_2$. A (huge) number of refurbished products sold in period 2 will also decrease the firm's intention to sell all products in the period.

Figure 5.8 illustrates the pricing and production decision of refurbished products when the supply of used products is no longer a constraint in refurbishing strategy, i.e., recovery fractions are high such that $0 < \theta \leq \bar{\theta}_\rho$ with $\bar{\theta}_\rho > 1$. It can be seen from

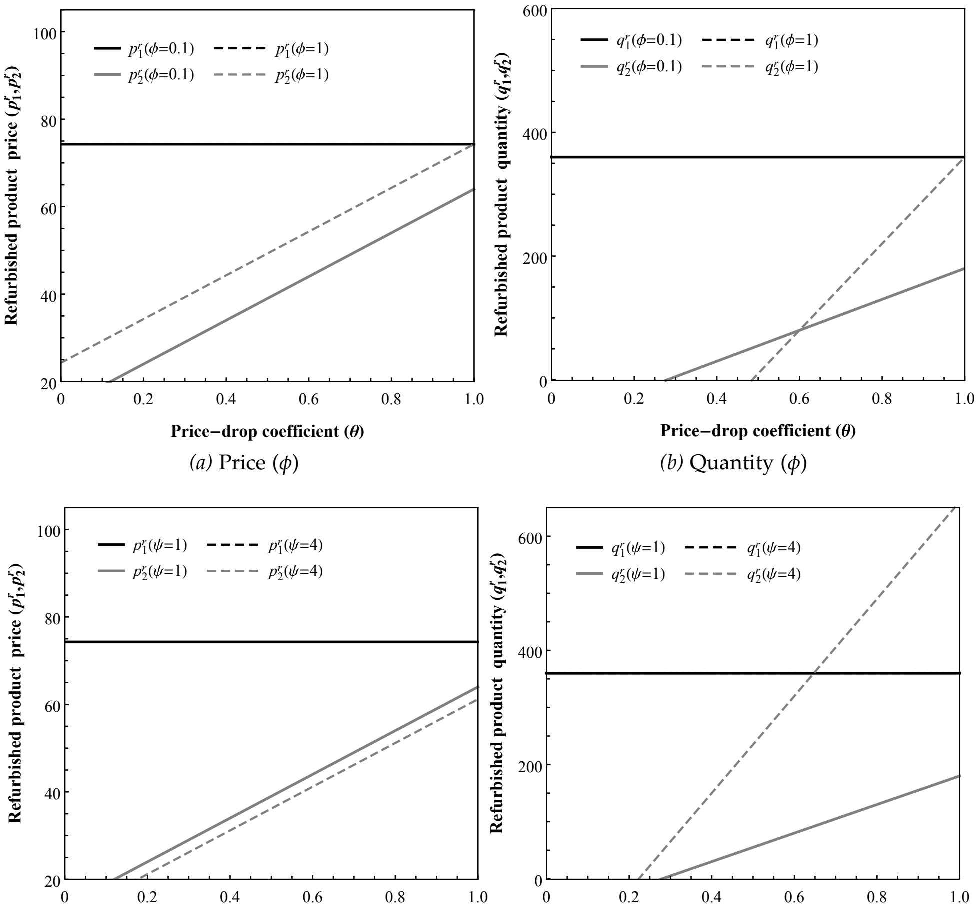


(a) Price (ρ_1) *(b)* Quantity (ρ_1)

(c) Price (ρ_2) *(d)* Quantity (ρ_2)

Figure 5.7: Refurbished product prices and quantities in period 1 and 2 when $p_1^n = 100$, $c_1^n = 60$, $Q^n = 1000$, $k_1 = 5$, $p_2^n = 120$, $c_2^n = 80$, $\phi = .1$, $\psi = 5$, $c^r = 20$, and $b_1 = .1$

the figure that the decision-making in period 1 and 2 are completely independent, and the firm does not collect all available used products in the two periods. We observe that the lower the price-drop coefficient (θ), the lower the number of refurbished products that should be sold. Moreover, having high cannibalization coefficient ϕ can have detrimental effects if the new product price drops too much since a low refurbished product price would increase the cannibalization level and decrease the profit margin. In this case, it would be more profitable to sell only



(a) Price (ϕ) *(b)* Quantity (ϕ) *(c)* Price (ψ) *(d)* Quantity (ψ)

Figure 5.8: Refurbished product prices and quantities in period 1 and 2 when $p_1^n = 100$, $c_1^n = 60$, $Q^n = 1000$, $k_1 = 4$, $p_2^n = 120$, $c_2^n = 80$, $\phi = .1$, $\psi = 1$, $c^r = 20$, and $b_1 = .01$

few refurbished products or does not engage in refurbishing. However, it can also be beneficial when the price-drop coefficient is relatively high since a high price would decrease the cannibalization level and increase the profit margin. In this case, the firm should increase the number of refurbished products sold in the market. Further, higher low-end demand (parameter ψ is high) leads the firm to sell more refurbished products, although the price-drop coefficient is low.

5.5. Conclusion

In this study, we investigate the strategic refurbishing decision across multiple product generations. To better understand the effect of multiple product generations on the refurbishing strategy, we construct a two-period production decision model and examine when is the best time to release the refurbished products, i.e., before the introduction of the next generation (period 1) or wait for it (period 2) and how the pricing and volume decisions are made. The critical components of our model are the issues of demand cannibalization, low-end demand, recovery fraction, and price-drop coefficient. If a newer generation is released, the previous one becomes unattractive, and thus the refurbished version of the old generation naturally is less desirable to consumers. Moreover, although the older generation has been discontinued, the price has dropped across the web. This influences the refurbished product's price since it should be lower than the price of the original product.

Our main observation shows that the firm should not only consider the best time for the refurbished product introduction, but also the production volume that should be produced and sold in each period. We derive conditions under which it is optimal for the manufacturer to release a new generation in period 1 or 2. The analytical results show that the optimal productions of refurbished products in each period are driven by the price-drop coefficient and recovery fractions. If the coefficient is low or the recovery fractions are relatively high, the total supply of used products is no longer a constraint in refurbishing strategy. Otherwise, the refurbishing is limited by the amount of core to acquire. Moreover, our core results indicate that having lower cannibalization level is not enough for the firm to introduce the refurbished products in period 2. The firm also needs to take into account the new price of the older generation and the low-end demand. Higher price-drop coefficient and low-end demand will lead the firm to sell more refurbished products or even introduce them in period 2. This is because the lower the price-drop coefficient, the lower the refurbished product price. If the product price cannot be charged at a high price, it would decrease the profit margin and increase the cannibalization level on new product sales. In addition, if the firm decides to invest to increase the reusability rate, it would not be profitable to sell all available refurbished products in just one period. The firm can sell them in both period 1 and 2 and focus on the optimal production in each period.

6
Conclusion

This chapter is devoted to present the conclusions of the research. In this dissertation, we studied revenue management and refurbishing strategy for firms engaged in the refurbishing economy. In Chapter 2, we conducted some behavioral studies to investigate the price-perceived quality relationships for refurbished products in various types of markets. In Chapter 3, 4, and 5, we developed analytical models that arise from various business problems in refurbishing. Specifically, Chapter 3 studied the revenue management in refurbishing duopoly involving two manufacturers selling both new and refurbished products; Chapter 4 investigated the authorization strategy in refurbishing involving a manufacturer and a third-party; and Chapter 5 explored the strategic decision making for refurbishing across new product generations.

6.1. Insights and Contribution

In this dissertation, we analyzed the refurbishing strategy based on behavioral studies and analytical models, and conclude that consumer behavior should be taken into consideration by manufacturers in strategic decision making. In this section, we summarize the main findings and insights of Chapter 2–5. In addition, we also discuss the future research directions.

6.1.1 Price-Perceived Quality Relationship for Refurbished Products

In Chapter 2, we conducted some behavioral studies to examine the relationship between price and perceived quality for refurbished products in various types of market: a secondary market (Study 1), a market with competition between new and refurbished products (Study 2), and the case of a market with competition between brands (Study 3). In particular, we examined the existence of an inverted U-shaped switching function in those various situations. The underlying assumption in current research is that consumers may use price as an indicator of refurbished product quality and begin to doubt the quality of the products when the price is relatively low. To the best our knowledge, this is the first study to explore how brands and competition intensity affect the price-perceived quality relationship for refurbished products. We also consider different approaches, i.e., price categorization and discrete choice experiment, in analyzing how consumers use prices as quality reference.

The experimental results show that price and perceived quality are highly correlated when the competitive intensity is low (Study 1 and 2). However, we obtained different results when using different approaches. Using discrete choice experiment, an inverted U-shaped switching function is only found in low-brand refurbished products. Consumers will start to become suspicious of the products' quality as the price get lower. In contrast, products with high-brand image will show a linear purchasing behavior because consumers have trust in the brand. On the other hand, using price categorization, the inverted U-shaped function is found in all products and brands. We observe that the different results between the methods are because of the methods' characteristics. In discrete choice experiments, consumers perceive a product option as a combination of attributes, and purchase decisions are made based on the consumer's utility maximization behavior. However, the consumers are unaware of the utilities that they attach to different attributes and only can indicate their preferences for different attribute combinations. On the other hand, in price categorization approach, respondents identify the range of acceptable prices for a single product with specific attributes. The procedure may put the idea into respondents' minds that there should be either a price that is too cheap or too expensive. Assuming that respondents seek to maximize their utility, discrete choice experiments are able to obtain a better understanding of consumer choice.

Further, if the competitive intensity is high (Study 3), we found that the inverted U-shaped cannibalization behavior is largely absent in a duopolistic setting. Although we observe the U-shaped behavior in the competition between firms with high brand-level difference (Apple versus Motorola), it is only apparent when the discount levels are quite high, and in fact, such steep discounts ($> 60 - 70\%$) are not common in reality. This is because a firm usually charges a price higher than its refurbishing cost in addition to a minimum profit margin. We also find that cross-cannibalization is an effect to be reckoned with, especially for low-brand valued firms facing competition from high-brand valued firms also offering refurbished products. On the other hand, a high-brand valued firm should be more concerned about internal cannibalization, while a low-brand valued firm needs not to worry too much about it.

6.1.2 Revenue Management in Refurbishing Duopoly with Cannibalization

In Chapter 3, we developed and analyzed a formal model to shed light onto how firms in a duopoly with different brand strengths should make strategic choices under (often publicly set) collection constraints. Our work differs from other models in the literature in the sense that we consider symmetric firms with different brand recognition. Both of our firms offer a new product and its refurbished version, with similar features. This allows us to introduce both internal and external (cross) cannibalization into our model, and the used product of a firm cannot be considered as a source of supply for another firm's refurbishing process. Our work contributes to the understanding of optimal refurbishment strategies in terms of the novelty of the model which based on the experimental results in Chapter 2. We introduced two types of cannibalization: Internal cannibalization of a new product that is caused due to the refurbished product made available by the same firm as a function of discount; and external (or cross) cannibalization that is caused by the presence of a competitors' refurbished product.

We observe that a high-brand firm has better business opportunities in refurbishing.

This is because the presence of their refurbished products sold at lower prices attracts consumers who switch from buying a new product of the low-brand valued firm. Hence, the high-brand valued firms can have huge potential gains in the market for their refurbished products. On the other hand, a low-brand valued firm has low internal and cross cannibalization. Hence, such a firm need not worry about cannibalization of new product sales. However, the low-brand firm should focus on estimating the potential market of refurbished products from low-end demand and could beat the high-brand firm through pricing. Our analytical results showed that manufacturers with a high brand value should increase the prices of their refurbished products if the cross-cannibalization coefficients of the low-brand consumers are higher. For low-brand firms, competing on price is challenging; instead, such firms should focus on beating the high-brand competitors in collection and refurbishing efforts. Finally, we show that the collection constraints have an effect on the pricing strategy of both the high-brand and the low-brand manufacturers. Such constraints typically set exogenously by public authorities will impact the actual pricing and market equilibria.

6.1.3 Authorization Strategy in Refurbishing with Consumer Behavior

In Chapter 4, we considered a supply chain consisting of two members, a manufacturer (OEM) that produces and sells new products and a refurbishing third party (3P) that produces and sells refurbished products. We developed and analyzed a formal model to examine the conditions under which both the OEM and the 3P may benefit via an authorization strategy. We studied the trade-off between the indirect benefit from authorizing a 3P and increase in market share versus the effect of cannibalization on new product sales. Based on the experimental results in Chapter 2, we assume the consumers switching from new to refurbished products follow an inverted U-shaped function, i.e., they get suspicious when the refurbished product prices are too low. This cannibalization function can also be viewed as a linear function when the price-quality threshold is sufficiently low. To the best our knowledge, we made the first attempt in the literature to incorporate the consumers purchasing behavior and the remanufacturable product supply in the authorization refurbishing strategy.

Our results show that the price-perceived quality threshold remanufacturable product supply should be taken into consideration by both the manufacturer and the 3P when dealing with authorization decisions. We show that the optimal solution for the 3P could be in a price-sensitive area, price-perceived quality threshold, or a quality-sensitive area. We show that the acceptable authorization fees for the 3P and the OEM are influenced by the pricing area of the 3P before and after being authorized. Hence, by knowing the area of the optimal refurbished product price, it will lead the two firms to reach a win-win solution. The 3P will accept the authorization fee when it is relatively low, while the OEM will obtain a higher profit in refurbishing authorization if the fee is relatively high. However, the OEM does not always benefit from higher authorization fee. This is because the 3P will increase the price as the increase of authorization fee, and consequently decrease the refurbished product quantity. Therefore, in order to reach an authorization agreement, the OEM does not need to offer its optimal fee because it might too high for the 3P to accept.

In terms of the remanufacturable product supply, we show that the lower reusability rate leads the 3P to concern on the price-sensitive area. We also show that the maximum acceptable authorization fee for 3P and the minimum acceptable fee for OEM when the product supply is limited are always lower than when the 3P could satisfy all demand. Thus, the 3P would prefer to accept authorization fees when the remanufacturable supply is large or can access more used products after being authorized. On the other hand, due to cannibalization, if the low-end demand is low, the manufacturer prefers to offer the refurbishing authorization to 3P who does not has too many refurbished products for sale. Therefore, the possibility of reaching a win-win solution for both the OEM and the 3P will increase as the low-end demand market base increases.

6.1.4 Strategic Decision Making for Refurbishing Across New Product Generations

In Chapter 5, we developed a two-period decision problem and analyzed the interaction between refurbishing and product innovation. Our work differs from other models in the literature in the sense that we more focus on the impact of new product generation life cycle on refurbishing strategy, whether manufacturer should launch the refurbished products before (period 1) or after (period 2) the introduction of the new generation. Hence, the refurbished products could be available with new products belonging to an earlier generation or recently released new products with the latest technology. We incorporated the critical components such as the issues of demand cannibalization, secondary market or low-end demand, recovery fraction, and the drop of new product price, into our model.

We show that the distribution of refurbished products should be produced and sold in each period is driven by the price-drop coefficient and recovery fractions. When the total remanufacturable product supply in two periods is relatively high, or the price-drop coefficient is low, the decision making in period 1 and 2 are completely independent. Otherwise, the decision making in period 2 is dependent on that of period 1. In period 1, the manufacturer has three options: full refurbishing, partial refurbishing, and no refurbishing. Having lower cannibalization level in period 2 is not enough for the firm to introduce the refurbished products in the period. The firm also needs to take into account the new price of older generation and the potential of low-end demand. Higher price-drop coefficient and low-end demand will lead the firm to sell more refurbished products or even introduce them in the second period. This is because if the product price cannot be charged at a high price, it would decrease the profit margin and increase the cannibalization level on new product sales. In addition, if the recovery fractions are relatively high, it would not be profitable to sell all available refurbished products in just one period (period 2). The firm can distribute them in both period 1 and 2 by determining the optimal production in each period.

6.2. Future Research Directions and Discussion

In this section, we briefly discuss some future research directions regarding the underlying concepts presented in this thesis. In Chapter 2, we have conducted a behavioral study to observe the relationship between price and perceived quality for refurbished products. In Chapter 5, we investigated the strategic decision making for refurbishing across new product generations. One interesting extension could be to conduct an empirical study to observe the impact of new product generations life cycle on refurbishing decision and on the price-perceived quality relationship. With respect to the limitation of our study, it is not clear whether the presence of refurbished version of the older generation has less cannibalization risk or may attract more customers due to the high price gap between the refurbished products and the new generation. Moreover, in Chapter 3, 4, and 5, we assume that the refurbishing operations have no effect on the firm's pricing, procurement, or other decisions about the new products. It is possible that the solutions of our models are better if these variables are endogenous. Another extension could be to consider the situation where the firm decides to re-optimize its new product prices at the same time it introduces refurbished products. In this case, the firm strategically optimizes its entire product line, resulting in a globally optimal solution.

We analyze the competition model between manufacturers or between a manufacturer and a third party in a stylized model. In practice, multiple manufacturers and/or third parties may be competing in the same market. It is insightful to construct and analyze an oligopolistic competition model with more competitive manufacturers selling their new and refurbished products in the same market. The duopoly analysis in this study serves as the first step in understanding the more general oligopoly case. We believe, intuitively, the purchasing behavior observed in the duopoly case will also be found in the oligopoly case since there will be an interaction between brands with different brand strength. However, a different cannibalization structure could be obtained in the oligopoly scenario, and we can investigate the effect of firm size on refurbishing decisions. Further, in the authorization strategy, we only consider the situation under which the manufacturer does not engage in refurbishing itself, and there is only one third party. There is no clear understanding of whether an authorization is a good choice for a manufacturer. In practice, there are several other ways for a manufacturer to participate in the secondary market: refurbishing and outsourcing. If the manufacturer integrates the refurbishing strategy into their business, the firm may benefit from refurbishing and could deter competition from a third party and limit the third party's access to refurbished products. Another alternative is that the manufacturer could choose to outsource the refurbishing operations to a third party. Hence, it would be insightful to have a comparative study conducted to analyze and compare those three refurbishing modes from both the manufacturer's and third party's perspective. From the third party's point of view, it is also important to choose one of the refurbishing modes, specifically when the firm also competes with other third parties. For example, the competition among authorized and unauthorized refurbished products will pose challenges for the third parties in developing refurbishing strategies.

Further, in this dissertation, we do not explicitly involve the environmental aspect in our analytical models and only focus on the economic side. A more comprehensive approach is to explicitly incorporate the environmental dimension into our models.

Strategic issues in refurbishing involve high-level decisions such as whether or not manufacturers (OEMs) should adopt a strategy of directly participating in the secondary market or even try to deter the secondary market of their products. Our results suggest that the manufacturer's choice not only depends on the cost savings and how many used products should be collected, but also on its brand recognition, consumer behavior, and the competitive environment. The effects of brand reputation on consumer behavior toward refurbished products come as one of the biggest surprises from the behavioral study. Firms with a high-end brand image or high-quality products experience linear cannibalization because the consumers trust the refurbished version of the product. Even in a competitive environment, the high-brand refurbished products are always dominant over its low-brand competitor. This is because the mid low-end market for new products is being cannibalized by refurbished high-end products. Therefore, the high-brand valued firms can have huge potential gains in the secondary market. In fact, Agrawal et al. (2015b) observe that refurbishing by high-brand manufacturer (i.e., Apple Inc.) can have a negative effect toward the refurbished products and on the perceived value of the brand. Due to the huge potential gains in the secondary market and the high cannibalization, the high-brand firm may find it profitable to directly participate in refurbishing business by themselves. The firm may also need to deter competition from third parties by creating internal policies through authorization schemes and/or lobbying external parties to make regulations against the selling of refurbished products. Such a strategy has been applied by Apple when they made an agreement with Amazon, which allows Amazon's online store to list the Apple's product line (Business, 2018; Check, 2018). The products can be sold and shipped by Amazon which are obtained directly from Apple. In return, Amazon will remove all unauthorized third parties selling refurbished iPhone from its site. In order to sell the refurbished iPhone on the Amazon online store, a third party has to apply to become an authorized third party with some requirements, including product quality and fees paid to Apple. If the high-brand firm does not offer refurbished products, third party would since there is a significant demand for the high-brand products at lower price. A third party does not produce and sell new products and thus, does not face the cannibalization cost of selling refurbished products. Hence, the third party may always find it profitable to refurbish.

For low-brand firms, competing on refurbished product price is challenging. When the high-brand competitor chooses to sell refurbished products, our results suggest that it might not be a good strategy for the low-brand firm to use the same strategy on the same market. The firm can offer the low-brand refurbished products in other market segments or places. For example, some Motorola smartphones were refurbished for reuse and then sent to developing countries (Motorola, 2020). The development of secondary markets could be strongly linked to growth in demand for the low-brand refurbished products in developing countries. Because of the economic conditions of the population, a significant demand of refurbished products could be imported from more developed countries. Our behavioral studies used a population with a focus only on U.S. consumers. Therefore, we may have different results in other cultures that have different norms for purchasing behavior and refurbished products. Another strategy that might be implemented by the low-brand firm for improving its profitability in a competitive environment is to focus on the new product innovation instead of participating directly in refurbishing. A promising direction for future research would be to explore the effect of the innovation rate of low-brand products in the presence of competition from high-brand refurbished products.

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A

Appendix of Chapter 2

A.1. Experimental Queries and Results of Study 1

In this section, the experimental designs, queries, and results of Study 1 are presented. Two different methods are used in Study 1, that is, price categorization and discrete choice experiment.

A.1.1 Experimental Design and Queries

A.1.1.1 Price Categorization

Experimental queries and demographics

Screen 1

The main objective of this research is to explore the price-level sensitivity for refurbished products based on attributes such as brand, product condition, seller identity, online marketplace, and eco-friendly certification. Price-sensitivity measurement has been established as a useful tool for pricing managers. Participants will be asked to complete the survey. We will only collect and process data that is strictly necessary for running the research.

Individual responses will not be shared with or disclosed to anyone outside the research team. However, we might use aggregated results from the collected data for scientific publications, presentations at conferences and workshops and other dissemination purposes.

Clicking on the "Agree" button indicates that you have read and understood the information provided, you voluntarily agree to participate in this study, your responses will be gathered to be used, stored, and shared in the ways described above.

Screen 2

Before we continue, we want to give you a basic definition of a refurbished product.

Refurbished product
Refurbished products are used items that customers have returned to the manufacturer because they have changed their minds or due to a defect. They can also be items or product demos with packaging damage in handling. To prepare a used item for resale, the manufacturer must put it through a detailed refurbishing process, including cleaning, running functionality tests, and repackaging. After a final check, the manufacturer can sell the product with a "remanufactured" or "refurbished" label. The refurbished products often come with warranties and sell for a good deal less than the new products.

Refurbished product condition
There are three possible conditions at which a refurbished product is available. An open box product is similar to a new one, except the item may be missing the original packaging or in the original packaging but not sealed. A refurbished product has been inspected, cleaned, and repaired to meet manufacturer specifications and is in excellent condition. This item may or may not be in the original packaging. A used condition product is fully operational and functions as intended, but may have some signs of cosmetic wear and has not been inspected by an authorized party. This item may be a store return that has been used.

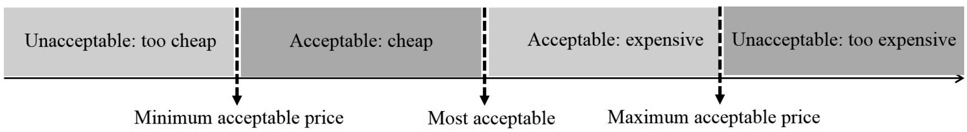
Seller identity
A used product could be refurbished either by an original equipment manufacturer (OEM) refurbished product has been refurbished directly by the original manufacturer; an authorized third party is a seller who has been approved and authorized by the OEM; an unauthorized third party is a seller who has not been approved by the OEM.

Eco-friendly certification
It is a system where labeling is used to certify that products have been produced using

environmentally sustainable practices. Carbon certifications: low carbon emissions during manufacturing. Sustainable product certification: the absence of toxic substances, efficient energy use, product recyclability, and packaging, as well as the manufacturer's socially responsible practices. Eco-certification: low level of environmental pollution, high safety and health standards, high levels of recyclable components and a balanced use of natural resources throughout a product's full lifecycle.

Screen 3

For the next products, we have listed a series of prices in USD. First look at all the prices. We are interested in knowing at which prices you would feel that the product is: unacceptable-too expensive, acceptable-expensive, most acceptable, acceptable-cheap, and unacceptable-too cheap.



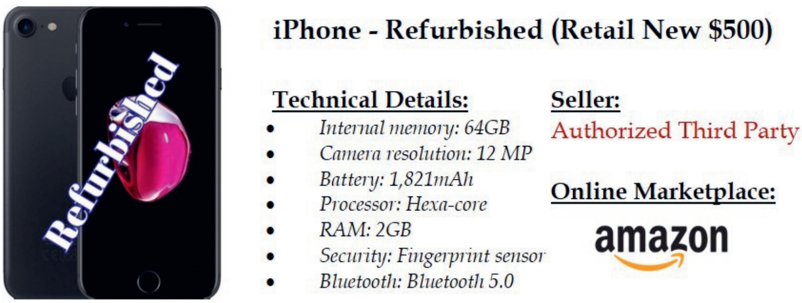
There are three questions in order to get those information:

- *Beyond what price would you consider it to be too expensive that you would never purchase it?*
- *What price would be the most acceptable?*
- *Below what price would you never buy it because you seriously doubt its quality?*

Screen 4

Please carefully read the product information.

- *Beyond what price would you consider it to be too expensive that you would never purchase it? (You can choose* $500 *if you do not consider all high prices as too expensive and would purchase it)*
- *What price would be the most acceptable? (Not cheap and not expensive)*
- *Below what price would you never buy it because you seriously doubt its quality? (You can choose* $25 *if you accept all low prices because you do not doubt the quality)*



Screen 5

Describe your feelings about the following statements.

	Strongly disagree (1)	(2)	(3)	(4)	(5)	(6)	(7) *Strongly agree*
The price of a product is a good indicator of its quality.	☐	☐	☐	☐	☐	☐	☐
The higher the price for a product, the higher the quality of the product.	☐	☐	☐	☐	☐	☐	☐
I enjoy the prestige of buying a high priced brand.	☐	☐	☐	☐	☐	☐	☐
It says something to people when you buy the high priced version of a product.	☐	☐	☐	☐	☐	☐	☐

Screen 6

Please indicate how knowledgeable you are of the following brands.

	Not at all knowledgeable (1)	(2)	(3)	(4)	(5) *Very knowledgeable*
Apple	☐	☐	☐	☐	☐
Motorola	☐	☐	☐	☐	☐

Please rank the following brands, indicate which brand you perceive as higher in quality and more trustworthy overall being the highest quality and the most trustworthy

☐ *Apple*	☐ *Motorola*

Screen 7

Demographic characteristics.

What is your gender

☐ *Female* ☐ *Male* ☐ *Prefer not to answer*

What is your age

□ < 18 □ 18 – 25 □ 26 – 35 □ 36 – 45 □ 46 – 55 □ > 55

What is your highest level of education

□ *Some high school* □ *Bachelors degree*
□ *High school diploma* □ *Some graduate work*
□ *Some university work* □ *Masters degree*
□ *Associates degree* □ *Professional degree*

What is your annual household income

□ < $12,000 □ $50,000 – $74,999
□ $12,000 – $15,999 □ $75,000 – $99,999
□ $16,000 – $24,999 □ > $100,000
□ $25,000 – $49,999

A.1.1.2 Discrete Choice Experiment

The syntax for Ngene and the chosen experimental designs are presented for Study 1 and the final questionnaire.

Ngene syntax efficient design

```
Design
;alts = refurbA, refurbB, neither
;rows = 20
;eff = (mnl,d)
;con
;cond:
        if(refurbA.condition=1, refurbA.seller=[1,2]),
        if(refurbB.condition=1, refurbB.seller=[1,2]),
        if(refurbA.seller=1,refurbA.market=[1]),
        if(refurbB.seller=1,refurbB.market=[1]),
        if(refurbA.seller=2,refurbA.market=[1,2]),
        if(refurbB.seller=2,refurbB.market=[1,2]),
        if(refurbA.seller=3,refurbA.market=[2,3]),
        if(refurbB.seller=3,refurbB.market=[2,3])
;model:
U(refurbA) = conditions*condition[1,2,3]+sellers*seller[1,2,3]
```

```
        + ecos*eco[1,2]+markets*market[1,2,3]
        + discount_linear*discountreb[.05,.1,.2,.3,.4,.5,.6,.7,.8,.9]*price[500]
        + discount_quadratic*discountreb*discountreb*price /
U(refurbB) = conditions*condition+sellers*seller
        +ecos*eco[1,2]+markets*market[1,2,3]
        + discount_linear*discountreb*price
        + discount_quadratic*discountreb*discountreb*price /
U(neither) = asc_neither
$
```

Efficient design - choice sets

Choice	*conda*	*sellera*	*ecoa*	*marketa*	*discounta*	*condb*	*sellerb*	*ecob*	*marketb*	*discountb*
1	1	1	2	1	.2	3	3	1	3	.7
2	3	2	1	1	.1	1	2	2	2	.6
3	2	2	1	1	.5	2	2	2	2	.05
4	2	2	1	2	.4	2	2	2	1	.9
5	3	3	1	2	.7	1	1	2	1	.2
6	1	2	1	2	.05	3	1	2	1	.5
7	3	2	2	2	.7	1	2	1	1	.2
8	1	1	2	1	.5	3	3	1	2	.05
9	3	3	1	3	.3	1	2	2	1	.8
10	2	3	2	3	.9	2	1	1	1	.4
11	2	1	1	1	.8	2	3	2	3	.3
12	1	2	2	1	.1	3	3	1	3	.5
13	2	3	2	2	.4	2	1	1	1	.9
14	2	1	1	1	.2	2	3	2	2	.7
15	2	3	2	3	.3	3	1	1	1	.8
16	1	2	1	1	.6	3	2	2	2	.1
17	3	1	2	1	.6	2	3	1	3	.1
18	3	3	2	3	.8	1	1	1	1	.3
19	1	2	1	2	.9	3	2	2	1	.4
20	3	1	2	1	.05	1	2	1	2	.6

Experimental queries and demographics

In the experiment, participants were assigned to only one brand, that is either Apple or Motorola.

Screen 1

This screen is the same as Screen 1 *of Section A.1.1.1.*

Screen 2

This screen is the same as Screen 2 *of Section A.1.1.1.*

Screen 3

The table in this screen illustrates an example of a choice task for Motorola smartphones. The similar example for Apple smartphones is shown in Table 2.3.

Assume that you are in need of a smartphone for your own use (not for sale or as a gift). You are offered 3 *alternatives: Buying a used/refurbished/open-box smartphone, buying a used/refurbished/open-box smartphone, not buying. The products have the same technical details: Internal memory:* 64*GB, camera resolution:* 12*MP, battery:* 1, 821*mAh, processor: hexa core, ram:* 2*GB, security: fingerprint sensor, bluetooth:* 5.0*.*

In the following questions, we are interested in knowing which alternative you would choose. There are 20 *choice sets. In each choice set, you are offered different product attributes and prices. Please carefully choose an alternative for yourself.*

Attributes	Option A	Option B	Option C
Brand	Motorola	Motorola	
Product condition			Not buying
Seller identity	Unauthorized third party	Original manufacturer	
Eco-friendly certification	Not mentioned	Not mentioned	
Marketplace	eBay	Motorola store	
Price (discount)	$100 (80% discount)	$350 (30% discount)	
Your choice	□	□	□

Screen 4

Describe your feelings about the following statements.

	Strongly disagree (1)	(2)	(3)	(4)	(5)	(6)	(7) *Strongly agree*
The price of a refurbished Apple smartphone is a good indicator of its quality.	☐	☐	☐	☐	☐	☐	☐
The higher the price for a refurbished Apple smartphone, the higher the quality of the product.	☐	☐	☐	☐	☐	☐	☐
For a refurbished Apple smartphone, I am not willing to go to extra effort to find lower price.	☐	☐	☐	☐	☐	☐	☐
For a refurbished Apple smartphone, the time it takes to find low prices is usually not worth the effort.	☐	☐	☐	☐	☐	☐	☐
For a refurbished Apple smartphone, I am not willing to go to extra effort to find lower price.	☐	☐	☐	☐	☐	☐	☐
For a refurbished Apple smartphone, the time it takes to find low prices is usually not worth the effort.	☐	☐	☐	☐	☐	☐	☐
For a refurbished Apple smartphone, I am very concerned about low prices, but I am equally concerned about product quality.	☐	☐	☐	☐	☐	☐	☐
When purchasing a refurbished Apple smartphone, I always try to maximize the quality I get for the money I spend.	☐	☐	☐	☐	☐	☐	☐

Screen 5

Please indicate how knowledgeable you are of the following brands.

	Not at all knowledgeable (1)	(2)	(3)	(4)	(5) *Very knowledgeable*
Apple	☐	☐	☐	☐	☐

Please choose the number corresponding to your answer.

	Very low quality (1)	(2)	(3)	(4)	(5) *Very high quality*
New Apple smartphone is of	☐	☐	☐	☐	☐
Refurbished Apple smartphone is of	☐	☐	☐	☐	☐

Screen 6

This screen is the same as Screen 7 (Demographic characteristics) of Section A.1.1.1.

A.1.2 Experimental Results

Table A.1: Estimation results of the MNL model

Parameter	Value	Std. error	T-test	P-value (p)	Robust std. error
Apple smartphone					
asc_neither	2.540***	.222	11.427	.000e+00	.251
b_condition	.092**	.034	2.746	6.033e-03	.034
b_seller	.551***	.068	8.056	8.882e-16	.071
b_eco	.090	.053	1.693	9.049e-02	.054
b_market	.158*	.065	2.433	1.499e-02	.065
b_discountlinear	4.204***	.508	8.278	2.220e-16	.546
b_discountquadratic	−1.745***	.434	−4.021	5.787e-05	.456
LL	−2135.55	AIC	4285.102	*	$p < .05$
Rho bar square	.226	BIC	4325.926	**	$p < .01$
Motorola smartphone					
asc_neither	2.759***	.226	12.187	.000e+00	.244
b_condition	.121***	.036	3.380	7.256e-04	.037
b_seller	.484***	.070	6.879	6.036e-12	.071
b_eco	.200***	.055	3.633	2.802e-04	.056
b_market	.049	.067	.723	4.695e-01	.067
b_discountlinear	3.371***	.526	6.405	1.507e-10	.546
b_discountquadratic	−.449	.453	−.991	3.219e-01	.465
LL	−2165.18	AIC	4344.36	***	$p < .001$
Rho bar square	.215	BIC	4385.18		

Table A.2: Example of calculating demand share of alternatives with the MNL utility scores

Attributes	Buying	Utility	Not buying	Utility
Apple smartphone				
Product condition	Refurbished	.184	–	
Seller identity	Authorized 3P	1.103	–	
Marketplace	Amazon	.316	–	
Eco-friendly certification	Not mentioned	2.095	–	
Price (discount)	250$ (50%)	1.666	–	
Total		3.358		2.540
Corresponding exponent	28.739		12.679	
Demand share	69%		31%	
Motorola smartphone				
Product condition	Refurbished	.242	–	
Seller identity	Authorized 3P	.968	–	
Marketplace	Amazon	.098	–	
Eco-friendly certification	Not mentioned	.200	–	
Price (discount)	250$ (50%)	1.573	–	
Total		3.080		2.759
Corresponding exponent	21.766		15.786	
Demand share	58%		42%	

Table A.3: Estimation results of the LC model for Apple smartphone

	Class 1: QD (83.27%)			Class 2: LD (16.73%)		
Parameter	Value	T-test	P-value (p)	Value	T-test	P-value (p)
asc_neither	2.599***	8.119	4.441e-16	3.616***	4.001	6.297e-05
b_condition	.101**	2.753	5.913e-03	.101**	2.753	5.913e-03
b_seller	.575***	7.592	3.153e-14	.575***	7.592	3.153e-14
b_eco	.308**	2.709	6.741e-03	−2.503***	−3.014	2.579e-03
b_market	.043	.485	6.274e-01	1.725***	3.383	7.181e-04
b_discountlinear	4.579***	8.887	.000e+00	4.579***	8.887	.000e+00
b_discountquadratic	−2.134***	−4.641	3.474e-06	–	–	–
LL	−2130.21	AIC	4282.424	**	$p < .01$	
Rho bar square	.227	BIC	4346.576	***	$p < .001$	

Table A.4: Estimation results of the LC model for Motorola smartphone

	Class 1: QD (11.97%)			Class 2: LD (88.03%)		
Parameter	Value	T-test	P-value (p)	Value	T-test	P-value (p)
asc_neither	2.491*	2.366	1.797e-02	6.206***	9.008	.000e+00
b_condition	.128*	2.071	3.840e-02	.128*	2.071	3.840e-02
b_seller	.826***	7.294	3.009e-13	.826***	7.294	3.009e-13
b_eco	2.223*	2.229	2.582e-02	.250**	2.739	6.170e-03
b_market	.165	1.649	9.921e-02	.165	1.649	9.921e-02
b_discountlinear	8.866***	6.149	7.789e-10	8.866***	6.149	7.789e-10
b_discountquadratic	−23.856***	−6.059	1.374e-09	−3.085**	−3.015	2.573e-03
LL	−2139.08	AIC	4300.158	*	$p < .05$	***
Rho bar square	.223	BIC	4364.31	**	$p < .01$	$p < .001$

Table A.5: Example of demand share of alternatives with the LC utility scores for Apple smartphone

Attributes	Buying	Utility		Not buying	Utility	
		Class 1	Class 2		Class 1	Class 2
Product condition	Refurbished	.202	.202		–	–
Seller identity	Authorized 3P	1.150	1.150		–	–
Marketplace	Amazon	.085	3.450		–	–
Eco-friendly certification	Not mentioned	.308	−2.503		–	–
Price (discount)	$250 (50%)	1.756	2.290		–	–
Total		3.501	4.589		2.599	3.616
Corresponding exponent		33.157	98.295		13.444	37.174
Demand share per class		71.15%	72.58%		28.85%	27.42%
Class size		83.27%	16.73%		83.27%	16.73%
Demand share per alternative	71.39%	59.25%	12.14%	28.61%	24.02%	4.59%

Table A.6: Example of demand share of alternatives with the LC utility scores for Motorola smartphone

Attributes	Buying	Utility		Not buying	Utility	
		Class 1	Class 2		Class 1	Class 2
Product condition	Refurbished	.257	.257		–	–
Seller identity	Authorized 3P	1.653	1.653		–	–
Marketplace	Amazon	.329	.329		–	–
Eco-friendly certification	Not mentioned	2.223	.250		–	–
Price (discount)	\$250 (50%)	−1.531	3.662		–	–
Total		2.931	6.151		2.491	6.206
Corresponding exponent		18.746	469.114		12.077	495.822
Demand share per class		60.82%	48.62%		39.18%	51.38%
Class size		11.97%	88.03%		11.97%	88.03%
Demand share per alternative	50.08%	7.28%	42.80%	49.92%	4.69%	45.24%

A.2. Experimental Queries and Results of Study 2

In this section, the experimental designs, queries, and results of Study 2 are presented.

A.2.1 Experimental Design and Queries

The syntax for Ngene and the chosen experimental designs are presented for Study 2 and the final questionnaire.

Ngene syntax efficient design

```
Design
;alts = refurbA, refurbB, new
;rows = 20
;eff = (mnl,d)
;con
;cond:
if(refurbA.condition=1, refurbA.seller=[1,2]), if(refurbB.condition=1, refurbB.seller=[1,2])
;model:
U(refurbA) = asc_refurbA + conditions*condition[1,2,3]+sellers*seller[1,2,3]
        + discount_linear*discountreb[.05,.1,.2,.3,.4,.5,.6,.7,.8,.9]*price[600]
        + discount_quadratic*discountreb*discountreb*price /
U(refurbB) = conditions*condition+sellers*seller + discount_linear*discountreb*price +
        discount_quadratic*discountreb*discountreb*price /
U(new) = asc_new
$
```

Efficient design - choice sets

Choice situation	*refurba. condition*	*refurba. seller*	*refurba. discountreb*	*refurbb. condition*	*refurbb. seller*	*refurbb. discountreb*
1	3	3	.05	1	1	.5
2	1	2	.9	3	2	.4
3	1	2	.7	3	2	.2
4	2	2	.4	2	2	.9
5	3	1	.3	1	2	.8
6	1	1	.05	3	3	.5
7	1	1	.5	3	3	.05
8	3	3	.8	1	1	.3
9	3	2	.6	1	2	.1
10	2	3	.4	2	1	.9
11	1	1	.6	3	3	.1
12	2	1	.9	2	3	.4
13	3	2	.8	1	2	.3
14	2	3	.5	2	1	.05
15	1	2	.1	3	1	.6
16	2	1	.2	2	3	.7
17	2	2	.3	2	2	.8
18	3	1	.2	2	3	.7
19	3	3	.7	1	1	.2
20	2	3	.1	3	1	.6

Experimental queries and demographics
In the experiment, participants were assigned to only one brand, that is either Apple or Motorola.

Screen 1

The main objective of this research is to explore the price-level sensitivity for refurbished products under a competitive setting involving refurbished and new products. Price-sensitivity measurement has been established as a useful tool for pricing managers. Participants will be asked to complete the survey. We will only collect and process data that is strictly necessary for running the research. Individual responses will not be shared with or disclosed to anyone outside the research team. However, we might use aggregated results from the collected data for scientific publications, presentations at conferences and workshops and other dissemination purposes.

Clicking on the "Agree" button indicates that you have read and understood the information provided, you voluntarily agree to participate in this study, your responses will be gathered to be used, stored, and shared in the ways described above.

Screen 2

This screen provides the basic definition of a refurbished product, refurbished product condition, and seller identity, as defined in Screen 2 *of Section A.1.1.1.*

Screen 3

The table in this screen illustrates an example of a choice task for Motorola smartphones. The similar example for Apple smartphones is shown in Table 2.4.

Assume that you are in need of a smartphone for your own use (not for sale or as a gift). You are offered 3 *products: used/refurbished/open box smartphone, used/refurbished/open box smartphone, new smartphone. The three products have the same technical details: Internal memory:* 64*GB, camera resolution:* 12*MP, battery:* 1,821*mAh, processor: hexa core, ram:* 2*GB, security: fingerprint sensor.*

In the following questions, we are interested in knowing which product you would choose. There are 20 *choice sets. In each choice set, you are offered different product conditions and prices. Please carefully choose a product that you would buy for yourself.*

Attributes	Option A	Option B	Option C
Brand	Motorola	Motorola	Motorola
Product condition			
Seller identity	Unauthorized third party	Authorized third party	Original manufacturer (Apple Inc.)
Price (discount)	$288 (40% discount)	$48 (90% discount)	$480
Your choice	☐	☐	☐

Screen 4

Describe your feelings about the following statements.

	Strongly disagree (1)	(2)	(3)	(4)	(5)	(6)	(7) *Strongly agree*
For refurbished Apple smartphone, the price of a product is a good indicator of its quality.	□	□	□	□	□	□	□
For refurbished Apple smartphone, the higher the price for a product, the higher the quality of the product.	□	□	□	□	□	□	□
For refurbished Apple smartphone, I am not willing to go to extra effort to find lower price.	□	□	□	□	□	□	□
For refurbished Apple smartphone, the time it takes to find low prices is usually not worth the effort.	□	□	□	□	□	□	□
For refurbished Apple smartphone, I am not willing to go to extra effort to find lower price.	□	□	□	□	□	□	□
For refurbished Apple smartphone, the time it takes to find low prices is usually not worth the effort.	□	□	□	□	□	□	□
For refurbished Apple smartphone, I am very concerned about low prices, but I am equally concerned about product quality.	□	□	□	□	□	□	□
For refurbished Apple smartphone, when purchasing a product, I always try to maximize the quality I get for the money I spend.	□	□	□	□	□	□	□

Screen 5

Please indicate how knowledgeable you are of the following brands.

	Not at all knowledgeable (1)	(2)	(3)	(4)	(5) *Very knowledgeable*
Apple	□	□	□	□	□

Please choose the number corresponding to your answer.

	Very low quality (1)	(2)	(3)	(4)	(5) *Very high quality*
New Apple smartphone is of	□	□	□	□	□
Refurbished Apple smartphone is of	□	□	□	□	□

Screen 6

This screen is the same as Screen 7 (Demographic characteristics) of Section A.1.1.1.

A.2.2 Experimental Results

Table A.7: Estimation results of the MNL model.

Parameter	Value	Std. error	T-test	P-value (p)	Robust std. error
Apple smartphone					
asc_new	1.569***	.185	8.468	.000e+00	.184
b_condition	.123***	.036	3.426	6.119e-04	.036
b_seller	.444***	.038	11.774	.000e+00	.037
b_discountlinear	3.845***	.479	8.023	1.110e-15	.477
b_discountquadratic	−1.706***	.417	−4.090	4.306e-05	.416
LL	−1786.91	AIC	3583.818		
Rho bar square	.208	BIC	3611.97		
Motorola smartphone					
asc_new	1.546***	.189	8.178	2.220e-16	.189
b_condition	.187***	.037	5.109	3.238e-07	.037
b_seller	.415***	.038	10.937	$.000e + 00$	.038
b_discountlinear	3.670***	.485	7.567	3.819e-14	.476
b_discountquadratic	−1.603***	.422	−3.794	1.485e-04	.415
LL	−1712.40	AIC	3434.808	***	$p < .001$
Rho bar square	.210	BIC	3462.763		

Table A.8: Relative importance of attributes for the MNL model

	Apple		Motorola	
Attributes	Utility range	Relative importance	Utility range	Relative importance
Discount	1.746	60.60%	1.689	58.35%
Product condition	.247	8.56%	.375	12.95%
Seller identity	.888	30.84%	.831	28.70%
Sum	2.881	100%	2.895	100%

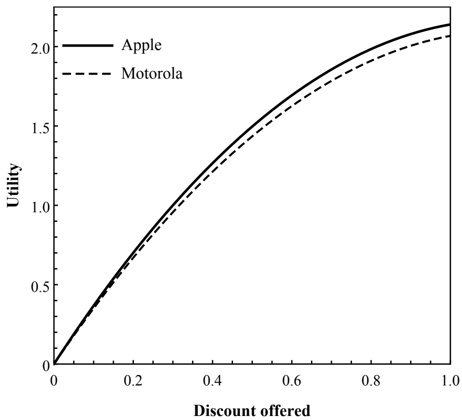
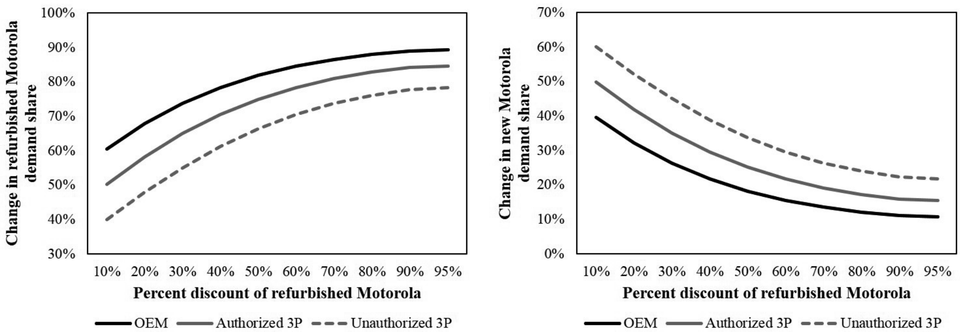


Figure A.1: Utility function of discounts offered in the MNL model

Table A.9: Example of demand share of alternatives with the MNL utility scores

Attributes	Refurbished smartphone	Utility	New smartphone	Utility
Apple smartphone				
Product condition	Refurbished	.247	New	
Seller identity	Authorized 3P	.888	OEM	1.569
Price (discount)	$300 (50%)	1.496	$600	
Total		2.631		1.569
Corresponding exponent	13.888		4.802	
Demand share	74.31%		25.69%	
Motorola smartphone				
Product condition	Refurbished	.375	New	
Seller identity	Authorized 3P	.831	OEM	1.546
Price (discount)	$240 (50%)	1.434	$480	
Total		2.640		1.546
Corresponding exponent	14.013	4.693		
Demand share	74.91%		25.09%	



(a) Refurbished Motorola *(b)* New Motorola

Figure A.2: Change in demand share of refurbished and new Motorola products from discount increases of refurbished products in the MNL model

Table A.10: Estimation results of the LC model for Apple smartphone (iPhone)

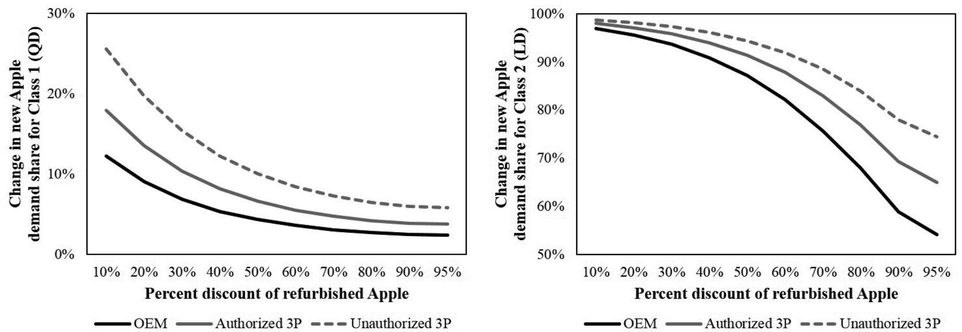
	Class 1: QD (85.1%)			Class 2: LD (14.9%)		
Parameter	Value	T-test	P-value (p)	Value	T-test	P-value (p)
asc_new	–	–	–	5.458***	6.271	3.588e-10
b_condition	.123***	3.353	7.995e-04	.123***	3.353	7.995e-04
b_seller	.452***	11.551	.000e+00	.452***	11.551	.000e+00
b_discountlinear	3.883***	7.563	3.930e-14	3.883***	7.563	3.930e-14
b_discountquadratic	−1.769***	−3.810	1.391e-04	–	–	–
LL	−1786.94	AIC	3585.872	***	$p < .001$	
Rho bar square	.208	BIC	3619.654			

Table A.11: Estimation results of the LC model for Motorola smartphone

	Class 1: QD (15.5%)			Class 2: LD (84.5%)		
Parameter	Value	T-test	P-value (p)	Value	T-test	P-value (p)
asc_new	–	–	–	1.823***	5.224	1.747e-07
b_condition	.202***	4.471	7.778e-06	.202***	4.471	7.778e-06
b_seller	.453***	7.828	4.885e-15	.453***	7.828	4.885e-15
b_discountlinear	2.755***	7.329	2.316e-13	2.755***	7.329	2.316e-13
b_discountquadratic	−4.435*	−2.004	4.506e-02	–	–	–
LL	−1716.99	AIC	3445.998	*	$p < .05$	
Rho bar square	.208	BIC	3479.543	***	$p < .001$	

Table A.12: Example of demand share of alternatives with the LC utility scores

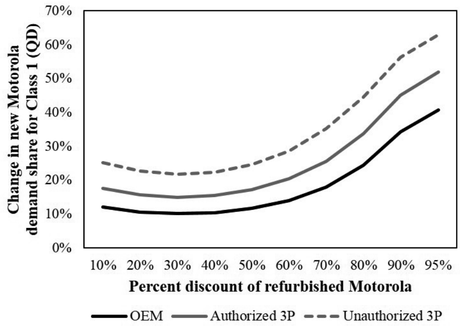
		Utility			Utility	
Attributes	Refurbished	Class 1	Class 2	New	Class 1	Class 2
Apple smartphone						
Product condition	Refurbished	.245	.245	New		
Seller identity	Authorized 3P	.904	.904	OEM	.000	5.458
Price (discount)	$300 (50%)	1.500	1.942	$600		
Total		2.649	3.091		.000	5.458
Corresponding exponent		14.140	21.999		1.000	234.628
Demand share per class		93.39%	8.57%		6.61%	91.43%
Class size		85.10%	14.90%		85.10%	14.90%
Demand share per product	80.75%	79.47%	1.28%	19.25%	5.63%	13.62%
Motorola smartphone						
Product condition	Refurbished	.405	.405	New		
Seller identity	Authorized 3P	.906	.906	OEM	.000	1.823
Price (discount)	$240 (50%)	.269	1.378	$480		
Total		1.580	2.689		.000	1.823
Corresponding exponent		4.855	14.717		1.000	6.1904
Demand share per class		82.92%	70.39%		17.08%	29.61%
Class size		15.50%	84.50%		15.50%	84.50%
Demand share per product	72.33%	12.85%	59.48%	27.67%	2.65%	25.02%



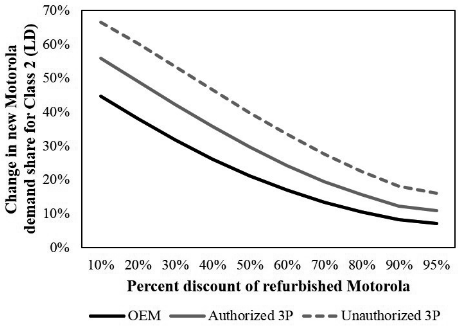
(a) Apple-Class 1 (QD)

(b) Apple-Class 2 (LD)

Figure A.3: Change in demand share of new Apple products from discount increases of refurbished products in the LC model

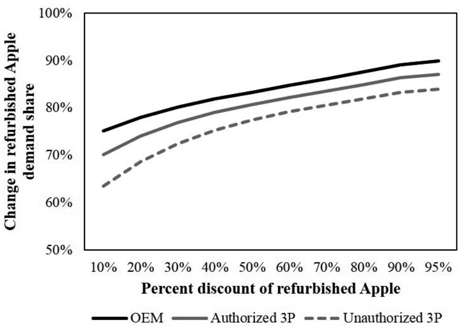


(a) Motorola-Class 1 (QD)

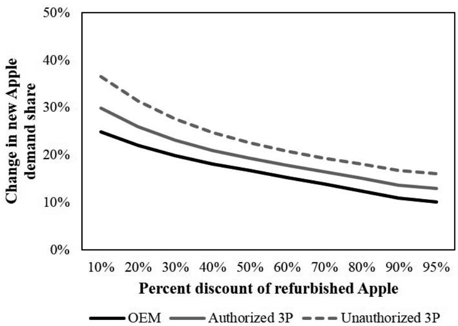


(b) Motorola-Class 2 (LD)

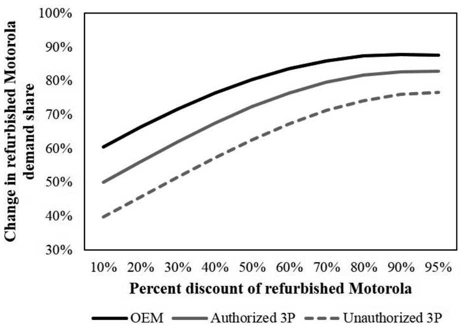
Figure A.4: Change in demand share of new Motorola products from discount increases of refurbished products in the LC model



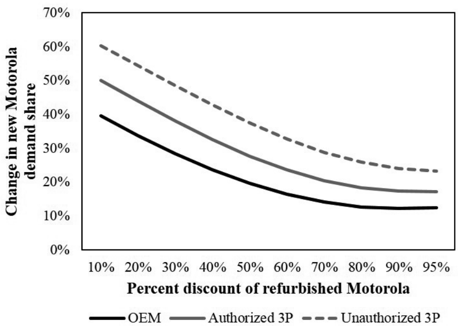
(a) Refurbished Apple



(b) New Apple



(c) Refurbished Motorola



(d) New Motorola

Figure A.5: Change in demand share of refurbished and newproducts from discount increases of refurbished products in the LC model

A.3. Experimental Queries and Results of Study 3

In this section, the experimental designs, queries, and results of Study 3 are presented.

A.3.1 Experimental Design and Queries

The syntax for Ngene and the chosen experimental designs are presented for Study 3 and the final questionnaire.

Ngene syntax efficient design

```
Design
;alts = brandA_refurb, brandB_refurb, brandA_new, brandB_new
;rows = 20
;eff = (mnl,d)
;con
;model:
U(brandA_refurb) = ascA_refurb + conditions*condition[1,2]
        + discount_linearA*discountreb[.05,.1,.2,.3,.4,.5,.6,.7,.8,.9]*priceA[600]
        + discount_quadraticA*discountreb*discountreb*priceA /
U(brandB_refurb) = conditions*condition + discount_linearB*discountreb*priceB[480]
        + discount_quadraticB*discountreb*discountreb*priceB /
U(brandA_new) = ascA_new/
U(brandB_new) = ascB_new/
$
```

Efficient design - choice sets

Choice situation	*branda_refurb. condition*	*branda_refurb. discountreb*	*brandb_refurb. condition*	*brandb_refurb. discountreb*
1	2	.05	1	.1
2	2	.9	1	.1
3	2	.1	1	.8
4	1	.9	2	.9
5	1	.6	2	.7
6	1	.5	2	.05
7	1	.3	2	.05
8	2	.8	1	.5
9	1	.05	2	.3
10	1	.1	2	.6
11	1	.4	2	.4
12	2	.7	1	.2
13	1	.8	2	.3
14	2	.5	1	.4
15	1	.2	2	.7
16	1	.7	2	.6
17	2	.3	1	.5
18	2	.6	1	.9
19	2	.4	1	.2
20	2	.2	1	.8

Experimental queries and demographics

In the experiment, participants were assigned to only one competition: Apple versus Motorola, Samsung versus Motorola, or Apple versus Samsung.

Screen 1

The main objective of this research is to explore the price-level sensitivity for refurbished products under a competitive setting involving two different brands. Price-sensitivity measurement has been established as a useful tool for pricing managers. Participants will be asked to complete the survey. We will only collect and process data that is strictly necessary for running the research. Individual responses will not be shared with or disclosed to anyone outside the research team. However, we might use aggregated results from the collected data for scientific publications, presentations at conferences and workshops and other dissemination purposes.

Clicking on the "Agree" button indicates that you have read and understood the information provided, you voluntarily agree to participate in this study, your responses will be gathered to be used, stored, and shared in the ways described above.

Screen 2

This screen provides the basic definition of a refurbished product and refurbished product condition, as defined in Screen 2 of Section A.1.1.1.

Screen 3

The tables in this screen illustrate the examples of a choice task for Samsung versus Motorola and a choice task for Apple versus Samsung. The similar example for Apple versus Motorola is shown in Table 2.5.

Assume that you are in need of a smartphone for your own use (not for sale or as a gift). You are offered 4 products: refurbished/used Apple smartphone, refurbished/used Motorola smartphone, new Apple smartphone, new Motorola smartphone. The four products have similar technical details: Internal memory: 64GB, camera resolution: 12MP, security: fingerprint sensor.

In the following questions, we are interested in knowing which product you would choose. There are 20 choice sets. In each choice set, you are offered different product conditions and prices. Pick carefully a product that you would buy for yourself.

Attributes	Option A	Option B	Option C	Option D
Brand	Samsung	Motorola	Samsung	Motorola
Product condition				
Price (discount)	\$540 (10% discount)	\$384 (20% discount)	\$600	\$480
Your Choice	☐	☐	☐	☐

Attributes	Option A	Option B	Option C	Option D
Brand	Apple	Samsung	Apple	Samsung
Product condition				
Price (discount)	\$540 (10% discount)	\$480 (20% discount)	\$600	\$600
Your Choice	☐	☐	☐	☐

Screen 4

Pick the choices closest to your personal opinion about refurbished or used phones of these brands.

	Very low quality (1)	(2)	(3)	(4)	(5) *Very high quality*
Refurbished Apple smartphone is of	☐	☐	☐	☐	☐
Refurbished Motorola smartphone is of	☐	☐	☐	☐	☐
Used Apple smartphone is of	☐	☐	☐	☐	☐
Used Motorola smartphone is of	☐	☐	☐	☐	☐

Screen 5

This screen is the same as Screen 7 (Demographic characteristics) of Section A.1.1.1.

A.3.2 Experimental Results

Table A.13: Estimation results of the MNL model for Apple versus Motorola

Parameter	Value	Std.error	T-test	P-value (p)	Robust std.error
asc_new_apple	2.182***	.184	11.868	.000e+00	.186
asc_new_motorola	1.901***	.186	10.200	.000e+00	.190
b_condition_apple	.679***	.082	8.268	2.220e-16	.081
b_condition_motorola	.518***	.094	5.524	3.307e-08	.087
b_discountlinear_apple	6.760***	.696	9.710	.000e+00	.669
b_discountlinear_motorola	5.649***	.835	6.768	1.304e-11	.775
b_discountquadratic_apple	−3.689***	.633	−5.825	5.707e-09	.606
b_discountquadratic_motorola	−2.962***	.744	−3.984	6.785e-05	.702
LL	−2704.41	AIC	5424.810	***	$p < .001$
Rho bar square	.205	BIC	5471.273		

Table A.14: Estimation results of the MNL model for Samsung versus Motorola

Parameter	Value	Std.error	T-test	P-value (p)	Robust std.error
asc_new_samsung	2.335***	.190	12.297	.000e+00	.191
asc_new_motorola	2.100***	.192	10.944	.000e+00	.192
b_condition_samsung	.882***	.085	10.390	.000e+00	.085
b_condition_motorola	.876***	.095	9.243	.000e+00	.091
b_discountlinear_samsung	5.791***	.726	7.979	1.554e-15	.699
b_discountlinear_motorola	4.063***	.814	4.994	5.923e-07	.792
b_discountquadratic_samsung	−3.376***	.662	−5.098	3.424e-07	.643
b_discountquadratic_motorola	−1.915**	.743	−2.578	9.945e-03	.726
LL	−2520.49	AIC	5056.984	**	$p < .01$
Rho bar square	.163	BIC	5102.481	***	$p < .001$

Table A.15: Estimation results of the MNL model for Apple versus Samsung

Parameter	Value	Std.error	T-test	P-value (p)	Robust std.error
asc_new_apple	1.720***	.176	9.789	0.000e+00	.171
asc_new_samsung	1.342***	.179	7.514	5.751e-14	.173
b_condition_apple	.398***	.080	4.948	7.483e-07	.080
b_condition_samsung	.338***	.080	4.200	2.670e-05	.079
b_discountlinear_apple	5.222***	.704	7.414	1.228e-13	.676
b_discountlinear_samsung	5.523***	.709	7.791	6.661e-15	.701
b_discountquadratic_apple	−3.028***	.631	−4.798	1.606e-06	.613
b_discountquadratic_samsung	−3.379***	.635	−5.325	1.009e-07	.628
LL	−3067.55	AIC	6151.094	***	$p < .001$
Rho bar square	.105	BIC	6197.622		

Table A.16: Partworth utilities for the MNL model

	Partworth utilities					
	Apple vs. Motorola		Samsung vs. Motorola		Apple vs. Samsung	
Attribute Level	Apple	Motorola	Samsung	Motorola	Apple	Samsung
Product=New	2.182	1.901	2.335	2.100	1.720	1.342
Product=Refurbished	1.359	1.035	1.765	1.753	.795	.676
Discount=10%	.639	.535	.545	.387	.492	.518
Discount=20%	1.204	1.011	1.023	.736	.923	.969
Discount=30%	1.696	1.428	1.433	1.047	1.294	1.353
Discount=40%	2.114	1.786	1.776	1.319	1.604	1.668
Discount=50%	2.457	2.084	2.051	1.553	1.854	1.917
Discount=60%	2.728	2.323	2.259	1.749	2.043	2.097
Discount=70%	2.924	2.503	2.399	1.906	2.172	2.210
Discount=80%	3.046	2.624	2.472	2.025	2.240	2.256
Discount=90%	3.095	2.685	2.477	2.106	2.247	2.234
Discount=95%	3.092	2.693	2.455	2.132	2.228	2.197

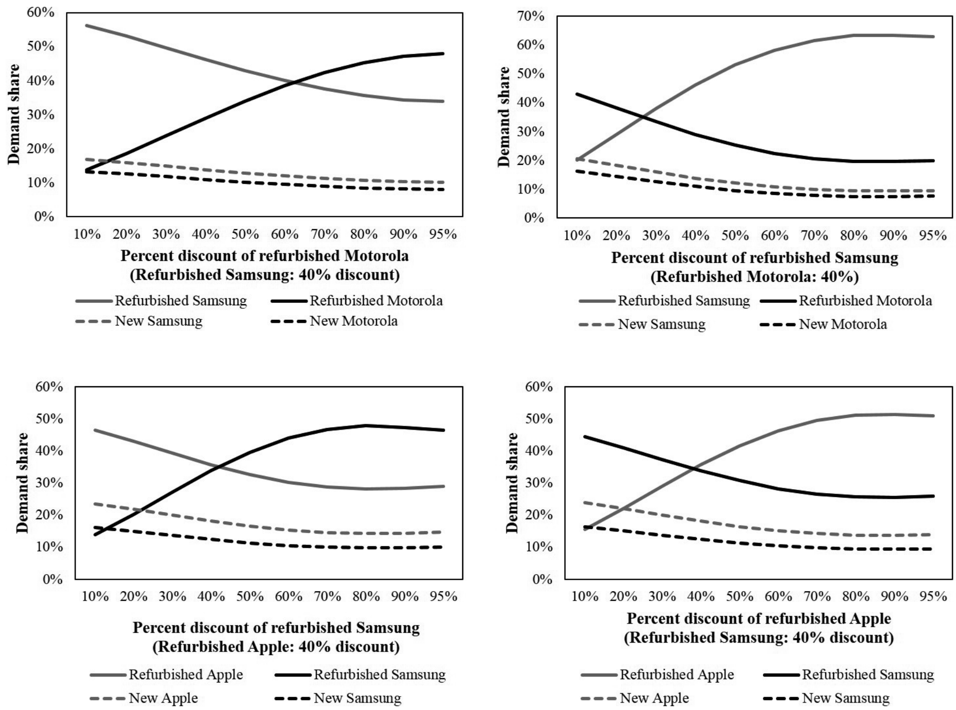


Figure A.6: Demand share for Samsung versus Motorola and Apple versus Samsung in the MNL model

Table A.17: Estimation results of the LC model for Apple versus Motorola

	Class 1: QD (59.64%)			Class 2: LD (40.36%)		
Parameter	Value	Std.error	P-value (p)	Value	Std.error	P-value (p)
asc_new_apple	2.439***	.218	.000e+00	2.916***	.497	4.255e-09
asc_new_motorola	2.083***	.231	.000e+00	2.962***	.468	2.433e-10
b_condition_apple	.814***	.078	.000e+00	.814***	.078	.000e+00
b_condition_motorola	.578***	.104	2.711e-08	.578***	.104	2.711e-08
b_discountlinear_apple	7.269***	.613	.000e+00	7.269***	.613	.000e+00
b_discountlinear_motorola	8.044***	.723	.000e+00	8.044***	.723	.000e+00
b_discountquadratic_apple	−5.009***	.622	8.882e-16	–	–	–
b_discountquadratic_motorola	−8.433***	1.191	1.407e-12	–	–	–
LL	−2688.76	AIC	5399.519	***	$p < .001$	
Rho bar square	.208	BIC	5463.406			

Table A.18: Estimation results of the LC model for Samsung versus Motorola

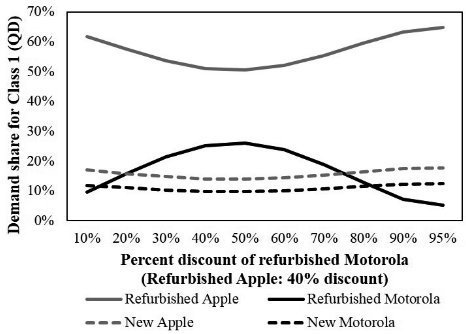
	Class 1: QD (73.96%)			Class 2: LD (27.04%)		
Parameter	Value	Std.error	P-value (p)	Value	Std.error	P-value (p)
asc_new_samsung	2.661***	.228	.000e+00	2.661***	.228	.000e+00
asc_new_motorola	2.427***	.229	.000e+00	2.427***	.229	.000e+00
b_condition_samsung	1.018***	.115	.000e+00	.905**	.330	6.090e-03
b_condition_motorola	.824***	.155	1.049e-07	1.511**	.481	1.710e-03
b_discountlinear_samsung	6.446***	.847	2.798e-14	6.446***	.847	2.798e-14
b_discountlinear_motorola	5.378***	.806	2.577e-11	5.378***	.806	2.577e-11
b_discountquadratic_samsung	−4.587***	.801	1.004e-08	–	–	–
b_discountquadratic_motorola	−4.111***	1.050	9.090e-05	–	–	–
LL	−2514.50	AIC	5051.006	**	$p < .01$	
Rho bar square	.164	BIC	5113.564	***	$p < .001$	

Table A.19: Estimation results of the LC model for Apple versus Samsung

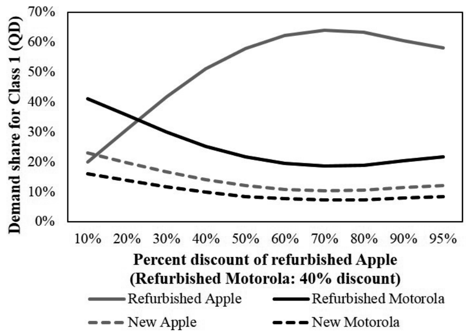
	Class 1: QD (79.50%)			Class 2: LD (20.50%)		
Parameter	Value	Std.error	P-value (p)	Value	Std.error	P-value (p)
asc_new_apple	1.166***	.307	1.467e-04	1.166***	.307	1.467e-04
asc_new_samsung	.787*	.309	1.076e-02	.787*	.309	1.076e-02
b_condition_apple	.399***	.110	2.757e-04	−5.696***	1.067	9.316e-08
b_condition_samsung	.500***	.129	1.001e-04	−4.810***	1.212	7.242e-05
b_discountlinear_apple	6.610***	.975	1.235e-11	6.610***	.975	1.235e-11
b_discountlinear_samsung	5.930***	.982	1.585e-09	5.930***	.982	1.585e-09
b_discountquadratic_apple	−4.052***	.878	3.904e-06	–	–	–
b_discountquadratic_samsung	−3.642***	.869	2.788e-05	–	–	–
LL	−3061.48	AIC	6144.965	*	$p < .05$	
Rho bar square	.106	BIC	6208.941	***	$p < .001$	

Table A.20: Partworth utilities for the LC model

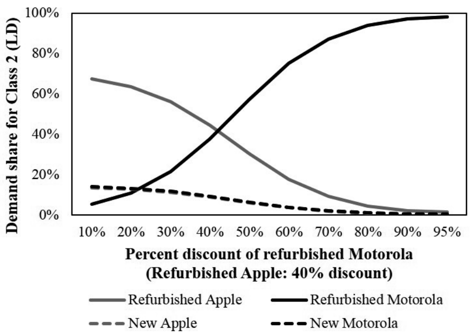
	Partworth utilities											
	Apple (A) vs. Motorola (M)				Samsung (S) vs. Motorola (M)				Apple (A) vs. Samsung (S)			
	Class 1: QD (59.64%)		Class 2: LD (40.36%)		Class 1: QD (73.96%)		Class 2: LD (27.04%)		Class 1: QD (79.50%)		Class 2: LD (20.50%)	
Attribute level	A	M	A	M	S	M	S	M	A	S	A	S
Product=New	2.439	2.083	2.916	2.962	2.661	2.427	2.661	2.427	1.166	.787	1.166	.787
Product=Refurbished	1.627	1.156	1.627	1.156	2.037	1.647	1.811	3.023	.797	1.000	−11.4	−9.62
Discount=10%	.677	.720	.727	.804	.599	.497	.645	.538	.620	.557	.661	.593
Discount=20%	1.254	1.272	1.454	1.609	1.106	.911	1.289	1.076	1.160	1.040	1.322	1.186
Discount=30%	1.730	1.654	2.181	2.413	1.521	1.244	1.934	1.614	1.618	1.451	1.983	1.779
Discount=40%	2.106	1.868	2.908	3.218	1.845	1.494	2.578	2.151	1.996	1.789	2.644	2.372
Discount=50%	2.382	1.914	3.635	4.022	2.076	1.662	3.223	2.689	2.292	2.054	3.305	2.965
Discount=60%	2.558	1.791	4.362	4.826	2.216	1.747	3.868	3.227	2.507	2.247	3.966	3.558
Discount=70%	2.634	1.499	5.089	5.631	2.265	1.751	4.512	3.765	2.641	2.366	4.627	4.151
Discount=80%	2.610	1.038	5.816	6.435	2.221	1.672	5.157	4.303	2.694	2.413	5.288	4.744
Discount=90%	2.485	.409	6.543	7.240	2.086	1.511	5.802	4.841	2.667	2.387	5.949	5.337
Discount=95%	2.385	.031	6.906	7.642	1.984	1.400	6.124	5.110	2.622	2.346	6.279	5.633



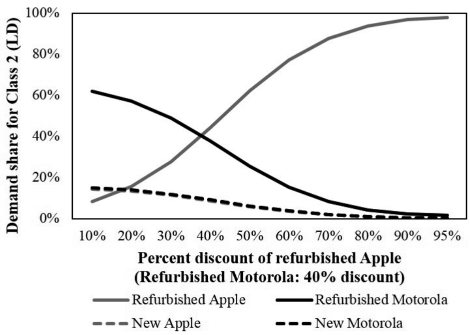
(a) Class QD: Refurbished Motorola



(b) Class QD: Refurbished Apple

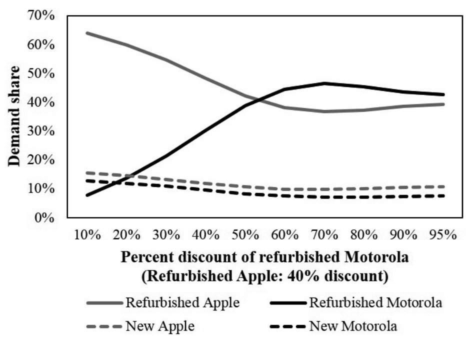


(c) Class LD: Refurbished Motorola

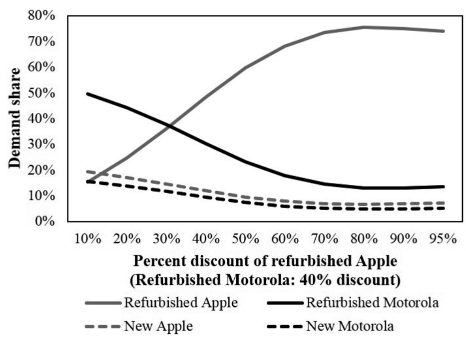


(d) Class LD: Refurbished Apple

Figure A.7: Demand share for each class for Apple versus Motorola in the LC model

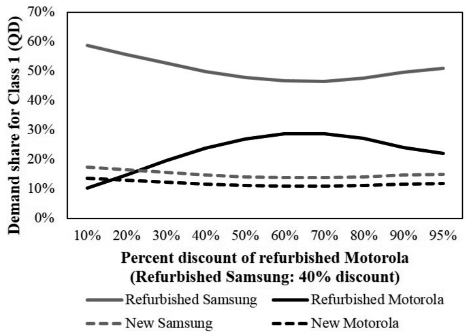


(a) Refurbished Motorola

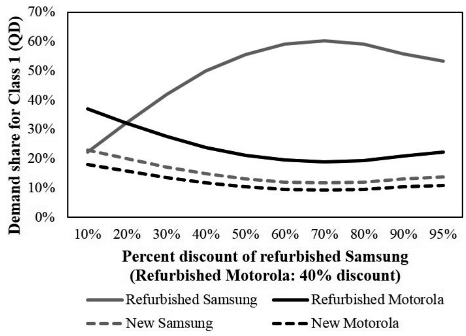


(b) Refurbished Apple

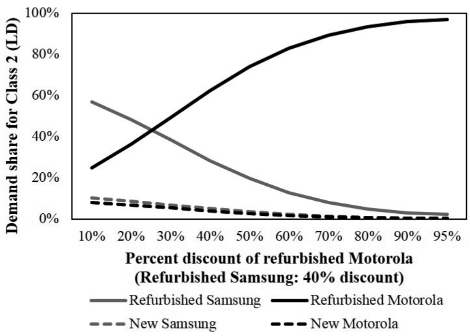
Figure A.8: Total demand share for Apple versus Motorola in the LC model



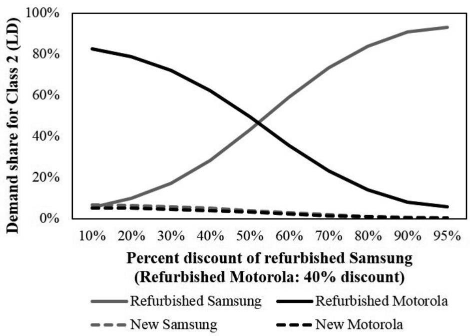
(a) Class QD: Refurbished Motorola



(b) Class QD: Refurbished Samsung

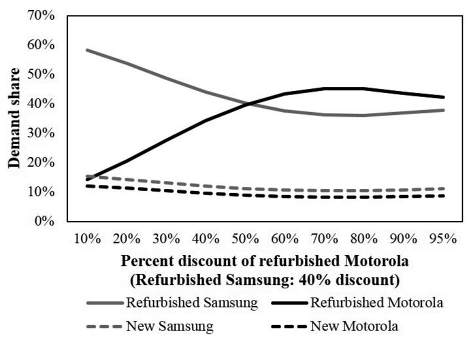


(c) Class LD: Refurbished Motorola

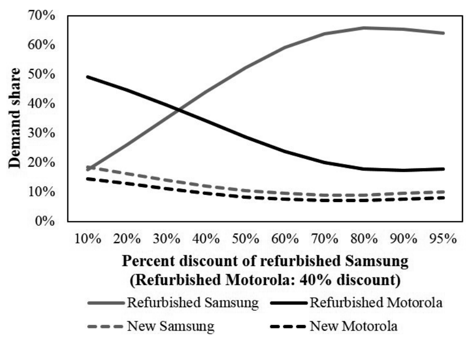


(d) Class LD: Refurbished Samsung

Figure A.9: Demand share for each class for Samsung versus Motorola in the LC model

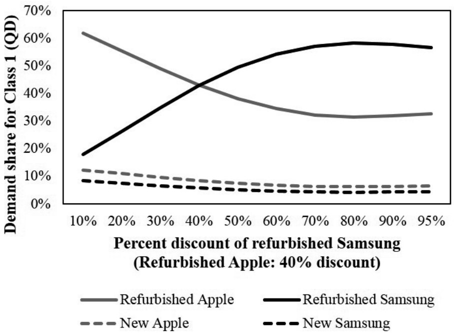


(a) Refurbished Motorola

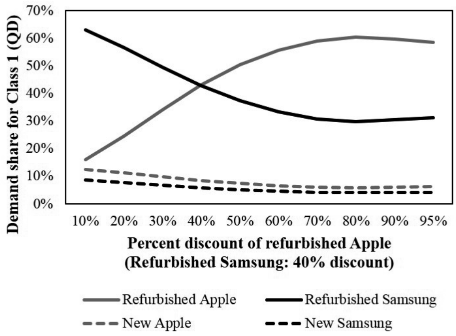


(b) Refurbished Samsung

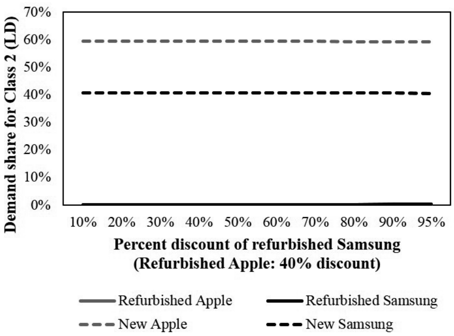
Figure A.10: Total demand share for Samsung versus Motorola in the LC model



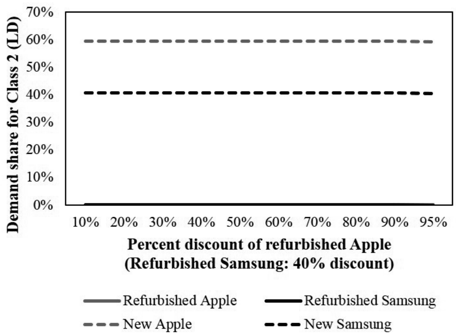
(a) Class QD: Refurbished Samsung



(b) Class QD: Refurbished Apple

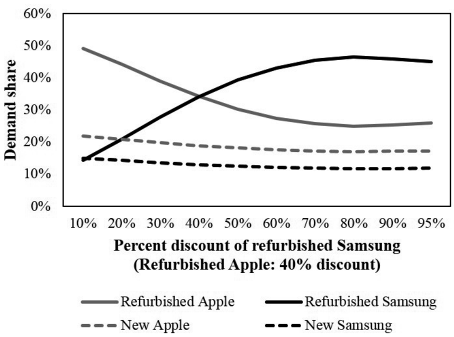


(c) Class LD: Refurbished Samsung

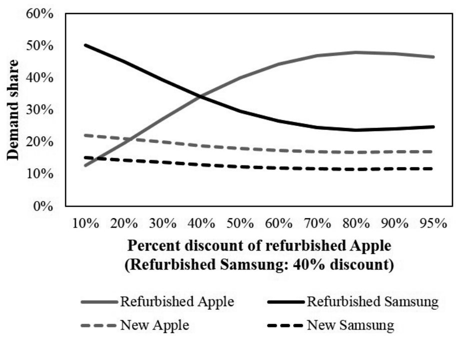


(d) Class LD: Refurbished Apple

Figure A.11: Demand share for each class for Apple versus Samsung in the LC model

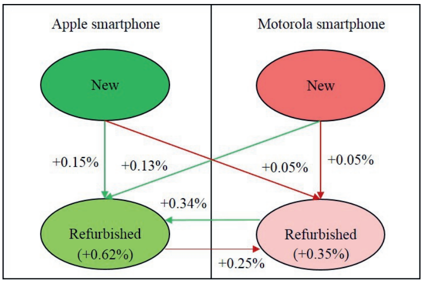


(a) Refurbished Samsung

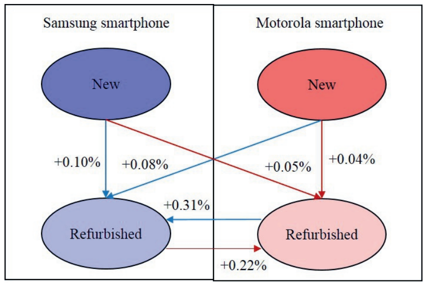


(b) Refurbished Apple

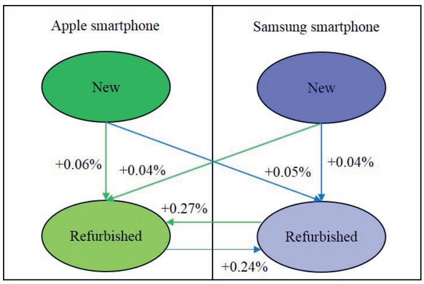
Figure A.12: Total demand share for Apple versus Samsung in the LC model



(a) Apple vs Motorola



(b) Samsung vs Motorola



(c) Apple vs Samsung

Figure A.13: Summary of cross-discount elasticities between product conditions and brands for the LC model

B

Appendix of Chapter 3

B.1. Proofs for Duopoly Competition

Proof of Lemma 3.1. Let $v_h = q_h^n - r_h p_h^n$ and $v_l = q_l^n - r_l p_l^n$ represent the minimum production of new products. The Lagrange function L_h for M_h's model can be expressed as follows:

$$L_h(p_h^r) = w_h^n(v_h + r_h p_h^r) + (p_h^r - c_h^r)(a_h - d_h p_h^r + m p_l^r) + \lambda_h(s_h - a_h + d_h p_h^r - m p_l^r),$$

where λ_h is a Lagrange multiplier. The Lagrangean is concave with respect to p_h^r. Hence, the Karush-Kuhn-Tucker (KKT) optimality conditions are:

$$\begin{aligned}
\frac{\partial L_h(p_h^r)}{\partial p_h^r} &= a_h + d_h c_h^r + r_h w_h^n - 2 d_h p_h^r + m p_l^r + \lambda_h d_h = 0; \\
\lambda_h(s_h - a_h + d_h p_h^r - m p_l^r) &= 0; \\
\lambda_h &\geq 0.
\end{aligned}$$

The Lagrangean of the M_l's objective function is

$$L_l(p_l^r) = w_l^n(v_l + r_l p_l^r) + (p_l^r - c_l^r)(a_l - d_l p_l^r + m p_h^r) + \lambda_l(s_l - a_l + d_l p_l^r - m p_h^r),$$

where λ_l is a Lagrange multiplier. The Lagrangean is concave with respect to p_l^r. Hence, the KKT optimality conditions are:

$$\frac{\partial L_l(p_l^r)}{\partial p_l^r} = a_l + d_l c_l^r - 2d_l p_l^r + m p_h^r + \lambda_h d_l = 0;$$
$$\lambda_l (s_l - a_l + d_l p_l^r - m p_h^r) = 0;$$
$$\lambda_l \geq 0.$$

We examine how the Lagrangean multipliers satisfy the non-negativity conditions of the optimization. Since the multipliers can be either zero or positive, we could have four cases to examine.

Case A: $\lambda_h = 0, \lambda_l = 0$.
Both firms M_h and M_l do not refurbish and sell all used products collected. Solving the gradient conditions simultaneously, we obtain the optimal prices

$$p_h^{r\,*} = \frac{2d_l\left(a_h + c_h^r d_h + r_h w_h^n\right) + m\left(a_l + c_l^r d_l\right)}{4d_h d_l - m^2},$$
$$p_l^{r\,*} = \frac{d_h\left(2a_l + 2c_l^r d_l\right) + m\left(a_h + c_h^r d_h + r_h w_h^n\right)}{4d_h d_l - m^2}.$$

To be physically consistent, we require that $0 \leq q_h^r < s_h$ and $0 \leq q_l^r < s_l$. Hence, we have the boundaries in case A:

$$\rho_{AC} - s_h\left(4d_h d_l - m^2\right) \leq d_h t_h\left(2d_h d_l - m^2\right) - m d_h d_l t_l < \rho_{AC},$$
$$\rho_{AB} - s_l\left(4d_h d_l - m^2\right) \leq d_l t_l\left(2d_h d_l - m^2\right) - m d_h d_l t_h < \rho_{AB},$$

where

$$\rho_{AC} = -d_h\left(2a_h d_l + m a_l\right) + d_h\left(c_h^n\left(2d_h d_l - m^2\right) - m d_l c_l^n\right) + r_h w_h^n\left(2d_h d_l - m^2\right) + s_h\left(4d_h d_l - m^2\right),$$
$$\rho_{AB} = -d_l\left(2a_l d_h + m a_h + m r_h w_h^n\right) + d_l\left(c_l^n\left(2d_h d_l - m^2\right) - m d_h c_h^n\right) + s_l\left(4d_h d_l - m^2\right).$$

Then, we have $\mu_{AC} t_l + \gamma_{hA_0} \leq t_h < \mu_{AC} t_l + \gamma_{AC}$ and $\mu_{AB} t_h + \gamma_{lA_0} \leq t_l < \mu_{AB} t_h + \gamma_{AB}$, where $\mu_{AC} = \frac{m d_h d_l}{d_h\left(2d_h d_l - m^2\right)}$, $\gamma_{AC} = \frac{\rho_{AC}}{d_h\left(2d_h d_l - m^2\right)}$, $\mu_{AB} = \frac{m d_h d_l}{d_l\left(2d_h d_l - m^2\right)}$, $\gamma_{AB} = \frac{\rho_{AB}}{d_l\left(2d_h d_l - m^2\right)}$, $\gamma_{hA_0} = \frac{\rho_{AC}}{d_h\left(2d_h d_l - m^2\right)} - \frac{s_h\left(4d_h d_l - m^2\right)}{d_h\left(2d_h d_l - m^2\right)}$, and $\gamma_{lA_0} = \frac{\rho_{AB}}{d_l\left(2d_h d_l - m^2\right)} - \frac{s_l\left(4d_h d_l - m^2\right)}{d_l\left(2d_h d_l - m^2\right)}$.

Case B: $\lambda_h = 0, \lambda_l > 0$.
Firm M_h does not refurbish and sell all used products that it collects, while M_l does. The optimal prices are

$$p_h^{r*} = \frac{2d_l\left(a_h + c_h^r d_h + r_h w_h^n\right) + m\left(a_l + c_l^r d_l + \lambda_l d_l\right)}{4d_h d_l - m^2},$$
$$p_l^{r*} = \frac{2d_h\left(a_l + d_l\left(c_l^r + \lambda_l\right)\right) + m\left(a_h + c_h^r d_h + r_h w_h^n\right)}{4d_h d_l - m^2}.$$

Solving the system of equations given by the KKT conditions with $\lambda_h = 0$, we obtain

$$\lambda_l = \frac{d_l\left(2a_l d_h - c_l^r\left(2d_h d_l - m^2\right)\right) + md_l\left(a_h + c_h^r d_h + r_h w_h^n\right) - s_l\left(4d_h d_l - m^2\right)}{d_l\left(2d_h d_l - m^2\right)}.$$

To be physically consistent, we require that $q_h^r < s_h$ and λ_l must satisfy the non-negativity condition. Hence, we have the boundaries in case B:

$$\rho_{BD} - s_h\left(2d_h d_l - m^2\right) \leq d_h t_h\left(d_h d_l - m^2\right) < \rho_{BD},$$
$$d_l t_l\left(2d_h d_l - m^2\right) - md_h d_l t_h > \rho_{AB},$$

where

$$\rho_{BD} = -d_h\left(a_h d_l + m\left(a_l - s_l\right)\right) + \left(d_h d_l - m^2\right)\left(d_h c_h^n + r_h w_h^n\right) + s_h\left(2d_h d_l - m^2\right),$$
$$\rho_{AB} = -d_l\left(2a_l d_h + ma_h + mr_h w_h^n\right) + d_l\left(c_l^n\left(2d_h d_l - m^2\right) - md_h c_h^n\right) + s_l\left(4d_h d_l - m^2\right).$$

Then, we have $\gamma_{BB_0} \leq t_h < \gamma_{BD}$ and $t_l > \gamma_{AB} + \mu_{AB} t_h$, where $\gamma_{BD} = \frac{\rho_{BD}}{d_h\left(d_h d_l - m^2\right)}$, $\mu_{AB} = \frac{md_h d_l}{d_l\left(2d_h d_l - m^2\right)}$, $\gamma_{AB} = \frac{\rho_{AB}}{d_l\left(2d_h d_l - m^2\right)}$, and $\gamma_{BB_0} = \frac{\rho_{BD}}{d_h\left(d_h d_l - m^2\right)} - \frac{s_h\left(2d_h d_l - m^2\right)}{d_h\left(d_h d_l - m^2\right)}$.

Case C: $\lambda_h > 0, \lambda_l = 0$.
Firm M_h refurbishes and sells all used products that it collects, while M_l does not. The optimal prices are:

$$p_h^{r*} = \frac{2d_l\left(a_h + d_h\left(c_h^r + \lambda_h\right) + r_h w_h^n\right) + m\left(a_l + c_l^r d_l\right)}{4d_h d_l - m^2},$$
$$p_l^{r*} = \frac{2d_h\left(a_l + c_l^r d_l\right) + m\left(a_h + d_h\left(c_h^r + \lambda_h\right) + r_h w_h^n\right)}{4d_h d_l - m^2}.$$

Solving the system of equations given by the KKT conditions with $\lambda_l = 0$, we obtain

$$\lambda_h = \frac{md_h\left(a_l + c_l^r d_l\right) + 2a_h d_h d_l - \left(2d_h d_l - m^2\right)\left(c_h^r d_h + r_h w_h^n\right) - s_h\left(4d_h d_l - m^2\right)}{d_h\left(2d_h d_l - m^2\right)}.$$

To be physically consistent, we require that $q_l^r < s_l$ and λ_h must satisfy the non-negativity condition. Hence, we have the boundaries in case C:

$$d_h t_h\left(2d_h d_l - m^2\right) - md_h d_l t_l > \rho_{AC},$$
$$\rho_{CD} - s_l\left(2d_h d_l - m^2\right) \le d_l t_l\left(d_h d_l - m^2\right) < \rho_{CD},$$

where

$$\rho_{AC} = -d_h\left(2a_h d_l + ma_l\right) + d_h\left(c_h^n\left(2d_h d_l - m^2\right) - md_l c_l^n\right) + r_h w_h^n\left(2d_h d_l - m^2\right) + s_h\left(4d_h d_l - m^2\right),$$
$$\rho_{CD} = -d_l\left(a_l d_h + m\left(a_h - s_h\right)\right) + d_l c_l^n\left(d_h d_l - m^2\right) + s_l\left(2d_h d_l - m^2\right).$$

Then, we have $t_h > \gamma_{AC} + \mu_{AC} t_l$ and $\gamma_{CC_0} \le t_l < \gamma_{CD}$, where $\mu_{AC} = \frac{md_h d_l}{d_h\left(2d_h d_l - m^2\right)}$, $\gamma_{AC} = \frac{\rho_{AC}}{d_h\left(2d_h d_l - m^2\right)}$, $\gamma_{CD} = \frac{\rho_{CD}}{d_l\left(d_h d_l - m^2\right)}$, and $\gamma_{CC_0} = \frac{\rho_{CD}}{d_l\left(d_h d_l - m^2\right)} - \frac{s_l\left(2d_h d_l - m^2\right)}{d_l\left(d_h d_l - m^2\right)}$.

Case D: $\lambda_h > 0, \lambda_l > 0$.
Both firms M_h and M_l refurbish and sell all used products collected. The optimal prices are:

$$p_h^{r*} = \frac{2d_l\left(a_h + d_h\left(c_h^r + \lambda_h\right) + r_h w_h^n\right) + m\left(a_l + c_l^r d_l + \lambda_l d_l\right)}{4d_h d_l - m^2},$$
$$p_l^{r*} = \frac{2d_h\left(a_l + d_l\left(c_l^r + \lambda_l\right)\right) + m\left(a_h + d_h\left(c_h^r + \lambda_h\right) + r_h w_h^n\right)}{4d_h d_l - m^2}.$$

Solving the system of equations given by the KKT conditions, we obtain

$$\lambda_h = \frac{md_h\left(a_l - s_l\right) + a_h d_h d_l - \left(d_h d_l - m^2\right)\left(c_h^r d_h + r_h w_h^n\right) - s_h\left(2d_h d_l - m^2\right)}{d_h\left(d_h d_l - m^2\right)},$$
$$\lambda_l = \frac{d_l\left(a_l d_h + m\left(a_h - s_h\right) + c_l^r\left(-\left(d_h d_l - m^2\right)\right)\right) - s_l\left(2d_h d_l - m^2\right)}{d_l\left(d_h d_l - m^2\right)}.$$

The Lagrangean multipliers λ_h and λ_l must satisfy the non-negativity conditions.

Hence,

$$d_h t_h \left(d_h d_l - m^2\right) > \rho_{BD} \ \text{ and } \ d_l t_l \left(d_h d_l - m^2\right) > \rho_{CD},$$

where

$$\begin{aligned}\rho_{BD} &= -d_h \left(a_h d_l + m\left(a_l - s_l\right)\right) + \left(d_h d_l - m^2\right)\left(d_h c_h^n + r_h w_h^n\right) + s_h \left(2d_h d_l - m^2\right),\\ \rho_{CD} &= -d_l \left(a_l d_h + m\left(a_h - s_h\right)\right) + d_l c_l^n \left(d_h d_l - m^2\right) + s_l \left(2d_h d_l - m^2\right).\end{aligned}$$

Then, we have $t_h > \gamma_{BD}$ and $t_l > \gamma_{CD}$, where $\gamma_{BD} = \frac{\rho_{BD}}{d_h(d_h d_l - m^2)}$ and $\gamma_{CD} = \frac{\rho_{CD}}{d_l(d_h d_l - m^2)}$. The critical values in all cases are summarize in Table B.1.

Table B.1: Critical values in the duopoly competition

Slope and intercept	Expression
μ_{AC}	$\frac{m d_h d_l}{d_h(2d_h d_l - m^2)}$
μ_{AB}	$\frac{m d_h d_l}{d_l(2d_h d_l - m^2)}$
γ_{AC}	$\frac{-d_h(2a_h d_l + m a_l) + d_h\left(c_h^n\left(2d_h d_l - m^2\right) - m d_l c_l^n\right) + r_h w_h^n\left(2d_h d_l - m^2\right) + s_h\left(4d_h d_l - m^2\right)}{d_h(2d_h d_l - m^2)}$
γ_{AB}	$\frac{-d_l(2a_l d_h + m a_h + m r_h w_h^n) + d_l\left(c_l^n\left(2d_h d_l - m^2\right) - m d_h c_h^n\right) + s_l\left(4d_h d_l - m^2\right)}{d_l(2d_h d_l - m^2)}$
γ_{BD}	$\frac{-d_h(a_h d_l + m(a_l - s_l)) + \left(d_h d_l - m^2\right)(d_h c_h^n + r_h w_h^n) + s_h\left(2d_h d_l - m^2\right)}{d_h(d_h d_l - m^2)}$
γ_{CD}	$\frac{-d_l(a_l d_h + m(a_h - s_h)) + d_l c_l^n\left(d_h d_l - m^2\right) + s_l\left(2d_h d_l - m^2\right)}{d_l(d_h d_l - m^2)}$
γ_{hA_0}	$\frac{\rho_{AC}}{d_h(2d_h d_l - m^2)} - \frac{s_h\left(4d_h d_l - m^2\right)}{d_h(2d_h d_l - m^2)}$
γ_{lA_0}	$\frac{\rho_{AB}}{d_l(2d_h d_l - m^2)} - \frac{s_l\left(4d_h d_l - m^2\right)}{d_l(2d_h d_l - m^2)}$
γ_{BB_0}	$\frac{\rho_{BD}}{d_h(d_h d_l - m^2)} - \frac{s_h\left(2d_h d_l - m^2\right)}{d_h(d_h d_l - m^2)}$
γ_{CC_0}	$\frac{\rho_{CD}}{d_l(d_h d_l - m^2)} - \frac{s_l\left(2d_h d_l - m^2\right)}{d_l(d_h d_l - m^2)}$

The Nash equilibrium solutions in all cases are summarize in Table B.2.

Proof of Corollary 3.1.

(a) The first derivatives of γ_{BD} and γ_{CD} with respect to c_i^r and c_i^n, $i = h, l$ are as follows:

$$\frac{\partial \gamma_{BD}}{\partial c_h^r} = \frac{\partial \gamma_{CD}}{\partial c_l^r} = 0, \quad \frac{\partial \gamma_{BD}}{\partial c_h^n} = 1 - \frac{r_h}{d_h}, \quad \frac{\partial \gamma_{CD}}{\partial c_l^n} = 1.$$

Table B.2: Nash equilibrium solutions in the duopoly competition

Case		Optimal solutions
Case A	${p_h^r}^* =$	$\frac{2d_l(a_h+c_h^r d_h+r_h w_h^n)+m(a_l+c_l^r d_l)}{4d_h d_l-m^2}$
	${p_l^r}^* =$	$\frac{d_h(2a_l+2c_l^r d_l)+m(a_h+c_h^r d_h+r_h w_h^n)}{4d_h d_l-m^2}$
Case B	${p_h^r}^* =$	$\frac{d_l(a_h+c_h^r d_h+r_h w_h^n)+m(a_l-s_l)}{2d_h d_l-m^2}$
	${p_l^r}^* =$	$\frac{m(a_h+c_h^r d_h+r_h w_h^n)+2d_h(a_l-s_l)}{2d_h d_l-m^2}$
Case C	${p_h^r}^* =$	$\frac{m(a_l+c_l^r d_l)+2d_l(a_h-s_h)}{2d_h d_l-m^2}$
	${p_l^r}^* =$	$\frac{d_h(a_l+c_l^r d_l)+m(a_h-s_h)}{2d_h d_l-m^2}$
Case D	${p_h^r}^* =$	$\frac{d_l(a_h-s_h)+m(a_l-s_l)}{d_h d_l-m^2}$
	${p_l^r}^* =$	$\frac{d_h(a_l-s_l)+m(a_h-s_h)}{d_h d_l-m^2}$

Hence, γ_{BD} and γ_{CD} are constant in refurbishing costs c_h^r and c_l^r. The threshold γ_{BD} is increasing in c_h^n with $0 < \gamma'_{BD}(c_h^n) < 1$ and γ_{CD} is increasing in c_l^n with $\gamma'_{CD}(c_l^n) = 1$.

(b) The first derivatives of γ_{BD} and γ_{CD} with respect to s_h and s_l are as follows:

$$\frac{\partial \gamma_{BD}}{\partial s_h} = \frac{2d_h d_l - m^2}{d_h\left(d_h d_l - m^2\right)} > 0, \quad \frac{\partial \gamma_{BD}}{\partial s_l} = \frac{m}{d_h d_l - m^2} > 0,$$
$$\frac{\partial \gamma_{CD}}{\partial s_h} = \frac{m}{d_h d_l - m^2} > 0, \quad \frac{\partial \gamma_{CD}}{\partial s_l} = \frac{2d_h d_l - m^2}{d_l\left(d_h d_l - m^2\right)} > 0.$$

If $d_l \leq d_h$, $\frac{\partial \gamma_{BD}}{\partial s_h} \leq \frac{\partial \gamma_{CD}}{\partial s_l}$. Since $d_h, d_l > m$, $\frac{\partial \gamma_{BD}}{\partial s_h} > \frac{\partial \gamma_{BD}}{\partial s_l}$ and $\frac{\partial \gamma_{CD}}{\partial s_l} > \frac{\partial \gamma_{CD}}{\partial s_h}$.

Proof of Proposition 3.1.

(a) The first derivatives of the optimal refurbished product prices with respect to b_h^h are as follows:

$$\frac{\partial {p_h^r}^*}{\partial b_h^h} = \frac{d_l q_h^n\left(\left(p_h^n - p_l^n\right)\left(d_l r_l + k_l m\right) + d_l s_h + m s_l\right)}{\left(d_h d_l - m^2\right)^2} > 0,$$
$$\frac{\partial {p_l^r}^*}{\partial b_h^h} = \frac{m q_h^n\left(\left(p_h^n - p_l^n\right)\left(d_l r_l + k_l m\right) + d_l s_h + m s_l\right)}{\left(d_h d_l - m^2\right)^2} > 0.$$

Hence, ${p_h^r}^*$ is increasing in b_h^h. When $m \neq 0$, ${p_l^r}^*$ is increasing in b_h^h. Since

$d_l > m$, $\frac{\partial p_h^{r*}}{\partial b_h^h} > \frac{\partial p_l^{r*}}{\partial b_h^h}$.

(b) The first derivatives of the optimal refurbished product prices with respect to b_l^h are as follows:

$$\frac{\partial p_h^{r*}}{\partial b_l^h} = \frac{d_l q_l^n \left(-d_l \left(k_h + r_h\right)\left(p_h^n - p_l^n\right) + d_l s_h + m s_l\right)}{\left(d_h d_l - m^2\right)^2},$$
$$\frac{\partial p_l^{r*}}{\partial b_l^h} = \frac{m q_l^n \left(-d_l \left(k_h + r_h\right)\left(p_h^n - p_l^n\right) + d_l s_h + m s_l\right)}{\left(d_h d_l - m^2\right)^2}.$$

From the expressions above, $\frac{\partial p_h^{*}}{\partial b_l^h}, \frac{\partial p_l^{r*}}{\partial b_l^h} > 0$ whenever $d_l s_h + m s_l > d_l \left(k_h + r_h\right)\left(p_h^n - p_l^n\right)$. Since $d_l > m$, $\frac{\partial p_h^{r*}}{\partial b_l^h} > \frac{\partial p_l^{r*}}{\partial b_l^h}$.

Proof of Proposition 3.2. The first derivatives of the optimal refurbished product prices with respect to s_h and s_l are as follows:

$$\frac{\partial p_h^{r*}}{\partial s_h} = -\frac{d_l}{d_h d_l - m^2} < 0, \quad \frac{\partial p_h^{r*}}{\partial s_l} = -\frac{m}{d_h d_l - m^2} < 0,$$
$$\frac{\partial p_l^{r*}}{\partial s_h} = -\frac{m}{d_h d_l - m^2} < 0, \quad \frac{\partial p_l^{r*}}{\partial s_l} = -\frac{d_h}{d_h d_l - m^2} < 0.$$

Hence, p_i^{r*} is decreasing in s_i and s_j, where $i, j \in \{h, l\}$, $i \neq j$. Since $d_h, d_l > m$, $\frac{\partial p_i^{r*}}{\partial s_i} < \frac{\partial p_i^{r*}}{\partial s_j}, i, j \in \{h, l\}, i \neq j$.

Proof of Proposition 3.3. The first derivatives of the optimal refurbished product prices with respect to k_h and k_l are as follows:

$$\frac{\partial p_h^{r*}}{\partial k_h} = \frac{d_l \left(\left(p_h^n - p_l^n\right)\left(d_l r_l + k_l m\right) + d_l s_h + m s_l\right)}{\left(d_h d_l - m^2\right)^2} > 0,$$
$$\frac{\partial p_h^{r*}}{\partial k_l} = \frac{m \left(-m \left(k_h + r_h\right)\left(p_h^n - p_l^n\right) + d_h s_l + m s_h\right)}{\left(d_h d_l - m^2\right)^2} > 0,$$
$$\frac{\partial p_l^{r*}}{\partial k_h} = \frac{m \left(\left(p_h^n - p_l^n\right)\left(d_l r_l + k_l m\right) + d_l s_h + m s_l\right)}{\left(d_h d_l - m^2\right)^2} > 0,$$
$$\frac{\partial p_l^{r*}}{\partial k_l} = \frac{d_h \left(-m \left(k_h + r_h\right)\left(p_h^n - p_l^n\right) + d_h s_l + m s_h\right)}{\left(d_h d_l - m^2\right)^2} > 0.$$

Hence, p_i^{r*} is increasing in k_i and k_j, where $i, j \in \{h, l\}$, $i \neq j$. Since $d_h, d_l > m$, $\frac{\partial p_i^{r*}}{\partial k_i} > \frac{\partial p_i^{r*}}{\partial k_j}, i, j \in \{h, l\}, i \neq j$.

Proof of Proposition 3.4. Let $\mu = \frac{k_h + r_h + r_l}{k_l}$ and $\gamma = (k_h + r_h)\left(p_h^n - p_l^n\right)$. The difference between p_h^{r*} and p_l^{r*} is as follows:

$$p_h^{r*} - p_l^{r*} = \frac{s_l\left(k_h + r_h + r_l\right) - k_l\left(s_h - \left(k_h + r_h\right)\left(p_h^n - p_l^n\right)\right)}{d_h d_l - m^2}.$$

Hence, if $s_h < \gamma + \mu s_l$, $p_h^{r*} > p_l^{r*}$. Otherwise, $p_h^* < p_l^*$. The first derivatives of the optimal refurbished product prices with respect to m are as follows:

$$\frac{\partial p_h^{r*}}{\partial m} = -\frac{k_l\left(k_l\left(k_h + r_h\right)\left(p_h^n - p_l^n\right) + s_l\left(d_h - m\right) - k_l s_h\right)}{\left(d_h d_l - m^2\right)^2},$$
$$\frac{\partial p_l^{r*}}{\partial m} = \frac{\left(d_h - m\right)\left(k_l\left(k_h + r_h\right)\left(p_h^n - p_l^n\right) + s_l\left(d_h - m\right) - k_l s_h\right)}{\left(d_h d_l - m^2\right)^2}.$$

From the expressions above, $\frac{\partial p_h^{r*}}{\partial m} < 0$ whenever $s_h < \gamma + \mu s_l$ and $\frac{\partial p_l^{r*}}{\partial m} < 0$ whenever $s_h > \gamma + \mu s_l$. Since $d_h - m > k_l$, $|\frac{\partial p_l^{r*}}{\partial m}| > |\frac{\partial p_h^{r*}}{\partial m}|$.

Proof of Proposition 3.5. Let $\gamma_h^s = \frac{d_l\left(r_h w_h^n + s_h\right)}{d_h d_l - m^2}$ and $\gamma_l^s = \frac{d_h s_l + m r_l w_l^n}{d_h d_l - m^2}$. The first derivatives of the optimal profits Π_h^* and Π_l^* with respect to s_h and s_l are as follows:

$$\frac{\partial \Pi_h^*}{\partial s_h} = \frac{d_l\left(a_h - r_h w_h^n - 2s_h\right) + m\left(a_l - s_l\right) + c_h^r\left(-\left(d_h d_l - m^2\right)\right)}{d_h d_l - m^2},$$
$$\frac{\partial \Pi_h^*}{\partial s_l} = -\frac{m\left(r_h w_h^n + s_h\right)}{d_h d_l - m^2}, \quad \frac{\partial \Pi_l^*}{\partial s_h} = -\frac{d_l r_l w_l^n + m s_l}{d_h d_l - m^2},$$
$$\frac{\partial \Pi_l^*}{\partial s_l} = \frac{d_h\left(a_l - 2s_l\right) + m a_h - c_l^r\left(d_h d_l - m^2\right) - m\left(s_h + r_l w_l^n\right)}{d_h d_l - m^2}.$$

From the expressions above, $\frac{\partial \Pi_i^*}{\partial s_j} < 0$, and $\frac{\partial \Pi_i^*}{\partial s_i} < 0$ whenever $p_i^r - c_i^r < \gamma_i^s$, where $i, j \in \{h, l\}$, $i \neq j$.

Proof of Proposition 3.6. Let $\mu_h^h = \frac{d_l(k_h+r_l)+k_l m}{d_l}$ and $\mu_l^h = \frac{d_l(k_h+r_h)+k_l m}{m}$. The first derivatives of the optimal profits Π_h^* and Π_l^* with respect to b_h^h and b_l^h are as follows:

$$\frac{\partial \Pi_h^*}{\partial b_h^h} = \frac{q_h^n\left(d_l s_h - w_h^n\left(d_l\left(k_h+r_l\right)+k_l m\right)\right)\left(\left(p_h^n-p_l^n\right)\left(d_l r_l+k_l m\right)+d_l s_h+m s_l\right)}{\left(d_h d_l-m^2\right)^2},$$

$$\frac{\partial \Pi_h^*}{\partial b_l^h} = \frac{d_l q_l^n\left(r_h w_h^n+s_h\right)\left(-d_l\left(k_h+r_h\right)\left(p_h^n-p_l^n\right)+d_l s_h+m s_l\right)}{\left(d_h d_l-m^2\right)^2},$$

$$\frac{\partial \Pi_l^*}{\partial b_h^h} = \frac{q_h^n\left(d_l r_l w_l^n+m s_l\right)\left(\left(p_h^n-p_l^n\right)\left(d_l r_l+k_l m\right)+d_l s_h+m s_l\right)}{\left(d_h d_l-m^2\right)^2},$$

$$\frac{\partial \Pi_l^*}{\partial b_l^h} = -\frac{q_l^n\left(d_l w_l^n\left(k_h+r_h\right)-m\left(s_l-k_l w_l^n\right)\right)\left(-d_l\left(k_h+r_h\right)\left(p_h^n-p_l^n\right)+d_l s_h+m s_l\right)}{\left(d_h d_l-m^2\right)^2}.$$

From the expressions above, $\frac{\partial \Pi_l^*}{\partial b_h^h}, \frac{\partial \Pi_h^*}{\partial b_l^h} > 0$. Moreover, $\frac{\partial \Pi_h^*}{\partial b_h^h} > 0$ whenever $s_h > \mu_h^h\left(p_h^n - c_h^n\right)$, and $\frac{\partial \Pi_l^*}{\partial b_l^h} < 0$ whenever $s_l < \mu_l^h\left(p_l^n - c_l^n\right)$.

Proof of Proposition 3.7. Let $\mu = \frac{k_h+r_h+r_l}{k_l}$, $\gamma = \left(k_h+r_h\right)\left(p_h^n-p_l^n\right)$, and $\beta = \frac{r_l w_l^n}{\mu}$. The first derivatives of the optimal profits Π_h^* and Π_l^* with respect to m are as follows:

$$\frac{\partial \Pi_h^*}{\partial m} = -\frac{k_l\left(r_h w_h^n+s_h\right)\left(s_l\left(k_h+r_h+r_l\right)-k_l\left(s_h-\left(k_h+r_h\right)\left(p_h^n-p_l^n\right)\right)\right)}{\left(d_h d_l-m^2\right)^2},$$

$$\frac{\partial \Pi_l^*}{\partial m} = \frac{\left(s_l\left(k_h+r_h+r_l\right)-k_l r_l w_l^n\right)\left(s_l\left(k_h+r_h+r_l\right)-k_l\left(s_h-\left(k_h+r_h\right)\left(p_h^n-p_l^n\right)\right)\right)}{\left(d_h d_l-m^2\right)^2}.$$

From the expressions above, $\frac{\partial \Pi_h^*}{\partial m} > 0$ whenever $s_h > \gamma + \mu s_l$. Moreover, $\frac{\partial \Pi_l^*}{\partial m} > 0$ whenever $\beta < s_l$ and $s_h < \gamma + \mu s_l$ (or $\beta > s_l$ and $s_h > \gamma + \mu s_l$); and $\frac{\partial \Pi_l^*}{\partial m} < 0$ whenever $\beta > s_l$ and $s_h < \gamma + \mu s_l$ (or $\beta < s_l$ and $s_h > \gamma + \mu s_l$).

C

Appendix of Chapter 4

C.1. Proofs for Authorization Scenario

Proof of Lemma 4.1. Unauthorized scenario. We need to evaluate the profit function Π_t^U in each subinterval $I_0 = (0, p_r^m]$ and $I_1 = (p_r^m, p_n]$. We have $\frac{\partial^2 \Pi_t^U}{\partial p_r^2} = -2d^U$ in I_1 and $\frac{\partial^2 \Pi_t^U}{\partial p_r^2} = -2d_u^U$ in I_0. It is assumed that $k^U > \rho r^U$. Hence, Π_t^U is always concave in p_r^U in both I_0 and I_1. By solving $\frac{\partial \Pi_t^U}{\partial p_r^U} = 0$ in each subinterval, we obtain the following optimal prices:

$$p_{r_1}^U = \frac{p_n + c_r^U}{2} \text{ and } p_{r_0}^U = \frac{1}{2}\Big(\frac{k^U p_n}{d_u^U} + c_r^U\Big),$$

where $p_{r_i}^U$ is the optimal price in subinterval I_i, $i = 0, 1$. It can be seen that $p_{r_1}^U$ is not influenced by p_r^m. Let $\xi_1^U = \frac{1}{2}(p_n + c_r^U)$. If $p_r^m \leq \xi_1^U$, $p_{r_1}^U$ exists, otherwise it does not. Let $\xi_2^U = \frac{\sqrt{z^2 - 8d^U r^U p_n c_r^U} + z}{4d^U}$, where $z = d^U c_r^U + (k^U + 2r^U)p_n$. It can be shown that $p_{r_0}^U$ exists whenever $p_r^m \geq \xi_2^U$. It can be shown that $\xi_1^U < \xi_2^U$. We consider the following three cases:

(a) If $p_r^m \leq \xi_1^U$, $p_{r_1}^U$ exists and $p_{r_0}^U$ does not exist. In this case, $p_r^U = p_{r_1}^U$.

We obtain the refurbished product quantity $q_r^U = \frac{d^U(p_n - c_r^U)}{2}$ and the third party's profit $\Pi_t^U = \frac{d^U(p_n - c_r^U)^2}{4}$. Hence, we have the new product quantity $q_n^U = \frac{Q_n(2 - b^U(p_n - c_r^U))}{2}$ and the OEM's profit $\Pi_o^U = \frac{Q_n w_n (2 - b^U(p_n - c_r^U))}{2}$.

(b) If $p_r^m \in (\zeta_1^U, \zeta_2^U)$, $p_{r_1}^U$ and $p_{r_0}^U$ do not exist. In this case, $p_r^U = p_r^m$. We obtain the refurbished product quantity $q_r^U = d^U(p_n - p_r^m)$ and the third party's profit $\Pi_t^U = d^U(p_n - p_r^m)(p_r^m - c_r^U)$. Hence, we have the new product quantity $q_n^U = Q_n - r^U(p_n - p_r^m)$ and the OEM's profit $\Pi_o^U = w_n(Q_n - r^U(p_n - p_r^m))$.

(c) If $p_r^m \geq \zeta_2^U$, $p_{r_0}^U$ exists and $p_{r_1}^U$ does not exist. In this case, $p_r^U = p_{r_0}^U$. We obtain the refurbished product quantity $q_r^U = \frac{k^U p_n - d_u^U c_r^U}{2}$ and the third party's profit $\Pi_t^U = \frac{(k^U p_n - d_u^U c_r^U)^2}{4 d_u^U}$. Hence, we have the new product quantity $q_n^U = \frac{Q_n\left(2 - b^U \rho\left(\frac{k^U p_n}{d_u^U} + c_r^U\right)\right)}{2}$ and the OEM's profit $\Pi_o^U = \frac{Q_n w_n\left(2 - b^U \rho\left(\frac{k^U p_n}{d_u^U} + c_r^U\right)\right)}{2}$.

The complete solutions are provided in Table B.1.

Authorized scenario. Using the same method as in the unauthorized scenario, we obtain the new thresholds $\zeta_1^A = \frac{1}{2}\left(c_g^A + p_n\right)$ and $\zeta_2^A = \frac{\sqrt{\hat{z}^2 - 8 d^A r^A p_n \left(c_g^A\right)} + \hat{z}}{4 d^A}$, where $\hat{z} = d^A\left(c_g^A\right) + \left(k^A + 2r^A\right) p_n$. The complete solutions are provided in Table B.2, where $\Pi_{o1}^A = (p_n - p_r^m)(g d^A - r^A w_n) + Q_n w_n$ and $\Pi_{o2}^A = \frac{w_n\left(2Q_n - \rho r^A\left(c_g^A + \frac{k^A p_n}{d_u^A}\right)\right) + g d_u^A\left(\frac{k^A p_n}{d_u^A} - c_g^A\right)}{2}$.

Table B.1: Optimal solutions for the unconstrained problem in the unauthorized scenario

Third party	$p_r^m \leq \zeta_1^U$	$p_r^m \in (\zeta_1^U, \zeta_2^U)$	$p_r^m \geq \zeta_2^U$
p_r^U	$\frac{p_n + c_r^U}{2}$	p_r^m	$\frac{\frac{k^U p_n}{d_u^U} + c_r^U}{2}$
q_r^U	$\frac{d^U(p_n - c_r^U)}{2}$	$d^U(p_n - p_r^m)$	$\frac{k^U p_n - d_u^U c_r^U}{2}$
Π_t^U	$\frac{d^U(p_n - c_r^U)^2}{4}$	$d^U(p_n - p_r^m)(p_r^m - c_r^U)$	$\frac{(k^U p_n - d_u^U c_r^U)^2}{4 d_u^U}$
OEM			
q_n^U	$\frac{2Q_n - r^U(p_n - c_r^U)}{2}$	$Q_n - r^U(p_n - p_r^m)$	$\frac{2Q_n - \rho r^U\left(\frac{k^U p_n}{d_u^U} + c_r^U\right)}{2}$
Π_o^U	$\frac{w_n(2Q_n - r^U(p_n - c_r^U))}{2}$	$w_n(Q_n - r^U(p_n - p_r^m))$	$\frac{w_n\left(2Q_n - {}^U\left(\frac{k^U p_n}{d_u^U} + c_r^U\right)\right)}{2}$

Table B.2: Optimal solutions for the unconstrained problem in the authorized scenario

Third party	$p_r^m \le \xi_1^A$	$p_r^m \in (\xi_1^A, \xi_2^A)$	$p_r^m \ge \xi_2^A$
p_r^A	$\frac{p_n+c_g^A}{2}$	p_r^m	$\frac{\frac{k^A p_n}{d_u^A}+c_g^A}{2}$
q_r^A	$\frac{d^A(p_n-c_g^A)}{2}$	$d^A(p_n-p_r^m)$	$\frac{k^A p_n-d_u^A c_g^A}{2}$
Π_t^A	$\frac{d^A(p_n-c_g^A)^2}{4}$	$d^A(p_n-p_r^m)(p_r^m-c_g^A)$	$\frac{(k^A p_n-d_u^A c_g^A)^2}{4d_u^A}$
OEM			
q_n^A	$\frac{2Q_n-r^A(p_n-c_g^A)}{2}$	$Q_n-r^A(p_n-p_r^m)$	$\frac{2Q_n-\rho r^A\left(\frac{k^A p_n}{d_u^A}\right)+c_g^A}{2}$
Π_o^A	$\frac{(p_n-c_g^A)(d^A g-r^A w_n)+2Q_n w_n}{2}$	Π_{o1}^A	Π_{o2}^A

Proof of Proposition 4.1. The first derivatives of the thresholds ξ_1^A and ξ_2^A with respect to g are as follows:

$$\frac{\partial \xi_1^A}{\partial g} = \frac{1}{2} \ge 0,$$
$$\frac{\partial \xi_2^A}{\partial g} = \frac{d^A c_g^A + \left(k^A - 2r^A\right) p_n}{4\sqrt{\left(d^A c_g^A + \left(k^A + 2r^A\right) p_n\right)^2 - 8 d^A r^A c_g^A p_n}} + \frac{1}{4} \ge 0.$$

Therefore, the thresholds ξ_1^A and ξ_2^A are increasing in g. It is easy to show that $\xi_2^A \le p_r^m$ and $\xi_1^A \ge p_r^m$ are satisfied when $g \le g_1$ and $g \ge g_2$, respectively, where

$$g_1 = \frac{p_r^m\left(2p_r^m d^A - \left(k^A + 2r^A\right) p_n\right)}{d^A p_r^m - p_n r^A} - c_r^A \quad \text{and} \quad g_2 = 2p_r^m - p_n - c_r^A.$$

Hence, $p_r^m \in (\xi_1^A, \xi_2^A)$ when $g \in (g_1, g_2)$.

Proof of Proposition 4.2.

(a) Let $p_r^m \le \xi_1^U$ and $p_r^m \le \xi_1^A$. Solving $\Pi_t^A \ge \Pi_t^U$ for g yields $g \le g_3^3$, where $g_3^3 = p_n - c_r^A - \frac{\sqrt{d^U}\left(p_n - c_r^U\right)}{\sqrt{d^A}}$. Solving $\Pi_o^A \ge \Pi_o^U$ for g yields $\bar{g}_3^3 \le g \le \tilde{g}_3^3$, where

$$\bar{g}_3^3 = \frac{d^A\left(p_n - c_r^A\right) + r^A w_n - \sqrt{\left(r^A w_n - d^A\left(p_n - c_r^A\right)\right)^2 + 4 d^A r^U w_n\left(p_n - c_r^U\right)}}{2d^A},$$
$$\tilde{g}_3^3 = \frac{d^A\left(p_n - c_r^A\right) + r^A w_n + \sqrt{\left(r^A w_n - d^A\left(p_n - c_r^A\right)\right)^2 + 4 d^A r^U w_n\left(p_n - c_r^U\right)}}{2d^A}.$$

(b) Let $p_r^m \in (\xi_1^U, \xi_2^U)$ and $p_r^m \le \xi_1^A$. Solving $\Pi_t^A \ge \Pi_t^U$ for g yields $g \le g_2^3$, where $g_2^3 = p_n - c_r^A - \frac{2\sqrt{d^U d^A (p_r^m - c_r^U)(p_n - p_r^m)}}{d^A}$. Solving $\Pi_o^A \ge \Pi_o^U$ for g yields $\bar{g}_2^3 \le g \le \tilde{g}_2^3$, where

$$\bar{g}_2^3 = \frac{d^A\left(p_n - c_r^A\right) + r^A w_n - \sqrt{\left(r^A w_n - d^A\left(p_n - c_r^A\right)\right)^2 + 8 d^A r^U w_n \left(p_n - p_r^m\right)}}{2d^A},$$

$$\tilde{g}_2^3 = \frac{d^A\left(p_n - c_r^A\right) + r^A w_n + \sqrt{\left(r^A w_n - d^A\left(p_n - c_r^A\right)\right)^2 + 8 d^A r^U w_n \left(p_n - p_r^m\right)}}{2d^A}.$$

(c) Let $p_r^m \in (\xi_1^U, \xi_2^U)$ and $p_r^m \in (\xi_1^A, \xi_2^A)$. Solving $\Pi_t^A \ge \Pi_t^U$ for g yields $g \le g_2^2$, where $g_2^2 = \frac{d^U c_r^U - d^A c_r^A + \left(d^A - d^U\right) p_r^m}{d^A}$. Solving $\Pi_o^A \ge \Pi_o^U$ for g yields $g \ge \bar{g}_2^2$, where $\bar{g}_2^2 = \frac{\left(r^A - r^U\right) w_n}{d^A}$.

(d) Let $p_r^m \ge \xi_2^U$ and $p_r^m \le \xi_1^A$. Solving $\Pi_t^A \ge \Pi_t^U$ for g yields $g \le g_1^3$, where $g_1^3 = p_n - c_r^A - \frac{k^U p_n - c_r^U d_u^U}{\sqrt{d^A}\sqrt{d_u^U}}$. Solving $\Pi_o^A \ge \Pi_o^U$ for g yields $\bar{g}_1^3 \le g \le \tilde{g}_1^3$, where

$$\bar{g}_1^3 = \frac{d^A\left(p_n - c_r^A\right) + r^A w_n - \sqrt{\left(r^A w_n - d^A\left(p_n - c_r^A\right)\right)^2 + 4 d^A \rho r^U w_n \left(c_r^U + \frac{k^U p_n}{d_u^U}\right)}}{2d^A},$$

$$\tilde{g}_1^3 = \frac{d^A\left(p_n - c_r^A\right) + r^A w_n + \sqrt{\left(r^A w_n - d^A\left(p_n - c_r^A\right)\right)^2 + 4 d^A \rho r^U w_n \left(c_r^U + \frac{k^U p_n}{d_u^U}\right)}}{2d^A}.$$

(e) Let $p_r^m \ge \xi_2^U$ and $p_r^m \in (\xi_1^A, \xi_2^A)$. Solving $\Pi_t^A \ge \Pi_t^U$ for g yields $g \le g_1^2$, where $g_1^2 = p_r^m - c_r^A - \frac{\left(k^U p_n - c_r^U d_u^U\right)^2}{4 d^A d_u^U (p_n - p_r^m)}$. Solving $\Pi_o^A \ge \Pi_o^U$ for g yields $g \ge \bar{g}_1^2$, where $\bar{g}_1^2 = w_n \left(\frac{r^A}{d^A} - \frac{\rho r^U \left(c_r^U d_u^U + k^U p_n\right)}{2 d^A d_u^U (p_n - p_r^m)}\right)$.

(f) Let $p_r^m \ge \xi_2^U$ and $p_r^m \ge \xi_2^A$. Let $z = k^A p_n - c_r^A d_u^A - \rho r^A w_n$ and

$$\bar{z} = 2\rho w_n \left(\frac{2 r^U d_u^A \left(c_r^U d_u^U + k^U p_n\right)}{d_u^U} - 3 k^A r^A p_n\right).$$

Solving $\Pi_t^A \ge \Pi_t^U$ for g yields $g \le g_1^1$, where $g_1^1 = \frac{k^A p_n}{d_u^A} - c_r^A - \frac{k^U p_n - c_r^U d_u^U}{\sqrt{d_u^U}\sqrt{d_u^A}}$. Solving

$\Pi_o^A \geq \Pi_o^U$ for g yields $\bar{g}_1^1 \leq g \leq \tilde{g}_1^1$, where

$$\bar{g}_1^1 = \frac{z - \sqrt{\bar{z} - 2k^A c_r^A d_u^A p_n + \left(\rho r^A w_n - c_r^A d_u^A\right)^2 + {k^A}^2 p_n^2}}{2d_u^A},$$
$$\tilde{g}_1^1 = \frac{z + \sqrt{\bar{z} - 2k^A c_r^A d_u^A p_n + \left(\rho r^A w_n - c_r^A d_u^A\right)^2 + {k^A}^2 p_n^2}}{2d_u^A}.$$

Proof of Lemma 4.2. Unauthorized scenario. Recall the proof of Lemma 4.1.

(a) If $p_r^m \leq \xi_1^U$ (price-sensitive area), $q_n^{U*} = \frac{Q_n\left(2-b^U\left(p_r^U - c_r^U\right)\right)}{2}$ and $q_r^{U*} = \frac{1}{2}d^U\left(p_n - c_r^U\right)$. The constraint is binding, i.e., $q_r^U > \delta q_n^U$, if $\delta < \delta_3^U$ or equivalently $k > k_3^U$, where $\delta_3^U = \frac{d^U\left(p_n - c_r^U\right)}{2Q_n - r^U\left(p_n - c_r^U\right)}$ and $k_3^U = \frac{2\delta Q_n}{p_n - c_r^U} - (\delta+1)r^U$. Hence, if $\delta \geq \delta_3^U$, $p_r^{U*} = p_{r_1}^U$. If $\delta < \delta_3^U$, $p_r^{U*} = p_{c_1}^U = \frac{d^U p_n - \delta\left(Q_n - r^U p_n\right)}{d^U + \delta r^U}$.

(b) If $p_r^m \in (\xi_1^U, \xi_2^U)$ (price-perceived quality threshold), $q_n^{U*} = Q_n - r^U\left(p_n - p_r^m\right)$ and $q_r^{U*} = d^U\left(p_n - p_r^m\right)$. The constraint is binding, i.e., $q_r^U > \delta q_n^U$, if $\delta < \delta_2^U$ or equivalently $k > k_2^U$, where $\delta_2^U = \frac{\left(k^U + r^U\right)\left(p_n - p_r^m\right)}{Q_n - r^U\left(p_n - p_r^m\right)}$ and $k_2^U = \frac{\delta Q_n}{p_n - p_r^m} - (\delta+1)r^U$. Hence, if $\delta \geq \delta_2^U$, $p_r^{U*} = p_r^m$. If $\delta < \delta_2^U$, $p_r^{U*} = p_{c_1}^U = \frac{d^U p_n - \delta\left(Q_n - r^U p_n\right)}{d^U + \delta r^U}$.

(c) If $p_r^m \geq \xi_2^U$ (quality-sensitive area), $q_n^{U*} = \frac{1}{2}\left(2Q_n - \rho r^U\left(c_r^U + \frac{k^U p_n}{d_u^U}\right)\right)$ and $q_r^{U*} = \frac{1}{2}\left(k^U p_n - c_r^U d_u^U\right)$. The constraint is binding, i.e., $q_r^U > \delta q_n^U$, if $\delta < \delta_1^U$, where $\delta_1^U = \frac{d_u^U\left(k^U p_n - c_r^U d_u^U\right)}{d_u^U\left(2Q_n - \rho r^U c_r^U\right) - k^U \rho r^U p_n}$. Hence, if $\delta \geq \delta_1^U$, $p_r^{U*} = p_{r_0}^U$. If $\delta_2^U < \delta < \delta_1^U$, $p_r^{U*} = p_{c_0}^U = \frac{k^U p_n - \delta Q_n}{d_u^U - \delta\rho r^U}$. If $\delta = \delta_2^U$, $p_r^{U*} = p_r^m$. If $\delta < \delta_2^U$, $p_r^{U*} = p_{c_1}^U$.

Authorized scenario.

(a) If $p_r^m \leq \xi_1^A$ (price-sensitive area), $q_n^{A*} = \frac{1}{2}\left(2Q_n - r^A\left(p_n - c_g^A\right)\right)$ and $q_r^{A*} = \frac{1}{2}d^A\left(p_n - c_g^A\right)$. The constraint is binding, i.e., $q_r^A > \delta q_n^A$, if $\delta < \delta_3^A$ or equivalently $k^A > k_3^A$, where $\delta_3^A = \frac{d^A\left(p_n - c_g^A\right)}{2Q_n - r^A\left(p_n - c_g^A\right)}$ and $k_3^A = \frac{2\delta Q_n}{p_n - c_g^A} - (\delta+1)r^A$. Hence, if $\delta \geq \delta_3^A$, $p_r^{A*} = p_{r_1}^A$. If $\delta < \delta_3^A$, $p_r^{A*} = p_{c_1}^A = \frac{d^A p_n - \delta\left(Q_n - r^A p_n\right)}{d^A + \delta r^A}$.

(b) If $p_r^m \in (\xi_1^A, \xi_2^A)$ (price-perceived quality threshold), $q_n^{A*} = Q_n - r^A(p_n - p_r^m)$ and $q_r^{A*} = d^A(p_n - p_r^m)$. The constraint is binding, i.e., $q_r^A > \delta q_n^A$, if $\delta < \delta_2^A$

or equivalently $k^A > k_2^A$, where $\delta_2^A = \frac{d^A(p_n - p_r^m)}{Q_n - r^A(p_n - p_r^m)}$ and $k_2^A = \frac{\delta Q_n}{p_n - p_r^m} - (\delta + 1)r^A$. Hence, if $\delta \geq \delta_2^A$, $p_r^{A*} = p_r^m$. If $\delta < \delta_2^A$, $p_r^{A*} = p_{c_1}^A = \frac{d^A p_n - \delta\left(Q_n - r^A p_n\right)}{d^A + \delta r^A}$.

(c) If $p_r^m \geq \xi_2^A$ (quality-sensitive area), $q_n^{A*} = \frac{1}{2}\left(2Q_n - \rho r^A\left(c_g^A + \frac{k^A p_n}{d_u^A}\right)\right)$ and $q_r^{A*} = \frac{1}{2}\left(k^A p_n - c_g^A d_u^A\right)$. The constraint is binding, i.e., $q_r^A > \delta q_n^A$, if $\delta < \delta_1^A$, where $\delta_1^A = \frac{d_u^A\left(k^A p_n - c_g^A d_u^A\right)}{d_u^A\left(2Q_n - \rho r^A c_g^A\right) - k^A \rho r^A p_n}$. Hence, if $\delta \geq \delta_1^A$, $p_r^{A*} = p_{r_0}^A$. If $\delta_2^A < \delta < \delta_1^A$, $p_r^{A*} = p_{c_0}^A = \frac{k^A p_n - \delta Q_n}{d_u^A - \delta \rho r^A}$. If $\delta = \delta_2^A$, $p_r^{A*} = p_r^m$. If $\delta < \delta_2^A$, $p_r^{A*} = p_{c_1}^A$.

Proof of Proposition 4.3. Let $\delta_U < \delta_3^U$, $\delta_A < \delta_3^A$, $g_{c3}^3 = p_r^A - p_r^U + \tau_c$ and $\bar{g}_{c3}^3 = \frac{Q_n w_n\left(k^U \tau_b - b^U \tau_k\right)}{d^U d^A}$. Solving $\Pi_t^A \geq \Pi_t^U$ for g yields $g \leq g_{c3}^3$. Solving $\Pi_o^A \geq \Pi_o^U$ for g yields $g \geq \bar{g}_{c3}^3$.

D

Appendix of Chapter 5

D.1. Proofs for Dynamic Programming

Proof of Proposition 5.1. Let $q_\rho = \rho_1 q_2^n + \rho_2 q_1^n$ and $\bar{q}_\rho = \frac{1}{2}\left(2q_1^r + a_2 - d_2 c^r - r_2 w^n\right)$. The Lagrangean and the Karush-Kuhn-Tucker conditions are:

$$\begin{aligned}
\Pi_2 =& w^n\left(r_2 p_2^r + v_2\right) + \left(p_2^r - c^r\right)\left(a_2 - d_2 p_2^r\right) \\
&+ \lambda(\rho_1(r_2 p_2^r + v_2) + \rho_2(r_1 p_1^r + v_1) + d_1 p_1^r + d_2 p_2^r - a_1 - a_2), \\
\frac{\partial \Pi_2}{\partial p_2^r} =& a_2 + d_2\left(c^r - 2p_2^r\right) + r_2 w^n = 0, \\
\frac{\partial \Pi_2}{\partial \lambda} =& \rho q_1^n - a_1 - a_2 + d_1 p_1^r + d_2 p_2^r = 0,
\end{aligned}$$

where λ is a Lagrange multiplier. The Lagrangean is concave with respect to p_2^r. Because the multiplier can be either zero or positive, there are two cases of interest to us.

Case A: $\lambda > 0$.

Solving the optimality conditions gives $p_2^{r\,*} = \frac{a_2 + d_2 c^r + r_2 w^n}{2d_2}$, $q_2^{r\,*} = \frac{1}{2}\left(a_2 - d_2 c^r - r_2 w^n\right)$. The condition $\lambda > 0$ gives $q_\rho \leq \bar{q}_\rho$.

Case B: $\lambda = 0$.
Solving the optimality conditions gives $p_2^{r\,*} = \frac{a_2+d_2c^r+r_2w^n}{2d_2}$ and $q_2^{r\,*} = \frac{1}{2}\left(a_2 - d_2c^r - r_2w^n\right)$. The condition $q_1^r + q_2^r < \rho_1 q_1^n + \rho_2 q_1^n$ gives $q_\rho > \bar{q}_\rho$.

Proof of Proposition 5.2. We maximize the total two-period profit Π, which is continuously differentiable and strictly concave in p_1^r. The profit function of manufacturer in two periods is as follows:

$$\begin{aligned}\Pi = \;& (p_1^n - c_1^n)q_1^n + (p_1^r - c^r)q_1^r + \Pi_2^*,\\ \text{s.t.}\;\; & q_1^r \le \rho_1 q_2^n.\end{aligned}$$

The Lagrangean and the Karush-Kuhn-Tucker conditions are:

$$\begin{aligned}&\Pi = w^n\left(r_1p_1^r + v_1\right) + \left(p_1^r - c^r\right)\left(a_1 - d_1p_1^r\right) + \Pi_2^*\left(p_1^r\right) + \mu\left(\rho_1\left(r_2p_2^r + v_2\right) - a_1 + d_1p_1^r\right),\\ &\frac{\partial\Pi}{\partial p_1^r} = 0,\;\; \frac{\partial\Pi}{\partial\mu} = \rho_1\left(r_2p_2^r + v_2\right) - a_1 + d_1p_1^r = 0,\end{aligned}$$

where μ is a Lagrange multiplier. Let $\bar{\theta}_\rho = \frac{\rho_1\left(d_2\left(r_2c^r+2Q^n\right)+r_2^2w^n\right)-d_2\left(a_1-d_1c^r-r_1w^n\right)}{d_2p_1^n\rho_1r_2}$. If $q_\rho \le \bar{q}_\rho$, $\bar{\theta}_\rho \le \theta$, otherwise $\bar{\theta}_\rho > \theta$. We consider two cases in Proposition 5.1.

Case A: $q_\rho \le \bar{q}_\rho$ or $\bar{\theta}_\rho \le \theta$ or $q_1^r + q_2^r = q_\rho$.
Because the multiplier μ can be either zero or positive, there are two subcases of interest to us.
Subcase A1: $\mu > 0$. Solving the optimality conditions gives $p_1^{r\,*} = \frac{a_1d_2-\rho_1(r_2(a_2-\rho_2v_1)+d_2v_2)}{d_1d_2-\rho_1\rho_2r_1r_2}$, $q_1^{r\,*} = \rho_1q_2^n$, $p_2^{r\,*} = \frac{a_2d_1-\rho_2(r_1(a_1-\rho_1v_2)+d_1v_1)}{d_1d_2-\rho_1\rho_2r_1r_2}$, and $q_2^{r\,*} = \frac{\rho_2(d_2(a_1r_1+d_1v_1)-\rho_1r_1(a_2r_2+d_2v_2))}{d_1d_2-\rho_1\rho_2r_1r_2}$. The condition $\mu > 0$ gives $\theta \le \bar{\theta}_1$, where $\bar{\theta}_1 = \frac{z_1+z_2+z_3+z_4+z_5-z_6}{d_2p_1^n(d_1+\rho_2r_1)(d_1d_2-\rho_1\rho_2r_1r_2)}$, where

$$\begin{aligned}
z_1 &= d_1d_2\left(\rho_1r_2\left(a_1 - d_1c^r - r_1w^n\right) + d_2\left(a_1 - r_1w^n\right) + d_1r_2w^n\right),\\
z_2 &= d_1d_2\rho_2\left(r_1\left(2a_1 + d_2c^r + r_2w^n\right) + 2d_1v_1\right),\\
z_3 &= \rho_1\rho_2\left(r_1\left(d_2r_2\left(a_1 + r_1w^n\right) - d_1r_2^2w^n\right) + 2d_1d_2r_2v_1\right),\\
z_4 &= \rho_1^2\rho_2r_2^2\left(r_1\left(a_1 + d_1c^r + r_1w^n\right) + 2d_1v_1\right),\\
z_5 &= \rho_2^2r_1\left(2d_2\left(a_1r_1 + d_1v_1\right) - \rho_1r_1\left(d_2r_2c^r + r_2^2w\right)\right),\\
z_6 &= 2d_2\rho_1Q^n\left(d_1\left(d_2 + \rho_1r_2 + \rho_2r_1\right) + \rho_2^2r_1^2\right).
\end{aligned}$$

Subcase A2: $\mu = 0$. Solving the optimality conditions gives $q_1^{r*} = \rho_1 q_2^n - \bar{q}_2^r$, $q_2^{r*} = \bar{q}_2^r + \rho_2 q_1^n$, and $p_1^{r*} = \frac{a_1 - q_1^{r*}}{d_1}$, where $\bar{q}_2^r = a_2 - d_2 p_2^{r*}$ and $p_2^{r*} = \frac{d_1(\bar{z}_1+\bar{z}_2)+\rho_2(\bar{z}_3+\bar{z}_4)+\bar{z}_5}{2\left(d_1\left((d_2+\rho_1 r_2)^2+2d_2\rho_2 r_1\right)+d_2\rho_2^2 r_1^2+d_2 d_1^2\right)}$, where

$$\begin{aligned}
\bar{z}_1 &= a_2\left(2\left(d_2+\rho_1 r_2\right)+d_1\right)+a_1 d_2 - d_2\left(r_1 w^n + 2\rho_1 v_2\right),\\
\bar{z}_2 &= r_2\left(\rho_1\left(a_1 - r_1 w^n - 2\rho_1 v_2\right)+d_1\left(w^n - \rho_1 c^r\right)\right),\\
\bar{z}_3 &= d_1 r_1\left(2a_2 + d_2 c^r\right) - d_2 r_1\left(a_1 + r_1 w^n\right),\\
\bar{z}_4 &= 2d_1\left(r_1 r_2 w^n - \left(d_2 - 1\right) v_1\right) - \rho_1 r_2\left(r_1\left(a_1 + d_1 c^r + r_1 w^n\right)\right),\\
\bar{z}_5 &= \rho_2^2 r_1^2\left(a_2 + d_2 c^r + r_2 w^n\right).
\end{aligned}$$

The condition $q_1^r \leq \rho_1 q_2^n$ gives $\theta > \bar{\theta}_1$. If $\theta \geq \bar{\theta}_2$, $\bar{q}_2^r = \rho_1 q_2^n$, where $\bar{\theta}_2 = \frac{\hat{z}_1+\hat{z}_2}{p_1(d_2+\rho_1 r_2)}$, where

$$\begin{aligned}
\hat{z}_1 &= c^r\left(d_2+\rho_1 r_2\right)+r_2 w^n\left(\frac{\rho_1 r_2}{d_2}+1\right)+2\rho_1 Q^n,\\
\hat{z}_2 &= \frac{\left(d_2+\rho_1 r_2\right)^2\left(a_1 - d_1 c^r - r_1 w^n\right)}{d_2\left(d_1+\rho_2 r_1\right)}+2\rho_2\left(\frac{a_1 r_1}{d_1}+v_1\right).
\end{aligned}$$

Hence, $q_1^{r*} = 0$ and $q_2^{r*} = q_\rho$ whenever $\theta \geq \bar{\theta}_2$.

Case B: $q_\rho > \bar{q}_\rho$ or $\bar{\theta}_\rho > \theta$ or $q_1^r + q_2^r = \bar{q}_\rho$.
Subcase B1: $\mu > 0$. Solving the optimality conditions gives

$$p_1^{r*} = \frac{2a_1 d_2 - \rho_1\left(r_2\left(a_2 + d_2 c^r + r_2 w^n\right)+2d_2 v_2\right)}{2d_1 d_2},$$

$q_1^{r*} = \rho_1 q_2^n$, $p_2^{r*} = \frac{a_2+d_2 c^r + r_2 w^n}{2d_2}$, and $q_2^{r*} = \frac{1}{2}\left(a_2 - d_2 c^r - r_2 w^n\right)$. The condition $\mu > 0$ gives $\rho_1 \leq \bar{\rho}_1$, where $\bar{\rho}_1 = \frac{d_2\left(a_1 - d_1 c^r - r_1 w^n\right)}{r_2\left(a_2+d_2 c^r + r_2 w^n\right)+2d_2 v_2}$.

Subcase B2: $\mu = 0$. Solving the optimality conditions gives

$$p_1^{r*} = \frac{a_1 + d_1 c^r + r_1 w^n}{2d_1},$$

$q_1^{r*} = \frac{1}{2}\left(a_1 - d_1 c^r - r_1 w^n\right) < \rho_1 q_2^n$, $p_2^{r*} = \frac{a_2+d_2 c^r + r_2 w^n}{2d_2}$, and $q_2^{r*} = \frac{1}{2}\left(a_2 - d_2 c^r - r_2 w^n\right) < q_\rho - q_1^{r*}$. The condition $q_1^r \leq \rho_1 q_2^n$ gives $\rho_1 > \bar{\rho}_1$.

Summary

Revenue Management and Strategy for the Refurbishing Economy

With the rapid introduction of new generations of consumer electronics, an increasing number of consumers buy new electronics before products actually break down. An increasing number of such products are being refurbished, implying they are improved by the original manufacturer (OEM) or by a third party (3P) who then sells the product as-new for a reduced price. The consumer market is segmented in terms of its preferences for new or refurbished products, and this makes decisions for both OEMs and 3Ps regarding engagement in refurbishing, the authorization of refurbishing, and product pricing increasingly complex.

In this dissertation, we study the revenue management and strategic decisions of such firms.

Price-Perceived Quality Relationship for Refurbished Products

Consumer behavior toward refurbished products is different from the behavior towards new products and depends on how they value the product characteristics and their perception of the products' quality. Hence, it is important to understand this behavior when dealing with pricing decisions for refurbished products. The principal keys in pricing decisions are the willingness-to-pay (WTP) and consumer

preferences. An empirical study is a valuable way to analyze this purchasing behavior. We conduct three different behavioral studies with regards to different market situations, i.e., consumer behavior to a single refurbished product (Study 1), a competition between new product and its refurbished version (Study 2), and a competition between brands (Study 3). The objective of Study 1 is to estimate the price-perceived quality for refurbished products with different attributes such as brand, product condition, seller identity, eco-friendly certification, product type, and online market place. The price-perceived quality effects are measured by using two methods, i.e., price categorization and discrete choice experiment. The results of price categorization show that the attributes have influence on the price-level sensitivity (sensitiveness to price and quality) of refurbished products and an inverted U-shaped purchasing function always exists when the consumers are only faced with a single refurbished product and there is no any product substitute available in the same market. However, the discrete choice experiments yield different results. The results of this method in Study 1 and Study 2 show that an inverted U-shape exists for a low-brand refurbished product and is absent when the brand recognition is relatively high. The consumers are more sensitive to changes in discounts (or prices) of a refurbished product with a higher brand value. Moreover, Study 3 showed that the inverted U-shaped cannibalization behavior, that had been demonstrated in a monopolistic setting, is largely absent in a duopolistic setting. If the difference between the two brand levels is getting larger, the stronger is the negative perception of the low-brand valued firms' refurbished products, and the market share difference at the same discounts also getting higher. The experimental results also show that cross-cannibalization is an effect to be reckoned with, especially for low-brand firms facing competition from high-brand firms offering refurbished products.

Revenue Management in Refurbishing Duopoly with Cannibalization

Based on the results of Study 3, we develop and analyze a formal model to shed light onto how such firms would need to make their strategic choices under duopolistic competition between firms with different brand strength, and under (often publicly set) collection constraints. Refurbishing has shown good economic potential, but firms remain wary due to the cannibalization effect on new product sales. The presence of competitors selling both the new product and its refurbished version adds an additional (cross-firm) dimension to this effect. Moreover, competitors may have similar brand strength or may be positioned differently in the market. Further, in practice, such firms are increasingly confronted by collection constraints, such as those imposed by national or supranational regulations. Our analytical results show that manufacturers with a strong brand should increase the prices of their refurbished products if the cross-cannibalization coefficients of the low-brand consumers are higher. For low-brand firms, competing on price is challenging; instead, such firms should focus on beating the high-brand competitors in collection and refurbishing efforts. Finally, we show that the collection constraints have an effect on the pricing strategy of both the high-brand and the low-brand manufacturers. As a consequence, such constraints that are typically set exogenously by public authorities will impact the actual pricing and market equilibria.

Authorization Strategy in Refurbishing with Consumer Behavior

Based on the results of Study 2, we develop and analyze a formal model to examine the conditions under which both the OEM and a 3P may benefit via an authorization strategy. The OEM usually has limited to no control over third party refurbishing firms. With the rapid growth of the market for refurbished electronic products, it would be beneficial for the OEM to cooperate with the 3P via an authorization scheme. We study the trade-off between the indirect benefit from authorizing a 3P and increase in market share vs. the effect of cannibalization on new product sales. We provide a general model for market segmentation and show how it can be adapted to fit the existing literature on market segmentation. We assume customers to follow a U-shaped cannibalization function, i.e., they get suspicious when the discounts are too high. This cannibalization function can also be viewed as a linear function when the price-quality threshold is sufficiently low. Our results show that authorization can be a win-win strategy for the OEM and the 3P when the functionality-oriented consumer segment is sufficiently large. There are three regions for 3P's optimal price – the price-sensitive area, the quality-sensitive area, and the price-quality threshold.

Strategic Decision Making for Refurbishing Across New Product Generations

OEMs usually release new-generation products at an intensive rate. Hence, the

OEM could choose to introduce the refurbished products before the introduction of the new model or wait for it. If a newer generation is introduced, the previous one becomes unattractive. If the OEM releases its refurbished products in this period, the firm may not need to worry about cannibalization. However, there may be some customers who are not willing to purchase the refurbished version of old generation. In order to deal with this problem, we construct and solve a two-period dynamic programming model constrained by the number of cores available for refurbishing, where the second period decision depend on the previous sales of refurbished product. Our study shows that in the first period, the manufacturer has three option decisions: full refurbishing, partial refurbishing, and no refurbishing. The decisions are driven by the price-drop coefficient, recovery fractions, demand cannibalization, and low-end demand.

Our models provide insight into the strategies that firms should follow in a market that is increasingly complex due to the presence of various generations of new and refurbished products, and firms that focus on refurbishing as their core business. With a circular economy that is developing more and more towards reusing our natural resources, we show that in such an economy, even without government interventions or taxation incentives, refurbished products can form a very relevant segment in the consumer electronics industry.

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If I have seen further it is by standing on the shoulders of Giants.
Isaac Newton, Letter To Robert Hooke, February 5, 1675

Nughthoh Arfawi Kurdhi
Eindhoven, January 2021

About the Author

Nughthoh Arfawi Kurdhi was born on July 17, 1985, Indonesia. He finished his Bachelor of Science degree in Mathematics from Sebelas Maret University in 2007. He subsequently obtained a Master of Science degree in Mathematics from Gadjah Mada University in 2010. After obtaining his master, in 2011, Nughthoh started his academic career as a lecturer and researcher in Department of Mathematics, Faculty of Mathematics and Natural Sciences, Sebelas Maret University.

In February 2017, Nughthoh Arfawi Kurdhi started his PhD program at the Operations, Planning, Accounting, and Control group of the school of Industrial Engineering, Department of Industrial Engineering and Innovation Science, Eindhoven University of Technology under supervision of Professor Jan C. Fransoo and dr. Shaunak Dabadghao, of which the results are presented in this dissertation. His work contributes to a richer understanding of the economics, pricing, and strategic behavior of firms offering refurbished products. As refurbishing is becoming more commonplace in more industries, the results can inform managers and public policy decisions makers about the right path to follow. Part of his work so far was presented at the 29th European Conference on Operational Research (EURO 2018) in Valencia, Spain, and the 2019 Manufacturing and Service Operations Management (MSOM 2019) Conference in Singapore. It will also be presented in the 31st Annual Conference Online, Production and Operations Management Society

(POMS 2021). Two manuscripts are under review at top journals A^+ in the field, and two other manuscripts will be submitted to some of the other top journals.

During his PhD, Nughthoh Arfawi Kurdhi was one of the tutors for 1CV10-Introduction to Financial and Management Accounting and 1CK40-Intermediate Finance and Accounting courses. He also completed courses (total workload: 908, 5 hours) as part of the PhD program of the Graduate Program Industrial Engineering. The courses were organized by the Mathematics of Operations Research (LNMB), the Graduate Program Operations Management & Logistics (GP-OML), the Beta Research School for Operations Management and Logistics, TU/e GP-IE, and TU/e Proof. Moreover, Nughthoh Arfawi Kurdhi was involved in supervising bachelor thesis of three students.

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