THREE ESSAYS ON PRODUCT DESIGN FOR THE ENVIRONMENT

BY

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DISSERTATION

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Business Administration
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2015

Urbana, Illinois

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ABSTRACT

Design is a powerful instrument by which the world is forged to satisfy the needs of mankind. As the awareness and pursuit of sustainability increases, we have seen the transition from "design for needs" to "design for environment". Design for the Environment (DfE) requires manufacturers to focus on conserving and reusing resources, minimizing waste, and reducing hazard during a design process. DfE includes, but not limited to Design for Recovery and Benign by Design. Manufacturers are facing the challenge and opportunity of incorporating DfE into their businesses. Eco-conscious product design is critical for the success of businesses, and, therefore, has been an important research focus. This dissertation presents a design approach to help manufacturers maximize profits through optimal eco-conscious product design, and to seek insights for policy makers and managers into inducing product design for the environment. The focus of this dissertation is the interaction between product design for the environment with market segmentation, inter-divisional coordination, and regulatory policies.

This dissertation presents two studies on Design for Recovery. The first study analyzes the effects of remanufacturable product design on market segmentation and trade-in prices. By identifying the system and market parameters under which it is optimal for a manufacturer to design a remanufacturable product, the study demonstrates that entering a remanufactured-goods market in and of itself does not necessarily translate into environmental friendliness. In addition, this study develops and compares several measures of environmental efficiency, and concludes that emissions per revenue can serve as the best proxy for emissions as a metric for measuring overall environmental stewardship.

The second study investigates the impact of decentralization of manufacturing and remanufacturing operations within a firm on product design, pricing, and profitability, and seeks inter-divisional incentive mechanism to

achieve firm-wide coordination. This study shows that decentralization and divisional conflict not only result in lower firm profit and product sales, but also create a hurdle for remanufacturable product design. Thus, an inter-divisional incentive mechanism is suggested to facilitate coordination between two profit-maximizing divisions. The study signifies a two-part coordination scheme (a transfer price and a fixed lump sum), through which a decentralized firm can achieve first-best total profit and production quantity; in addition, the manufacturing division is incentivized to design new products to be remanufacturable.

The last study focuses on Benign by Design. In this essay, an innovative pharmaceutical company decides whether to adopt green pharmacy in response to the regulatory policy of the pharmaceutical stewardship and/or patent term extension, as well as the competition from a generic company. One the one hand, the patent term extension can encourage the innovative company to invest in green pharmacy, and the regulator can induce green pharmacy with short extended term when market competition is intensive. On the other hand, a pharmaceutical company will neither go green nor bear all the compliance cost in the presence of the take-back regulation because the compliance cost is traditionally independent of the choice of green pharmacy. Results show that although adding the take-back regulation on top of the patent term extension generally reduces firm profit and requires a longer term extension, such combined policy can excel the single policy of patent term extension under certain circumstances. In addition, a modified take-back policy that associates compliance cost with the firm's choice of green pharmacy is better than the patent term extension when the competition intensity is relatively high.

To my parents and husband, for their love and support.
To our only planet.

ACKNOWLEDGMENTS

First and foremost, I would like to express sincere gratitude to my co-advisors Professor Dilip Chhajed and Professor Nicholas C. Petruzzi for sharing with me their expertise, vision and passion for research, and for showing me the ropes in teaching during my entire Ph.D. study. I deeply appreciate that they believe in me and devoted many evenings, weekends and lunch hours to helping me. This dissertation would not have been possible without their step-by-step guidance and unparalleled support.

I would also like to give my profound thanks to Professor Zhixi Wan and Professor Michael Lim for their guidance and support, for serving on my doctoral committee and for invaluable comments and suggestions in the preparation of this dissertation.

Over the past five years, it has been my great honor to work with the faculty of Operations Management (Process Management) in the Department of Business Administration, UIUC: Prof. Anupam Agrawal, Prof. Gopesh Anand, Prof. Dharma Kwon, Prof. Fataneh Taghaboni-Dutta, Prof. Han Ye, and Dr. Meng Li. Working with them has been an invaluable and enlightening experience.

My thanks also go to my colleagues and friends, in particular to all the former and current students in the BA Department: Kunpeng Li, Chongqi Wu, Wenjun Gu, Wenxin Xu, Karthik Murali, Youngsoo Kim, Xuefeng Liu, Ying Xiao, Ya Tang, Duo Jiang, Kezhou Wang, Yifan Wei and Yaxian Xie. Big thanks to my officemate, Wenxin, for helping me like a sister. I am also very thankful to my other friends, including, Chen Yao, Cong Zhang, Bing Zuo, Shuoyuan He, Qian Yin, Qingzhou Luo, Qingxi Li, Yu Qian, among others, for making my stay at Urbana-Champaign a memorable one. I would also like to extend my heartfelt thanks to my previous advisor and colleagues in China, Professor Peng Tian and Professor Guohua Wan for their continuing support and encouragement.

Last but not least, I want to thank my parents, including my in-laws, and my husband for their unconditional love, gracious understanding, and boundless support in all the ways in my life. They have been my inspiration and motivation for moving my study and career forward. My grandma, who rests in peace, shares credit on every goal I achieve. I dedicate this dissertation to them.

Thank you all very much.

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CHAPTER 1

INTRODUCTION

"Rethinking the future: It is a profound challenge, at the end of an era of cheap oil and materials to rethink and redesign how we produce and consume; to reshape how we live and work, or even to imagine the jobs that will be needed for transition."

– Dame Ellen Patricia MacArthur.

1.1 Design for Recovery and Benign by Design

Design is one of the most powerful, inspiring, and enlightening instrument by which the world is forged to satisfy the needs of mankind. As the awareness and pursuit of sustainability increases, manufacturers are faced with the challenge and opportunity of conducting green businesses, which drives the transition from a "design for needs" to a "design for environment". Design for the Environment (DfE) is "a design process that must be considered for conserving and reusing the earth's scarce resources; where energy and material consumption is optimized, minimal waste is generated and output waste streams from any process can be used as the raw materials of another" (Billatos and Basaly 1997). According to United Nations Economic and Social Commission for Western Asia (ESCWA 2014), one of the central concepts of DfE is the design for reuse or disposal. Product design is the beginning of the life of a product, and it occupies great importance in terms of environmental impact of the product from cradle (raw materials) to its grave (recovery or disposal).

In end-of-life recovery, part of unwanted products become useful components of other products (Fitzgerald et al. 2007). End-of-life recovery can be achieved by various means, such as reuse, reconditioning, refurbishing, remanufacturing, and recycling. Reuse and reconditioning require very few reprocessing operations; reuse involves almost no value-adding treatments while reconditioning requires minor value-adding treatments of cleaning, lubricating, or polishing. Refurbishing and remanufacturing both include replacement of used parts; a remanufactured product is built with upgraded parts while a refurbished product is built with parts that maintain the original specifications (Kwak 2012). Recycling is the simplest but the least resource-efficient form of recovery. The unwanted products are usually deformed so that raw materials can be extracted to produce different products. Among these five forms of recovery, remanufacturing and refurbishing rely heavily on the ease of inspection, cleaning, and disassembly (Sundin and Bras 2005). It is evident that the difficulties in inspection, cleaning, and disassembly can only be lowered or removed if products are designed for remanufacturing and refurbishing. Therefore, Chapter 2 and 3 of this dissertation mainly focus on the design for remanufacturing.

End-of-life recovery is profitable when the residual value of unwanted products are high. If the residual value is small, unwanted products are disposed rather than recovered. The process of disposal generates negative environmental impacts by potentially consuming energy, releasing emissions, and contaminating surface and waters. Although efforts have been made to reduce such impacts through end-of-pipe-control approach, it is always better to prevent waste through benign design than to treat or clean up waste afterwards. For example, *green chemistry* emphasizes the design of safer chemicals (minimize the toxicity of chemical products), design for degradation (chemicals break down easily and do not persist in the environment), and design for energy efficiency (minimize the energy requirements of chemical processes) (Anastas and Warner 1998). Similarly, *green pharmacy* is the design of pharmaceutical products and processes that eliminates or reduces the use and generation of hazardous substances (EEA 2010). To achieve *green chemistry* and *green pharmacy*, design for benignity is key. Thus, Chapter 4 studies several issues concerning a “benign-by-design” approach.

1.2 Motives for DfE

The transition from a “design for needs” to a “design for environment” can be traced back to the early 1970s (Madge 1993). Today, Design for the Environment (DfE), along with Green Design (GD), Environmentally Conscious Design (ECD) and EcoDesign, is becoming a common practice in many manufacturing and service industries (Giudice et al. 2006). Economic profitability and environmental legislations are, among others, the key drivers for DfE.

Profitability is the ultimate motivation for DfE, enabling manufacturers to control cost, charge green premium and expand market. In many cases, remanufacturing operations can be less expensive and more environmentally friendly than manufacturing operations for manufacturers (Wu 2012). For example, a remanufactured alternator offers 50% cost saving and 60-70% energy and material consumption as compared to a new product (Fatimah et al. 2013). However, products that are not designed to be easily remanufactured could result in very high costs, which makes remanufacturing barely profitable (Sundin 2001, Kerr and Ryan 2001, Franke et al. 2006).

Not only does DfE help manufacturers to lower cost, it also allows companies to segment customers and practice price differentiation. Bhattacharya and Sen (2003, 2004) pointed out that customers tend to establish strong and committed relationship with companies and products that "help them satisfy one or more important self-definitional needs". Surveys and studies indicate that some customers (usually with more psychological benefits obtained from purchasing a sustainable item) are willing to pay a green premium on eco-safe products (Cremer and Thisse 1999, Chen 2001, Sengupta 2012). As a result, DfE helps transform the end-of-life operations from a "cost center" to a new "revenue center" (Guide Jr and Van Wassenhove 2009).

Moreover, DfE creates a bigger pie for manufacturers as businesses and market opportunities expand. For example, offering remanufactured products is an approach that can attract new end-customers by expanding product lines to include less expensive alternative. BMW Exchange Part offers remanufactured components at a price 30-50% cheaper than new counterparts (Thierry et al. 1995). By selling recovered products at a low price, manufacturers can attract consumers who would otherwise not purchase (Debo et al. 2005). Meanwhile, according to Cone Corporate Citizenship Study (2002), 84% Americans reported that they would switch brands to one associated with a good cause, given similar price and quality. Therefore, manufacturers can employ DfE to maintain its market share or gain a larger share. The U.S. Environmental Protection Agency (EPA), who promotes the Design for the Environment Program, also demonstrates this possible boundary:

> "Companies that have invested in safer chemistry and earned the (EPA Design for the Environment) label have entered an expanding marketplace for sustainable products. These companies can look forward to growing their businesses and adding green jobs to the economy. Participants in the green marketplace include major retailers, such as Wal-Mart, Safeway, Home Depot, and Target, which have given special status to Design for the Environment-labeled products, and government purchasers who are increasingly specifying the Design for the Environment label in their purchasing requirements."
>
> – EPA Design for the Environment (http://www.epa.gov/dfe/faqs.html)

Environmental legislation has also been identified as a motivator for "design for environment". Environmental legislation influences product design in various ways. First, regulations, such as the Restriction of Hazardous Substances (RoHS) Directive and recycled-content mandates, instigate design changes by prohibiting or restricting the use of some substances (Toffel 2003). Second, take-back requirements, such as Waste Electrical and Electronic Equipment (WEEE) Directive and End of Life Vehicle (ELV) Directive, motivate manufacturers to modify product design such that end-of-life product recovery becomes profitable or end-of-life product disposal becomes easy and safe. This can be achieved, for example, by adopting easy-disassembly or ready-recycling product and process design (Toffel 2004). A list of Product Stewardship and Extended Producer Responsibility (EPR), also called "Producer Takeback", can be found at `http://www.calrecycle.ca.gov/epr/PolicyLaw/default.htm#World`. Third, legislation on landfill taxes, energy taxes, recycling subsidies and emissions trading encourages manufacturers to design or redesign products and process in order to reduce the consumption of energy and materials, or to minimize pollution and waste (Calcott and Walls 2000, 2005, Plambeck and Wang 2009).

1.3 Barriers to DfE

Although the transition from a "design for needs" to a "design for environment" was initiated more than four decades ago, many managerial decisions fail to follow the paradigms of sustainability (Flannery and May 2000, Seitz 2007). As a case in point, although Caterpillar undertook both manufacturing and remanufacturing operations, its engine design priorities were still largely governed by the needs of the manufacturing process (Stahel 1995). There are three types of barriers to the growth of DfE: (1) high cost, (2) perceived value, and (3) cannibalization and competition.

In order to take advantage of the cost savings, manufacturers have to design and produce products to be refurbishable or remanufacturable, which could require costly materials and advanced technology (Lee and Bony 2008). The cost saving from DfE may not always justify the additional expenses on materials and technology. Moreover, original equipment manufacturers (OEMs) need to pay higher prices for take-back operations and face strong variations in quality, quantity and time of returned products (Guide Jr and Van Wassenhove 2001), which can make DfE unattractive. DfE meets extreme obstacle when the residual value of end-of-life products is nominal and the environmental legislation to encourage responsible behavior is not available.

DfE relies on the market demand and profitability. Recovered products may not be well received by consumers because these products are associated with lower quality as compared to new products (Guide Jr and Li 2010). Consequently, a consumer's willingness-to-pay (WTP) for a recovered product is generally less than the WTP for a new counterpart, which drives down both demand and profit of DfE. Furthermore, customers are not always strategic in the sense that they do not consider life cycle costs of products (Gray and Charter 2007). DfE may result in higher price but allows easy replacement of parts and components, which could be beneficial to the consumers, in the long run. Customers, however, may only compare the current price without taking into account the future benefits.

The potential for cannibalization and competition is another major barrier that prevents manufacturers to implement DfE. From one point of view, selling refurbished or remanufactured products could cause extensive cannibalization to the new products, hence impeding the profitability (Thomas 2003, Ferguson and Toktay 2006, Atasu et al. 2008). In such a case, manufacturers would rather not invest in designing products to be refurbishable or remanufacturable. From another point of view, even if OEM do not tap into remanufactured-goods markets by themselves, third-party remanufacturers, who only target at the secondary markets, could collect, recover and resell used products (Ferguson and Toktay 2006, Oraiopoulos et al. 2012). The external competition from recovered products may drive OEMs to 'clean the market' so that independents do not have access to cores (Seitz 2007). Even worse, OEMs will eliminate the secondary market by deliberately designing products that are exceedingly difficult to take apart and recover. Gell (2008) reported that toner cartridge OEMs deter remanufacturers by using anti reuse devices (ARUDs) such as sonic welding and unnecessary adhesive tapes, techniques that restrict toner cartridges to being either single-cycle or short-life.

1.4 The Objective and the Plan

The principal goals of this dissertation are: (1) to explore the relationship among Design for the Environment (DfE), profitability and environment, and (2) to develop and examine mechanisms that facilitate DfE. Improving the adopting of DfE is only achievable by understanding the economic and environmental implications of DfE. However, such implications have not been clear, which hinders the application of DfE. Also, as discussed in Section 1.3, barriers to both Design for Recovery and Design for Benignity widely exist, and questions still linger over how to induce DfE. Thus, the contribution of the work is two-fold. On the one hand, this dissertation provides clear understanding of Design for the Environment by integrating the perspectives on profitability and environment. On the other hand, this dissertation seeks insights for regulators and managers on how to incent manufacturers or design decision makers to implement DfE.

This dissertation consists of three essays, each modeling a product design problem within a certain operations management context. In general, Figure 1.1 describes the connections among three essays.

Chapter 2 analyzes the effects of remanufacturable product design on market segmentation and trade-in prices by studying a two-stage profit-maximization problem in which a price-setting manufacturer can choose whether or not to open a remanufactured-goods market for its product. By identifying the condition under which it is optimal for a manufacturer to design a remanufacturable product, the study demonstrates that entering a

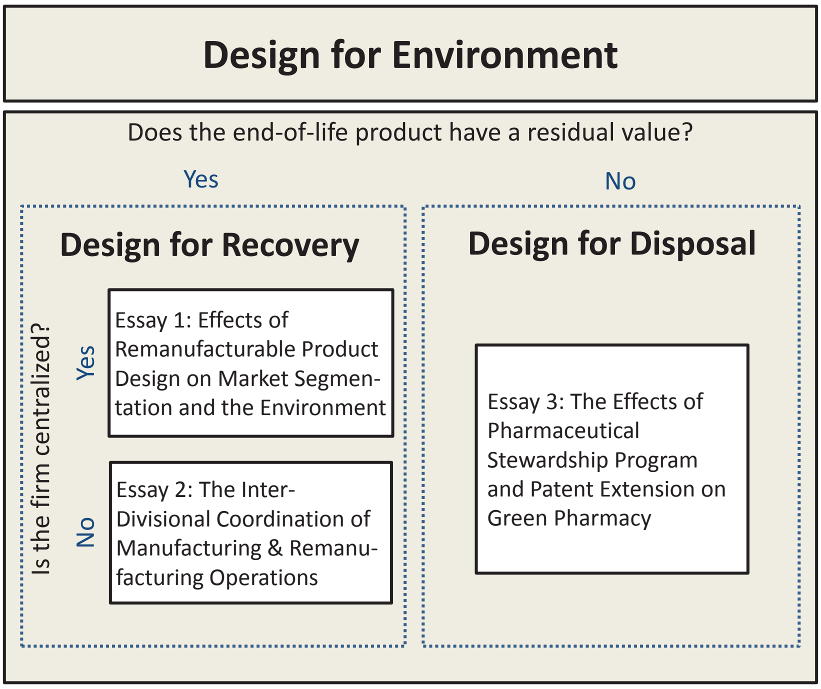

Figure 1.1: Connections among Three Essays

remanufactured-goods market in and of itself does not necessarily translate into environmental friendliness. Meanwhile, external restrictions imposed on total greenhouse gas emissions draw criticism in their own right because they risk stifling growth or reducing overall consumer welfare. Given these trade-offs, this study, therefore, develops and compares several measures of environmental efficiency, and concludes that emissions per revenue can serve as the best proxy for emissions as a metric for measuring overall environmental stewardship.

Chapter 3 investigates the impact of decentralization of manufacturing and remanufacturing operations within a firm on product design, pricing, and profitability, and seek inter-divisional incentive mechanism to achieve firm-wide coordination. Specifically, a supply chain includes a retailer and a firm consisting of two divisions. Within the firm, one division is responsible for designing and manufacturing new products while the other division is responsible for remanufacturing operation. This study shows that decentralization and divisional conflict not only results in lower firm profit and product sales, but also creates a hurdle for remanufacturable product design. Thus, in this study, an inter-divisional incentive mechanism is suggested to facilitate coordination between two profit-maximizing divisions. It can be demonstrated that through a two-part coordination scheme (a transfer price and a fixed lump sum), a decentralized firm can achieve first-best total profit and product quantity; additionally, the manufacturing division is incentivized to design new products to be remanufacturable.

Chapter 4 focuses on the impact of the pharmaceutical take-back regulation and patent extension on the choice of green design by pharmaceutical companies. In this essay, an innovative pharmaceutical company faces price-dependent demand and decides whether to adopt green pharmacy in response to the regulatory policy on pharmaceutical stewardship and/or patent extension as well as the competition from a generic company. The pharmaceutical company incurs a fixed cost to choose green pharmacy. The study demonstrates that the innovative company may pursue green pharmacy in the presence of the take-back regulation but will never voluntarily do so in the presence of the take-back regulation. From the regulator's perspective, it can induce green pharmacy with short extended term when market competition is intensive. In addition, adding the take-back regulation on top of the patent term extension excels the patent term extension when the compliance cost is relatively small, the fixed investment cost and the collection rate are relatively large, the competition is either nominal or sufficiently intensive, and the environmental issue is rather urgent. Lastly, a modified take-back policy that associates compliance cost with the firm's choice of green pharmacy is superior to the patent extension when the competition intensity is relatively high.

Chapter 5 draws conclusions and contains a summary of the contributions of the work. Also, it describes the limitations and lists several possible extensions and several ways forward.

CHAPTER 2

EFFECTS OF REMANUFACTURABLE PRODUCT DESIGN ON MARKET SEGMENTATION AND THE ENVIRONMENT

"Why do we send valuable items like aluminium and food waste to landfill when we can turn them into new cans and renewable energy? Why use more resources than we need to in manufacturing? We must now work together to build a zero waste nation - where we reduce the resources we use, reuse and recycle all that we can and only landfill things that have absolutely no other use."

– Hilary James Wedgwood Benn.

2.1 Introduction

The demand for remanufactured products has grown tremendously in recent years. According to United States International Trade Commission (USITC) estimates, the U.S. market for remanufactured goods increased by 15 percent from $36.0 billion in 2009 to $41.5 billion in 2011, and the value of U.S. remanufactured production grew by 15 percent to at least $43.0 billion during that same period, thus supporting 180,000 full-time U.S. jobs and contributing to $11.7 billion U.S. exports (USITC 2012). Accordingly, a growing number of manufacturers are actively engaging in remanufacturing, many of which offer trade-in programs to promote sales of upgraded products, use collected used products for remanufacturing, and maintain sufficient control over the entire product life cycle (Li et al. 2011). As a case in point, Oracle makes available its Upgrade Advantage Program (UAP) to the users of its servers, storage systems, and select components. This program provides trade-in discounts toward new Oracle hardware when customers return qualified used equipment, which includes both originally new and remanufactured products. Meanwhile, Oracle's Remanufactured Products Program targets customers who require same-as-new quality and warranty products but can afford only reduced prices. Oracle currently offers over 70 items across 11 different product lines on its factory remanufactured products listing, with list prices ranging from $250 to $220,000 per unit (Oracle 2013). Moreover, through these programs, Oracle has secured exclusive control over its remanufactured-goods market for itself and its partner (Oraiopoulos et al. 2012) and it has boosted sales of new products as well.

For many manufacturers, offering remanufactured products is an approach that not only can attract new end-customers by expanding product lines to include less expensive alternatives, but also can help protect the environment by consuming fewer resources and by reducing overall carbon emissions. For instance, the Bosch eXchange workshop is a program that replaces faulty vehicle parts with certified remanufactured parts, at a price that is between 30 and 40 percent lower than the price of new parts. But, in addition, this program also has resulted in Bosch emitting 23,000 fewer metric tons of CO_2 in 2009 because it remanufactured 2.5 million parts in lieu of manufacturing them anew (Bosch 2010). Similarly, Cummins' remanufacturing business, also known as ReCon, reclaimed 50 million pounds of product in 2012 and avoided 200 million pounds of greenhouse gas (GHG) emissions by offering 1,000 components and 2,000 engine part numbers as alternatives to their new-product counterparts (Cummins 2012).

Despite these documented benefits of remanufacturing, many manufacturers have yet to embrace the idea of tapping into remanufactured-goods markets (Ferguson 2010). Indeed, as Ferguson (2010) reports, Hauser and Lund estimated in 2008 that only 6% of over 2000 remanufacturing firms in their database were original equipment manufacturers (OEMs). And from 2009 to 2011, only 2% among total sales of all manufactured products by U.S. firms in seven remanufacturing-intensive sectors was estimated to be remanufactured goods (USITC 2012). One major reason why manufacturers have been reluctant to introduce remanufacturing operations is the apprehension that the sale of remanufactured products would cannibalize their new product offerings (Atasu et al. 2010). But, in addition, other technical and management issues include uncertainty in the quantity, quality and timing of returned products (Guide Jr 2000; Toktay et al. 2004; Clottey et al. 2012), high core and labor costs and lack of skilled workers (USITC 2012), and possible theft of intellectual property (Martin et al. 2010).

As highlighted above, there are trade-offs involved in a manufacturer's decision to open a remanufactured-goods market for its product. Thus, the decision is a function of the system and market parameters. Therefore, in this chapter, the following research questions are addressed: Under what conditions should a manufacturer expand its product line to include making a remanufactured good available to its market? Moreover, if the manufacturer does enter into remanufacturing, then what should be the optimal trade-in program? What would be the resulting return rate through the trade-in program? Regardless, what would be the optimal market segmentation strategy and what would be the environmental implications of that strategy?

To answer these questions, this chapter develops and studies a two-stage profit-maximization problem in which a price-setting manufacturer can choose whether or not to open a remanufactured-goods market for its product by designing its product either to be remanufacturable or non-remanufacturable, respectively. If the manufacturer designs its product to be remanufacturable, then it also must determine its optimal pricing strategy, which involves a price for selling new products in the first period, a trade-in allowance for new products returned after the first period in exchange for either a new or remanufactured product in the second period, a price for selling new products in the second period, and a price for selling remanufactured products in the second period. If the manufacturer instead designs its product to be non-remanufacturable, then it still must determine its corresponding optimal pricing strategy, but in this case the optimal pricing strategy requires specification only of first and second period prices of new products.

Given this modeling construct, we explore and draw implications from the optimal market segmentation policies. Upon doing so, we find that it is optimal for a manufacturer to design a remanufacturable product (and thus open a remanufactured-goods market for its products) when the value-added from remanufacturing is relatively high but product durability is relatively low and innovation is nominal. In many cases, however, we find that it is not optimal for the manufacturer to design its product to be remanufacturable, which helps validate to some extent the documented evidence indicating the reluctance of so many manufacturers to enter the remanufactured-goods market.

In addition, we find that the optimal trade-in program is such that the return rate could be low, depending on the problem parameters. In particular, we find that when the production cost of a non-remanufacturable product is high but the remanufacturing cost is low, the manufacturer designs its new products to be remanufacturable but then limits the incentive for customers to return those products in exchange for a new or remanufactured replacement by virtue of offering a relatively low trade-in price. In addition, under such circumstances, not only is a small fraction of products returned through the trade-in program, but also is only a small fraction of those returns then remanufactured. Hence, under such circumstances, the return rate and the remanufacturing rate of returned products are low.

Thus, we emphasize that entering a remanufactured-goods market in and of itself does not necessarily translate into environmental friendliness. Despite the fact that the negative environmental impact of a given unit of a remanufactured product is usually less than that of a new one, a low price for remanufactured products could attract demand from consumers who otherwise would not purchase new products at higher prices. This demand increase in remanufactured products thus would mean that additional resources may be consumed to fulfill customer demand, thereby potentially resulting in a more damaging environmental impact overall (e.g., more GHG emissions). Meanwhile, restrictions imposed on GHG emissions draw criticism in their own right because they risk stifling growth or reducing overall consumer welfare. Given these trade-offs, we therefore develop and compare several measures of environmental efficiency that take into consideration both environmental issues and economic performance or social welfare. Among these measures, we conclude that a manufacturer that remanufactures its products generally produces lower GHG emissions per dollar of revenue than a manufacturer that does not remanufacture. In fact, manufacturers such as Apple (2013), Cummins (2012) and Dell (2013) have been measuring their environmental performance using such an efficiency ratio.

Chapter 2 is organized as follows. Related literature is reviewed in Section 2.2. Section 2.3 formulates the model and provides structural results, and detailed analysis is provided in Section 2.4 to identify the optimal design decision, market segmentation, return rate and remanufacturing rate. We then investigate and compare several environmental impact measures in Section 2.5. A summary of the findings, implications, and limitations are in Section 2.6.

2.2 Relation to Literature

A large number of studies in recent years have focused on the strategic, tactical, and operational issues of remanufacturing, as comprehensively reviewed by Guide Jr and Van Wassenhove (2009) and by Souza (2013). Among this literature, several themes have emerged to establish why and how OEMs voluntarily enter remanufacturing markets including, but not limited to, the following reasons: to enhance profit opportunities (Toffel 2004), to better manage demand (Ferrer and Swaminathan 2006, 2010), to help segment consumer markets (Debo et al. 2005, Atasu et al. 2008) and to mitigate the effects of external remanufacturing competition (Majumder and Groenevelt 2001, Ferguson and Toktay 2006) while prudently managing potential cannibalization within its own product line (Moorthy 1984, Guide Jr and Li 2010). We contribute to this literature by endogenizing the decision to design for remanufacturability (*i.e.,* whether or not to design a product that can be remanufactured). In doing so, we incorporate a cost trade-off by recognizing that producing a remanufacturable product is usually more costly than producing a non-remanufacturable product, but that is in exchange for potential savings when the product is remanufactured. Meanwhile, we endogenize the trade-in price, which serves as both an incentive for customers to return used products and as a lever for the manufacturer to further segment the market.

We also contribute to the remanufacturing literature that investigates trade-in programs and their implications for pricing and discounting strategies. Along this theme, Oraiopoulos et al. (2012) and Agrawal et al. (2008) consider the role of a trade-in program in facilitating product returns (for remanufacturing) and in providing a lever to segment vertical markets through price. Ray et al. (2005) study the trade-in strategy for remanufacturing products by considering both durability and the age of products. They find that if the trade-in allowance is age-independent, then the trade-in allowance first increases in durability but after a certain threshold, it starts decreasing. They conclude that a firm should offer the maximum trade-in allowance when products are of medium durability. Moreover, with an optimized trade-in program, some customers carry back used products for resale value and others may continue using their products for another period. In a related vein, return rates can be modeled exogenously because manufacturers often must comply with laws and regulations such as the Waste Electrical and Electronic Equipment (WEEE) Directive, which specifies a minimum percentage of e-waste that needs to be collected by manufacturers. However, firms can actually benefit from actively controlling the return rate of used products (Guide Jr 2000, 2001). Atasu and Souza (2013) show that the optimal recovery rate (*i.e.*, the return rate multiplied by the fraction of returned products that are recovered) can be zero or positive but the firm never chooses high product quality or price when the rate is endogenous. We relax their assumption that the return rate is independent of prices and instead model it as the proportion of new products sold in the first period that are later returned by customers who maximize their surplus. Hence, our return rate is related to customer utility from new, used and remanufactured products, to the retail prices of new and remanufactured products as well as to the trade-in price. Furthermore, we then examine the remanufacturing rate, which we define as the proportion of returned products that are eventually remanufactured by the manufacturer.

Although environmental performance can be positively correlated to financial performance (Klassen and McLaughlin 1996, Corbett and Klassen 2006), these two metrics often lead to conflict for manufacturers (Kleindorfer et al. 2005). Moreover, environmentally responsible practices such as leasing and product recovery are not necessarily superior to no-leasing or no-recovery scenarios (Agrawal et al. 2012, Atasu and Souza 2013). As to remanufacturing, Gu et al. (2012) show that the presumed environmental efficiency of remanufactured products could be compromised if either the ratio of per-unit environmental impact associated with remanufactured or new products is high, or the remanufacturing cost is high. The studies mentioned above limit their discussion by using aggregated measure of environmental impact. A common belief is that environmental regulations based on such a measure erode competitiveness (Porter and van der Linde 1995). Hence, we contribute to the literature by defining and evaluating different environmental efficiency measures that relate them to other outcomes such as profit, revenue or social welfare.

This study is most closely related to Oraiopoulos et al. (2012), who explore the conditions under which an OEM should allow or restrict the opening of a secondary market for remanufactured products operated by third-party entrants and how such decisions and trade-in prices are affected by the relicensing fee. By examining combined effects of inherent product durability, added value of remanufacturing process, innovation and cost, they show that when consumers' willingness to pay for a remanufactured product is sufficiently high compared to inherent product durability, it is not optimal for the OEM to eliminate the secondary market because cannibalization effects are outweighed by relicensing revenue and resale value effects. This study differs from their work in several ways. First, product design is endogenous to our model, that is, our manufacturer decides whether or not to design its new products to be remanufacturable. If the manufacturer chooses a remanufacturable design, a higher production cost of new products incurs to the firm due to R&D expenses and additional resource consumption. Second, we consider the manufacturer to be a price-setter for both new and remanufactured products. Under this assumption, we therefore have no relicensing fee, but instead introduce a new consumer type, namely consumers who buy a new product in the first period and replace it with a remanufactured product in the second period. Third, this study emphasizes the environmental implications of an optimal strategy.

2.3 Assumptions and Models

2.3.1 Modeling Framework

Manufacturer. We consider a two-period, profit-maximization problem for a price-setting manufacturer. The manufacturer makes design decision k at the beginning of the time horizon, where $k = 0$ denotes a non-remanufacturable design (in which case new products are non-remanufacturable) and $k = 1$ denotes a remanufacturable design (in which case new products are remanufacturable). In the first period, the manufacturer determines the price p_1 at which new products are sold in the period. In the second period, if $k = 0$, then the manufacturer only determines the price p_2 at which new products are sold in the period; however, if $k = 1$, then the manufacturer determines the prices p_2 and p_r at which new and remanufactured products are respectively sold in the period. Meanwhile, if $k = 1$, then the manufacturer also determines the trade-in allowance s for buyers who return a used product to buy either a new or a remanufactured one in the second period.

Only returned products may be remanufactured and therefore the number of remanufactured products cannot exceed the number of products returned.

The production cost of a new product depends on the design decision k. We assume that the unit cost to produce a new non-remanufacturable product (defined by $k = 0$) and a new remanufacturable product (defined by $k = 1$) is c_0 and c_1, respectively, where $c_1 \geq c_0$ reflects the increased complexity required to make a product remanufacturable (Subramanian 2012). The unit cost to remanufacture a product is c_r. We assume $c_r < c_0$ because the per-unit remanufacturing cost can be as low as 40 to 65 percent less than that of its new products (Ginsburg 2001).

Consumers. Willingness-to-pay (WTP) θ for a new product in the first period is heterogeneous and uniformly distributed in the interval $[0, 1]$, with market size normalized to 1. We assume θ to be independent of k since a consumer's sustainability considerations are normally separate from the attribute of the products themselves (Galbreth and Ghosh 2013). We call a customer with WTP equal to θ a customer of type θ. Consistent with Oraiopoulos et al. (2012), we make the following five assumptions: First, we assume that the new product in the second period (if offered) is an upgraded version of the one produced and sold in the first period, characterized by innovation factor α, where $\alpha \geq 1$. Thus, if a consumer is willing to pay θ for the new product in the first period, then her WTP for an upgraded new product in the second period is $\alpha \cdot \theta$. Second, we assume that a new product in the first period depreciates with use and is characterized by durability factor δ, where $\delta < 1$. Thus, if the customer's WTP is θ for a new product in the first period, then her valuation associated with keeping the product in the second period is $\delta \cdot \theta$. Third, we assume that a consumer's WTP for a remanufactured product is less than her WTP for a new product. Thus, if a consumer is willing to pay θ for a new product in the first period, then her WTP for a remanufactured product in the second period is $\delta_r \cdot \theta$, where remanufacturing valuation factor $\delta_r \in (0, 1)$. Fourth, we assume that remanufacturing improves the condition of a used product. Thus, $\delta_r > \delta$. Fifth, we assume that the one-period utility from an upgraded product is less than the combined utility from a new product bought in the first period and used for two periods. Thus, $\alpha < 1 + \delta$.

If a new product is remanufacturable ($k = 1$), then a customer purchases at most one new unit in each period. If the customer makes a purchase in the first period, then in the second period, she can either trade it in for a new product (segment nn), trade it in for a remanufactured product if one is available (segment nr) or keep it and thereby exit the market (segment nu). If the customer does not make a purchase in the first period, then in the second period, she can either buy a new product (segment on), buy a remanufactured product if available (segment or), or remain out of the market altogether (segment oo). Therefore, in principle, there exist six customer segments distinguished by different customer buying strategies for the two periods. We use "customer segment" and "customer strategy" interchangeably unless otherwise distinguished.

Consumers are strategic in the sense that they make purchase decisions based on the total consumer surplus associated with both periods, which we define as the product valuations net of trade-in price s (if applicable) minus the product prices p_1, p_2 and p_r, as applicable. Thus, like Oraiopoulos et al. (2012), we essentially assume that consumers know the trade-in program as well as the price list for both periods before making decisions. Note that consumers who otherwise would have a negative consumer surplus do not make any purchases (segment oo). We denote segment size by d with a subscript to refer to the segment, e.g., d_{nn} denotes the size of customer segment nn. Therefore, we have $d_{nn} + d_{nr} + d_{nu} + d_{on} + d_{or} + d_{oo} = 1$. For parsimony, we assume that used products cannot be directly traded between customers. If a new product is non-remanufacturable ($k = 0$), then the market segmentation is analogous except that $k = 0$ means that $d_{nr} = d_{or} = 0$ by definition. Table 2.1 summarizes the total consumer surplus associated with each strategy for a customer of type θ, given p_1, p_2, p_r and s, as applicable for a given k. In Table 2.1, note that because $\alpha > \delta_r$ by assumption, a consumer belonging to segment nn has a higher WTP θ for a new product than a consumer belonging to segment nr (denoted by $\Theta_{nn} \succ \Theta_{nr}$). More broadly, by virtue of the five WTP assumptions itemized at the beginning of this subsection, we have $\Theta_{nn} \succ \Theta_{nr} \succ \Theta_{nu} \succ \Theta_{on} \succ \Theta_{or}$. Thus, the customer segmentation orderings implicit in Table 2.1 (and in Table 2.2 later) hold true for any given pricing scheme p_1, p_2, p_r and s.

Profit-maximization Problem: Let Π^k be the manufacturer's total profit over the two periods, given design decision k. If new products are designed to be non-remanufacturable ($k = 0$), then the manufacturer's prob-

Table 2.1: Consumer Surplus of Each Strategy for Consumers of Type θ

Strategy	1^{st} Period	2^{nd} Period	Consumer Surplus $S(\theta)$
nn	buy new	buy new	$(\theta - p_1) + s + (\alpha\ \theta - p_2)$
nr	buy new	buy remanufactured	$(\theta - p_1) + s + (\delta_r \theta - p_r)$
nu	buy new	continue to use	$(\theta - p_1) + \delta\ \theta$
on	inactive	buy new	$\alpha\ \theta - p_2$
or	inactive	buy remanufactured	$\delta_r \theta - p_r$
oo	inactive	inactive	0

lem is

$$
\begin{aligned}
\Pi^0 &= \max_{p_1, p_2} (p_1 - c_0) \cdot (d_{nn} + d_{nu}) + (p_2 - c_0) \cdot (d_{nn} + d_{on}) \qquad (2.1)\\
s.t. \quad & d_{nn} + d_{nu} + d_{on} \leq 1 \\
& d_{nn}, d_{nu}, d_{on} \geq 0 \\
& p_1, p_2 \geq 0
\end{aligned}
$$

Alternatively, if new products are designed to be remanufacturable ($k = 1$), then the manufacturer's problem becomes

$$
\begin{aligned}
\Pi^1 &= \max_{p_1, p_2, p_r, s} (p_1 - c_1) \cdot (d_{nn} + d_{nr} + d_{nu}) + (p_2 - c_1) \cdot (d_{nn} + d_{on}) \\
&\quad + (p_r - c_r) \cdot (d_{nr} + d_{or}) - s \cdot (d_{nn} + d_{nr}) \qquad (2.2)\\
s.t. \quad & d_{or} \leq d_{nn} \\
& d_{nn} + d_{nr} + d_{nu} + d_{on} + d_{or} \leq 1 \\
& d_{nn}, d_{nr}, d_{nu}, d_{on}, d_{or} \geq 0 \\
& p_1, p_2, p_r, s \geq 0
\end{aligned}
$$

where $d_{or} \leq d_{nn}$ is true because the number of units remanufactured cannot exceed the number of units returned, *i.e.,* $d_{nr} + d_{or} \leq d_{nn} + d_{nr}$ or, equivalently, $d_{or} \leq d_{nn}$. Design decision k is determined by maximizing $\Pi^* = \max\{\Pi^0, \Pi^1\}$ and the corresponding optimal decisions are denoted as k^*, p_1^*, p_2^*, p_r^* and s^*.

2.3.2 Solution Procedure

For any given product design, we use Table 2.1 to obtain the indifference point θ between any pair of customer segments such that a customer of type θ is indifferent between two strategies, and under the assumption that $0 < \delta < \delta_r < 1 < \alpha < 1 + \delta$, we produce Table 2.2 accordingly. In Table 2.2, customers with WTP above the indifference point θ in a cell belong to the customer segment of the corresponding row and those with WTP below the indifference point θ belong to the customer segment of the corresponding column. If the indifference point θ is greater than or equal to one (less than or equal to zero), then it means that all customers prefer the strategy of the corresponding column (row) to the strategy of the corresponding row (column). We therefore can derive the size of each segment by comparing these indifference points. For example, if products are remanufacturable, then Table 2.2(a) establishes that, for a customer to choose strategy nr, her WTP θ must satisfy

$$\theta \in \left\{\max\left\{\frac{p_r - s}{\delta_r - \delta}, \frac{p_1 - p_2 + p_r - s}{1 + \delta_r - \alpha}, p_1 - s, \frac{p_1 + p_r - s}{1 + \delta_r}, 0\right\},\right.$$
$$\left.\min\left\{\frac{p_2 - p_r}{\alpha - \delta_r}, 1\right\}\right\} \tag{2.3}$$

In other words, if $k = 1$, then for a customer to choose strategy nr, that strategy must yield a higher consumer surplus than would strategies nu, on, or, oo. As per the "nr" row of Table 2.2(a), this would be true if

$$\theta \geq \max\left\{\frac{p_r - s}{\delta_r - \delta}, \frac{p_1 - p_2 + p_r - s}{1 + \delta_r - \alpha}, p_1 - s, \frac{p_1 + p_r - s}{1 + \delta_r}\right\}. \tag{2.4}$$

Meanwhile, for the customer to choose strategy nr, that strategy also must yield a higher consumer surplus than would strategy nn, which would be true if $\theta \leq \frac{p_2 - p_r}{\alpha - \delta_r}$, as per the "$nr$" column of Table 2.2(a). Note that $\theta \in [0, 1]$, thus Equation 2.3 follows. Given (2.3), then, the size of customer segment nr is

$$d_{nr} = \max\left\{0, \min\left\{\frac{p_2 - p_r}{\alpha - \delta_r}, 1\right\} - \right.$$
$$\left.\max\left\{\frac{p_r - s}{\delta_r - \delta}, \frac{p_1 - p_2 + p_r - s}{1 + \delta_r - \alpha}, p_1 - s, \frac{p_1 + p_r - s}{1 + \delta_r}, 0\right\}\right\} \tag{2.5}$$

Table 2.2: Indifference Point θ for Any Pair of Strategies

(a) Remanufacturable Design

$k=1$	nr	nu	on	or	oo
nn	$\frac{p_2-p_r}{\alpha-\delta_r}$	$\frac{p_2-s}{\alpha-\delta}$	p_1-s	$\frac{p_1+p_2-p_r-s}{1+\alpha-\delta_r}$	$\frac{p_1+p_2-s}{1+\alpha}$
nr		$\frac{p_r-s}{\delta_r-\delta}$	$\frac{p_1-p_2+p_r-s}{1+\delta_r-\alpha}$	p_1-s	$\frac{p_1+p_r-s}{1+\delta_r}$
nu			$\frac{p_1-p_2}{1+\delta-\alpha}$	$\frac{p_1-p_r}{1+\delta-\delta_r}$	$\frac{p_1}{1+\delta}$
on				$\frac{p_2-p_r}{\alpha-\delta_r}$	$\frac{p_2}{\alpha}$
or					$\frac{p_r}{\delta_r}$

(b) Non-remanufacturable Design

$k=0$	nu	on	oo
nn	$\frac{p_2}{\alpha-\delta}$	p_1	$\frac{p_1+p_2}{1+\alpha}$
nu		$\frac{p_1-p_2}{1+\delta-\alpha}$	$\frac{p_1}{1+\delta}$
on			$\frac{p_2}{\alpha}$

Notice, therefore, that segment nr does not exist if and only if $\min\left\{\frac{p_2-p_r}{\alpha-\delta_r}, 1\right\} \leq \max\left\{\frac{p_r-s}{\delta_r-\delta}, \frac{p_1-p_2+p_r-s}{1+\delta_r-\alpha}, p_1-s, \frac{p_1+p_r-s}{1+\delta_r}, 0\right\}$. Notice, therefore, that segment nr does not exist if and only if $\min\left\{\frac{p_2-p_r}{\alpha-\delta_r}, 1\right\} \leq \max\left\{\frac{p_r-s}{\delta_r-\delta}, \frac{p_1-p_2+p_r-s}{1+\delta_r-\alpha}, p_1-s, \frac{p_1+p_r-s}{1+\delta_r}, 0\right\}$. The size of all other customer segments, for a given value of k, can be derived in the same fashion. Technical supplement for details on how to derive the size of each segment is available upon request.

Let $\mathbf{M}$=($sgn(d_{nn})$, $sgn(d_{nr})$, $sgn(d_{nu})$, $sgn(d_{on})$, $sgn(d_{or})$) denote a specified market configuration, where $sgn(x) = 1$ if $x > 0$ and $sgn(x) = 0$ if $x \leq 0$. Thus, for example, $\mathbf{M}$=(1,1,0,0,0) represents the market configuration in which some customers buy new products in the first period and then trade them in for either new or remanufactured products in the second period ($d_{nn}, d_{nr} > 0$) but no customer exits the market after the first period or enters it in the second period ($d_{nu} = d_{on} = d_{or} = 0$). Given this definition of $\mathbf{M}$, note that $k = 0$ if and only if $\mathbf{M}$=(*,0,*,*,0), where * can be 0 or 1; all other configurations correspond to $k = 1$. In principle, there are $2^5 - 1 = 31$ non-trivial possible market configurations of which 7 are associated with non-remanufacturable design ($k = 0$) and 24 are associated with remanufacturable design ($k = 1$). However, the following two propositions establish that certain configurations cannot exist in an optimal solution, thus eliminating them from consideration. The proofs of both propositions are provided in Appendix A.

Proposition 2.3.1 *Given any product specification and market condition*

(c_0, c_1, c_r, α, δ and δ_r), the following are true:

(i) *$d_{or} > 0 \Rightarrow d_{nn} > 0$, i.e., **M=(0,*,*,*,1)** does not exist, where * can be 0 or 1.*

(ii) *$d_{nr} > 0 \Rightarrow d_{on} = 0$ and $d_{on} > 0 \Rightarrow d_{nr} = 0$, i.e., **M=(*,1,*,1,*)** does not exist, where * can be 0 or 1.*

(iii) *$d_{nr} = d_{nu} = d_{on} = d_{or} = 0 \Rightarrow d_{nn} = 0$, i.e., **M=(1,0,0,0,0)** does not exist.*

Intuitively, Proposition 2.3.1(i) is a result of the fact that the manufacturer cannot remanufacture more products than are returned ($d_{or} \leq d_{nn}$). According to the proof of Proposition 2.3.1(ii), the existence of segment *on* effectively requires that $p_1 - s$ (the price of new products in the first period net of their trade-in value) must be relatively large while $p_2 - p_r$, the price difference of new and remanufactured products in the second period, must be relatively small, which in turns makes it irrational to buy a new product in the first period and then trade it in for a remanufactured product because $p_1 - s + p_r$ is relatively large. Similarly, for segment *nr* to exist, $p_1 - s$ must be relatively small and $p_2 - p_r$ must be relatively large, in which case there would be no demand for new products in the second period because p_2 is relatively large. The proof of Proposition 2.3.1(iii) indicates that if products are designed to be non-remanufacturable ($k = 0$) and if there exist customers who makes purchases in both periods, then it means that p_1 must be sufficiently low so as to entice some other customers to purchase new products in the first period without then purchasing anew in the second period, thus rendering it impossible to sell products only to customers with the highest valuation (segment *nn*).

In all, Proposition 2.3.1 eliminates 15 of the 31 theoretically possible market configurations from consideration. Next, Proposition 2.3.2 eliminates 2 more of the remaining 16.

Proposition 2.3.2 *Given any product specification and market condition (c_0, c_1, c_r, α, δ and δ_r), the following are true:*

(i) *It is more profitable to offer only new products in the first period ($d_{nu} > 0$ and $d_{nn} = d_{nr} = d_{on} = d_{or} = 0$) than it is to offer only new products in the second period ($d_{on} > 0$ and $d_{nn} = d_{nr} = d_{nu} = d_{or} = 0$), i.e., **M=(0,0,1,0,0)** dominates **M=(0,0,0,1,0)**.*

(ii) *If new products are non-remanufacturable ($d_{nr} = d_{or} = 0$), then it is more profitable to offer new products for one-time purchase only in the first period ($d_{nu} > 0$ and $d_{nn} = d_{on} = 0$) than it is to offer new products for one-time purchase in either the first period or the second period ($d_{nu}, d_{on} > 0$ and $d_{nn} = 0$), i.e.,* ***M****=(0,0,1,0,0) dominates* ***M****=(0,0,1,1,0).*

To help explain Proposition 2.3.2(i), note that the assumption $1 + \delta > \alpha$ suggests that if a manufacturer offers only new products, either in the first period or in the second period, then it should be optimal to produce and sell the products earlier rather than later, everything else being equal. In other words, if innovation is not sufficient, then it does the firm no benefit to delay the introduction of a new product for a minor update. Moreover in such a case, new products will be non-remanufacturable because the firm will not remanufacture them. In a similar vein, Proposition 2.3.2(ii) is a byproduct of product cannibalization in our two-period model. In particular, if the manufacturer offers new products that are non-remanufacturable in both periods, then some customers will prefer to buy new products in the first period rather than to buy in the second period. Note the unit profit of selling one new product in the second period is usually smaller than the unit profit of selling one in the first period that can be used in both periods (see proof for details). Consequently, the manufacturer prefers to price products such that customers will only make purchases in the first period rather than in the second.

Although Propositions 2.3.1 and 2.3.2 analytically eliminate all but 14 possible market configurations from the search for the optimal solutions to (2.1) and (2.2), we find that we need to rely on a numerical search routine to complete the optimization over the remaining feasible set of configurations. To that end, we condition the remaining search on the different feasible market configurations. In particular, for any given feasible market configuration, we numerically solve either (2.1) or (2.2), as applicable, by applying the Matlab build-in quadratic programming function *quadprog*. We then compare the profit associated with each of the resulting solutions (one for each feasible market configuration) to obtain the optimal solution k^*, p_1^*, p_2^*, p_r^* and s^* for any given parameter set. (See Technical Supplement for algorithm details and justification.) Finally, we repeat this process for an exhaustive set of input parameters to populate a comprehensive database of solutions

Table 2.3: Parameter Ranges for Numerical Study

Parameter	**Increment (I)**	**Min**	**Max**
c_0	0.1^*	I	$1-I$
c_1	0.1^*	g_0	$1-I$
c_r	0.1^*	I	c_0-I
α	0.1^*	1	$2-3\times I$
δ	0.1^*	$\alpha-1+I$	$1-2\times I$
δ_r	0.1^*	$\delta+I$	$1-I$

* we choose increment $I=0.005$ in the cases when more than one parameters are fixed.

to the manufacturer's maximization problem. Table 2.3 summarizes the specific parameter ranges used in the process for which we solved the firm's optimization problem. Given Table 2.3, the total number of parameter combinations $(c_0, c_1, c_r, \alpha, \delta, \delta_r)$ using an increment $I=0.1$ for all parameters is 18,720. However, in addition, we solved another approximately 36,000 instances by applying a smaller increment $I=0.005$. Thus our analysis below is based on solutions to approximately 54,000 instances of the problem.

2.4 Analysis

In this section, we compile and explore the database of optimal designs and market configurations as well as the corresponding optimal profits and return rates produced by the numerical optimization routine applied to the comprehensive set of problem instances as described above. To set the stage, we note first that, although 14 possible market configurations survive the elimination procedure implied by Propositions 2.3.1 and 2.3.2, we find that seven of those that remain never appear in our database of optimal solutions. Thus, we find that, of the 31 non-trivial possible market configurations that can exist in principle, only eight remain as potentially optimal for a given set of problem parameters taken from Table 2.3. We label these 8 configurations as M1 through M8, and we provide each of their specifications in Table 2.4. From Table 2.4, note that M1, M2 and M3 each have $d_{nr}=d_{or}=0$, which implies that $k^*=0$ when any one of these configurations is optimal; and M4 to M8 each of have either or both $d_{nr}>0$ or $d_{or}>0$, which implies that $k^*=1$ when any one of these configurations is optimal.

Table 2.4: Taxonomy of Optimal Solution

k^*	$k^* = 0$			$k^* = 1$				
Mkt Conf.	M1	M2	M3	M4	M5	M6	M7	M8
d_{nn}	+	+		+	+	+		
d_{nr}					+	+	+	+
d_{nu}	+	+	+	+	+		+	
d_{on}	+							
d_{or}				+		+		

Notes:+ means the segment size is positive; blank cell means the segment size is zero.

2.4.1 Optimal Market Segmentation

We first investigate the effects of exogenous parameters (production cost c_0 and c_1, remanufacturing cost c_r, innovation factor α, durability factor δ and remanufacturing factor δ_r) on the size of each customer segment in an optimal solution, as depicted in Figures 2.1 and 2.2. In Figure 2.1, we use base values of $c_0 = 0.5, c_1 = 0.55$ and $c_r = 0.2$ and explain the effect of varying c_0, c_1 and c_r on the optimal customer segmentation. In Figure 2.2 we repeat this by varying parameters α, δ and δ_r.

We find that the cost parameters c_0, c_1 and c_r have an indirect impact on consumer behavior. In particular, the cost structure first affects the manufacturer's optimal design and market configuration, which in turn influences the size of various customer segments (see Figure 2.1). If the production cost of non-remanufacturable products c_0 is low relative to c_1, the manufacturer designs its products to be non-remanufacturable (*i.e.,* $k^* = 0$). Intuitively, this is true because the cost premium of making the product remanufacturable is significant. Therefore, segment *nr* and *or* exist only when c_0 is relatively large (see Figure 2.1(a)). On the contrary, as shown in Figures 2.1(b) and 2.1(c), if the production cost of remanufacturable products c_1 is close to c_0 or the remanufacturing cost c_r is low, the manufacturer designs its products to be remanufacturable, which makes sense because, then, the manufacturer can reap the added value of remanufacturing without incurring much additional cost. As a result, customers buy remanufactured products when c_1 or c_r is relatively low. Moreover, the lower is c_r, the more are the customers who buy remanufactured products (*i.e.,* the larger is segment *nr*) and the fewer are the customers who buy new products (*i.e.,* the smaller

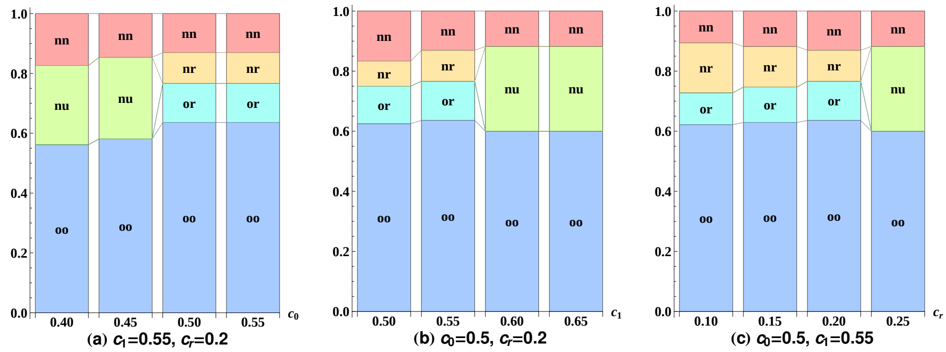

Figure 2.1: Customer Segments ($\alpha = 1.25$, $\delta = 0.4$ and $\delta_r = 0.8$)

is segment nn). Intuitively, a lower c_r allows the manufacturer to lower the price of remanufactured products. Interestingly, however, the size of segment or also increases as c_r increases (see Figure 2.1(c)). This is because some customers who otherwise would choose strategy nr when c_r is small switch to strategy or when c_r is large, which results in a higher p_r and a lower s. Nevertheless, as a whole, the overall sale of remanufactured products reduces as c_r increases (see Figure 2.1(c)). In a similar vein, the overall sale of remanufactured products initially increases as c_1 increases because some customers who otherwise would choose strategy nn when c_1 is small switch to purchase remanufactured products in the second period when c_1 (and, correspondingly p_1 and p_2) grow larger. Eventually, however, if c_1 is sufficiently large, then the manufacturer's optimal design becomes $k^* = 0$ in which case segments nr and or necessarily disappear altogether because remanufactured products are not available.

Looking next at Figure 2.2, we find that when innovation factor α increases, more customers buy new products in both periods (*i.e.*, d_{nn} increases), but fewer customers buy remanufactured products (*i.e.*, $d_{nr} + d_{or}$ decreases). This is because customers are willing to pay more for upgraded products when α is larger. Interestingly, however, we find that although the overall demand for remanufactured products ($d_{nr} + d_{or}$) decreases in α, the size of segment or increases in α. Intuitively, this happens because, as α increases, the manufacturer can provide less incentive to attract previous buyers (*i.e.*, provide smaller s), which enables it to reduce its price for remanufactured products (*i.e.*, reduce p_r) to expand segment or. Similarly, a larger durability factor δ means that more customers find it optimal to continue using the old

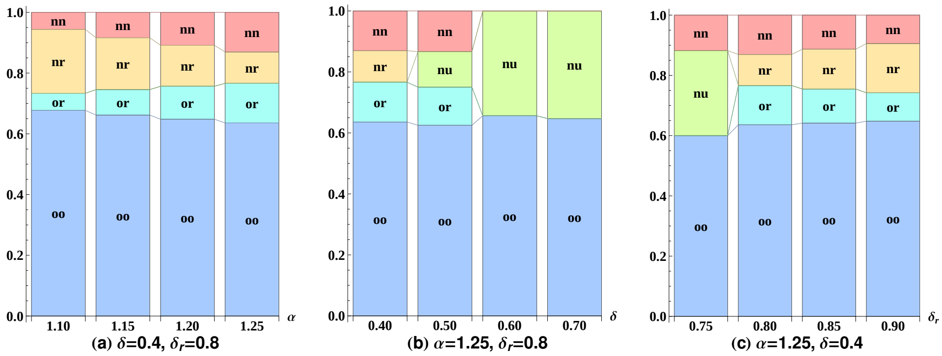

Figure 2.2: Customer Segments ($c_0 = 0.5, c_1 = 0.55$ and $c_r = 0.2$)

Table 2.5: Characterization of the Optimal Solution ($c_0 = 0.5$, $c_r = 0.2$, $\alpha = 1.25$)

Mkt Conf.	M1	M2	M3	M4*	M5*	M6*	M7*	M8*	
Fig 2.3(a) $c_1 = 0.50$ (%)	0.0	0.0	7.0	64.4	0.0	27.2	1.4	0.0	100%
Fig 2.3(b) $c_1 = 0.55$ (%)	0.0	34.0	40.1	2.1	0.0	23.5	0.3	0.0	100%
Fig 2.3(c) $c_1 = 0.60$ (%)	0.0	45.9	45.4	0.0	0.0	8.7	0.0	0.0	100%

Notes: * indicates market configurations corresponding to $k^* = 1$. Each row represents the percentage of cases (varying δ and δ_r) for which the given market configuration constitutes the optimal solution for given c_1.

product in the second period (*i.e.*, d_{nu} increases), while fewer customers buy upgraded or remanufactured products (*i.e.*, d_{nn}, d_{nr} and d_{or} all decrease). In general, δ_r produces the mirror effect that c_r produces as shown in Figure 2.2(c). In particular, as δ_r increases, while d_{nr} increases and d_{nu} decreases; and the progressions of d_{or} and d_{nn} are monotonically decreasing as long as $k^* = 1$.

2.4.2 Optimal Product Design

As seen from Figure 2.2, the manufacturer tends to design a non-remanufacturable product ($k^* = 0$) when product durability δ is relatively large or remanufacturing valuation factor δ_r is relatively small. We next examine more closely the effect of these two parameters on the optimal product design. Toward that end, Figure 2.3 illustrates the optimal product design and market configurations as functions of (δ, δ_r) space for various values of c_1, given that $c_0 = 0.5, c_r = 0.2$ and $\alpha = 1.25$. Each solid curve in the figure represents the threshold above which $k^* = 1$.

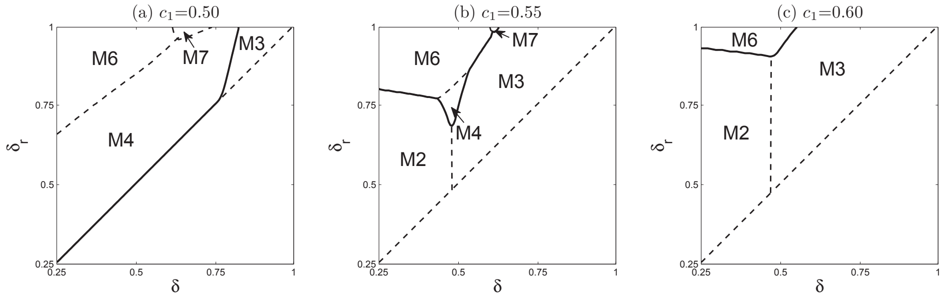

Figure 2.3: Optimal Product Design and Market Configurations ($c_0 = 0.5$, $c_r = 0.2$, $\alpha = 1.25$)

Notes: The southeast area is outside the bounds of discussion because $\delta < \delta_r$. In each plot, $k^* = 1$ when (δ, δ_r) lies above the bold solid curve and $k^* = 0$ when (δ, δ_r) lies below the bold solid curve.

As Figure 2.3 illustrates, it is optimal to design new products to be remanufacturable ($k^* = 1$) only when the product durability δ is sufficiently low and the remanufacturing valuation factor δ_r is sufficiently high. Moreover, the higher is the cost to produce remanufacturable products c_1, the more dramatic is this effect. Hence, it is optimal for the manufacturer to produce remanufacturable products not only when a customer's WTP is high for a remanufactured product and low for a used product, but also when the production cost is sufficiently low to justify the endeavor. Intuitively, if new products were to provide relatively high utility in the second period, as compared to remanufactured products, then it would be difficult for the manufacturer to attract customers to the remanufactured products in the second period. Indeed, notice from Figure 2.3 that although it is predominately optimal for the manufacturer to design a remanufacturable product when there is no cost premium associated with that decision (*i.e.*, when $c_1 = c_0$), if c_1 is even just 10%-15% higher than c_0, the product design threshold moves northwest rapidly, thus leaving a much smaller region in which $k^* = 1$. To quantify this observation, we probe deeper using Table 2.5. In Table 2.5, we specify as percentages the optimal market configuration areas depicted in Figure 2.3. For example, in reference to Figure 2.3(a), of all the problem instances derived from Table 2.5 by setting $c_1 = 0.5$ (and $c_0 = 0.5$, $c_r = 0.2$, $\alpha = 1.25$), but varying δ and δ_r, market configuration M3 is optimal for only 7% (whereas M4 is optimal for 64.4%, M6 is optimal for 27.2%, and M7 is optimal for 1.4%). Given Table 2.5, then, note that as c_1 increases from 0.50 to 0.55 to 0.60, the corresponding percentage of problem instances for which

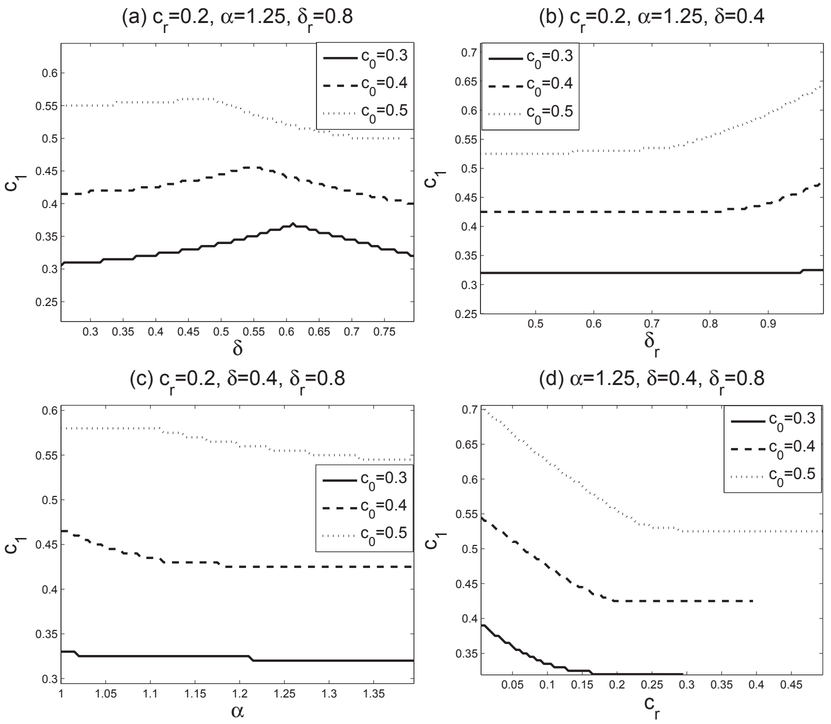

Figure 2.4: Maximum Threshold of c_1 for a Remanufacturable Design

$k^* = 1$ (M4-M8) decreases rapidly, but at a decreasing rate, from 93% to 25.9% to 8.7%.

To further relate the above observation to optimal design, we next find the upper bound of c_1 beyond which the manufacturer chooses not to design a remanufacturable product. Figure 2.4 depicts this threshold as a function of various problem parameters. In Figure 2.4, values of c_1 below a given threshold function correspond to $k^* = 1$ and values above the threshold function correspond to $k^* = 0$. Intuitively, when customers are willing to pay more for a remanufactured product (*i.e.,* the larger is δ_r) or when the remanufacturing cost is lower (*i.e.,* the smaller is c_r), the manufacturer will continue to design and produce remanufacturable products at higher costs (*i.e.,* at higher values of c_1). However, it is interesting to note from Figure 2.4(a) that the remanufacturable design threshold of c_1 is not a monotone function of product durability δ. To help explain this observation, it is useful to examine the corresponding optimal market configuration when $k^* = 0$. In doing so, we find that when δ is small, the profit associated with selling new products in both periods is higher than that associated with selling new products only in the first period because customers who keep using old products do not pay a large premium for product durability. But, if new products are available in both periods when customers also have the option to continue using used products, then any increase in δ essentially intensifies product cannibalization. As a result, when δ is small and increases, the manufacturer will choose to remanufacture even for increased costs c_1 associated with doing so. In contrast, segment nu is sufficiently lucrative to deter the manufacturer from selling new products in the second period, in which case, any increase in δ essentially means that the manufacturer can charge a higher price for new products and generate higher profits without worrying about product cannibalization. Consequently, when δ is large and increases, the manufacturer, ceteris paribus, requires a lower c_1 to justify remanufacturing.

2.4.3 Optimal Return and Remanufacturing Rates

Environmental laws such as the Waste Electrical and Electronic Equipment (WEEE) Directive requires its member states to recollect a specific percent of e-waste put on their markets (WEEE Directive, 2012). Nevertheless, manufacturers recollect used products not only to comply with laws and regulations, but also to remanufacture them to boost economic success. In our model setting, the return rate is determined by the trade-in allowance s. Hence, in this section, we study the implied return rate corresponding to the manufacturer's optimal product design and market segmentation strategy. However, the return rate in and of itself is not necessarily the same as the remanufacturing rate, meaning that not all returned products are necessarily remanufactured upon their return. Hence, in this section, we also study the resulting remanufacturing rate associated with the manufacturer's optimal strategy.

2.4.3.1 Return Rate

We define return rate (r) as the proportion of new products sold in the first period that are later recollected by the manufacturer, that is,

$$r = \frac{d_{nn} + d_{nr}}{d_{nn} + d_{nr} + d_{nu}}$$

Table 2.6: Return Rate when $k^* = 1$

Opt Mkt Conf.	$r < 0.5$	$0.5 \leq r < 1$	$r = 1$	Subtotal
M4	22.8%	23.0%	0%	45.8%
M5	1.2%	2.3%	0%	3.5%
M6	0%	0%	19.3%	19.3%
M7	1.2%	4.8%	0%	6.0%
M8	0%	0%	25.4%	25.4%
Total	25.2%	30.1%	44.7%	100%

Because $r \in (0, 1]$ if new products are remanufacturable (*i.e.* if $k^* = 1$) and $r = 0$ if (and only if) new products are non-remanufacturable (*i.e.* if $k^* = 0$), we restrict our discussion only to cases in which new products are remanufacturable. In other words, we focus here on the cases from Sections 2.4.1-2.4.2 in which the optimal market configuration is a member of the set {M4, M5, M6, M7, M8}. Table 2.6 aggregates and summarizes the return rates associated with those cases. As Table 2.6 highlights, if the manufacturer designs its product to be remanufacturable, then it is optimal for the manufacturer to set s such that all first-period customers return the product (*i.e.*, $r = 1$) in only 44.7% of the corresponding solutions. Note that $r = 1$ means that no customer who makes a purchase in the first period keeps the product for further use in the second period (*i.e.*, $r = 1 \Rightarrow d_{nu} = 0$). Thus, $r = 1$ corresponds to cases in which either market configuration M6 or M8 is optimal. Alternatively, if for any given set of parameters, either M4, M5, or M7 is the optimal configuration, then it means that $r < 1$. For these cases, given that $r < 1$, Table 2.6 further identifies whether or not r is especially low. There are two reasons why the optimal market configuration can be such that r is especially low. On the one hand, r can be low if a sufficiently large portion of the consumer market values continued use of products enough relative to their trade-in value not to make it worth the trade. This is reflected in Table 6 by the case in which M7 is the optimal configuration. On the other hand, r can be low if it is optimal for the manufacturer to design its trade-in program primarily as a mechanism to fine tune the segmentation of its markets through its pricing tactics. This is reflected in Table 2.6 by the cases in which M4 and M5 are the optimal configurations.

To probe deeper, consider Figure 2.5, which depicts how the return rate

r, as well as and the associated trade-in price s required to induce that return rate, change as selected parameters change. As Figure 2.5(a) shows, both r and s generally increase as δ_r increases. This basically reflects the fact that, the higher is δ_r, the more profit the manufacturer can gain from remanufactured products and, thus, the more incentive the manufacturer has to increase its trade-in price so that it can recollect enough used products to sufficiently endow its remanufacturing operation. However, as δ increases, r actually decreases despite increases in s. The intuition is as follows. The higher is δ, the more a consumer values ownership of a previous purchase relative to a replacement purchase, regardless of whether that replacement would be new or remanufactured. Hence, the higher is δ, the higher the trade-in price needs to be to stimulate any returns, but, at the same time, the less willing are consumers to respond to that incentive. Conversely, Figure 2.5(b) indicates that r generally increases, while s generally decreases, with increases in α. Intuitively, if α is relatively large, then it means that consumers are more willing to buy new products in the second period, thus they are willing to trade-in previous purchases without deterrence from a relatively lower s. Nevertheless, as Figure 2.5(c) illustrates, r and s both grow comparatively larger when a high c_0 is coupled with a small c_r. Intuitively, in such a scenario, the potential benefit of cost savings (*i.e.*, $c_0 - c_r$) dominates the potential negative effect of product cannibalization; hence, it is profitable to recollect more used products for remanufacturing and that requires a relatively larger s to fuel the process.

2.4.3.2 Remanufacturing Rate

Although the return rate r effectively reveals how much incentive a manufacturer provides consumers through its trade-in price s to return used products for replacement purchases, not all recollected products will necessarily be remanufactured, particularly if the manufacturer uses its trade-in program simply as a way to more finely segment its market through pricing tactics. Therefore, it is important also to examine the remanufacturing rate (rm), which we define as the proportion of returned products that are actually remanufactured. That is,

$$rm = \frac{d_{nr} + d_{or}}{d_{nn} + d_{nr}}$$

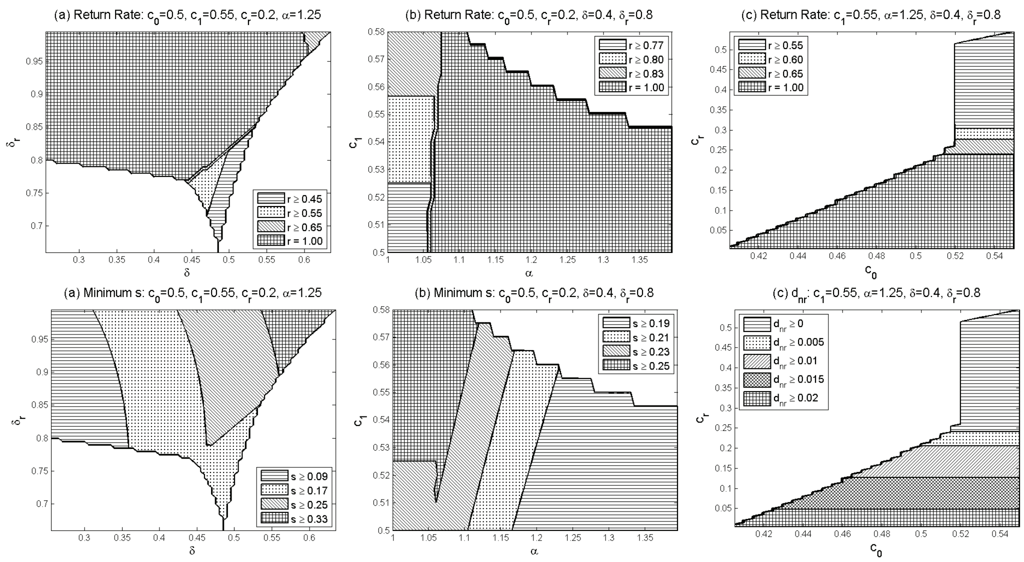

Figure 2.5: Return Rate and Minimum s

Notes: Pattern areas represent when it is optimal for the manufacturer to design and produce remanufactured products.

By definition, $rm \in (0, 1]$ and is only valid if $k^* = 1$. If $rm = 1$, then it means that the manufacturer recollects used products solely for the purpose of remanufacturing rather than for the purpose of fine-tuning its market segmentation. According to Table 2.7, we find that $rm = 1$ in more than half of the optimal solutions corresponding to $k^* = 1$ (58.4%). On the contrary, we also find that $rm < 0.5$ in more than one third of optimal solutions corresponding to $k^* = 1$ (37.5%). It is these cases, in particular, that suggest that it very well could be in the manufacturer's interest to use its trade-in program not for the purpose of endowing its remanufacturing process, per se, but rather for the purpose of stimulating repurchases of new products while reducing the cannibalization of those repurchases. As Table 2.7 illustrates, this occurs when M4 or M5 is the optimal market configuration. Indeed, according to Table 2.7, M5 is especially likely to be associated with a low rm. Intuitively, this is true because M5 is optimal when α is relatively small, which signifies that remanufactured products intensively cannibalize the sale of new products, when c_1 is close to c_0, which signifies that the cost of offering a trade-in program is low, and when c_r is large, which signifies that the cost of producing remanufactured products is high.

Given Table 2.7, Figure 2.6 further illustrates how rm changes as selected parameters change. Like the return rate r, and for analogous reasons,

Table 2.7: Remanufacturing Rate when $k^* = 1$

Opt Mkt Conf.	$rm < 0.5$	$0.5 \leq rm < 1$	$rm = 1$	Subtotal
M4	32.9%	2.1%	10.8%	45.8%
M5	3.5%	0.0%	0%	3.5%
M6	1.1%	2.0%	16.2%	19.3%
M7	0%	0%	6.0%	6.0%
M8	0%	0%	25.4%	25.4%
Total	37.5%	4.1%	58.4%	100%

the remanufacturing rate rm increases in δ_r and decreases in δ (see Figure 2.6(a)). However, unlike the return rate r, the remanufacturing rate rm generally decreases in α (see Figure 2.6(b)). This is true because, when α is relatively large, it means that customers prefer upgraded products to remanufactured products, thus a remanufacturable product design primarily serves the purpose of more finely segmenting the market, and this drives rm down. Nevertheless, Figure 2.6(b) also suggests that rm generally increases as c_1 increases. This is true because, as c_1 increases, it becomes more costly for the manufacturer to produce remanufacturable products. As a result, the manufacturer will choose a remanufacturable product design only if it is profitable to sell remanufactured products, which drives rm up. By comparing Figure 2.6(c) to 2.5(c), we find that although the manufacturer recollects more than half of the products it sells in the first period when c_0 and c_r are both high (Figure 2.5 (c)), the manufacturer actually remanufactures less than 10% of those recollected units (Figure 2.6 (c)). This is because when the cost of producing non-remanufacturable products c_0 is high, switching to a remanufacturable design does not significantly increase the associated production cost (*i.e.*, $c_1 - c_0$ is relatively small) but it does enable the manufacturer to extract additional value by further segmenting its market through its trade-in program. However, because of the relatively high remanufacturing cost c_r, it is not profitable to remanufacture the recollected products. As a result, although r is sufficiently large, rm is nevertheless close to zero.

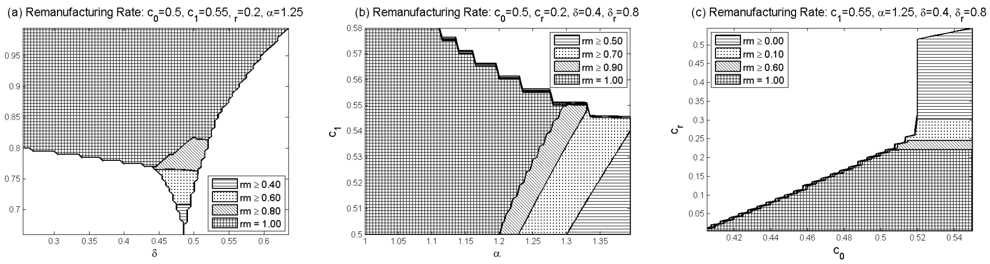

Figure 2.6: Remanufacturing Rate

Notes: Pattern areas represent when it is optimal for the manufacturer to design and produce remanufactured products.

2.5 Environmental Impact

Among other reasons, return rates in general, and remanufacturing rates in particular, are important because they serve as useful metrics that help gauge how a manufacturer's product design affects its environmental impact. However, metrics for assessing environmental impact have yet to be standardized. For example, whereas the EPA focuses on establishing standards that essentially limit the emissions released through per-unit consumption (United States Environmental Protection Agency 2012), the EU Emissions Trading System (EU ETS) focuses on establishing standards that essentially limit the emissions released during production (EU ETS 2012). Moreover, regardless of laws and regulations, manufacturers sometimes adopt their own environmental performance metrics for internal control. For example, one such metric, adopted by Apple Inc., is emissions per revenue (Apple 2013). Accordingly, in this section, we assess the environmental impact of the manufacturer's optimal product design and market segmentation strategy from Section 2.4 by considering its performance across several commonly applied metrics introduced by government or industry. Toward that end, we compare the manufacturer's optimal product design $k^* \in \{0, 1\}$ from Section 2.4 to the environmentally friendly design $k^{ef} \in \{0, 1\}$ associated with a given environmental impact metric, where the definition of k^{ef} depends on the specific metric ef under consideration. For example, if $ef(k)$ denotes the specific metric under consideration such that the lower is $ef(k)$ the more environmentally friendly is the product design, then we say that $k^{ef} = 1$ if and only if $ef\,(k = 1) \leq ef\,(k = 0)$. For each environmental impact measure ef that we consider in this section, we compare k^* to k^{ef} for each of the 18,720 problem instances defined by Table 2.3 when using the increment $I = 0.1$; and for any given problem instance and specified value of k, we assume that the manufacturer chooses the optimal market segmentation conditioned on that value of k.

Within this context, we compare k^* and k^{ef} across the comprehensive set of problem instances to assess the extent to which a manufacturer's remanufacturable product design (whether optimal or not) will be environmentally friendly (*i.e.*, $k^{ef} = 1$), on the one hand, and the extent to which a manufacturer's optimal product design is consistent with the environmentally friendly design (*i.e.*, $k^* = k^{ef}$), on the other hand, for different definitions of environmental impact metric ef. Moreover, we compare and contrast these assessments across the various definitions of ef to ascertain the virtues associated with adopting or imposing any particular metric over another. We begin by establishing the notion of total emissions within the context of our model.

2.5.1 Emissions

Given that one of the most acknowledged environmental impact metrics is total emissions, we model emissions in a similar spirit as Agrawal et al. (2012), Atasu and Souza (2013) and Gu et al. (2012). In particular, we assume that the emissions of producing one unit of new product is e_p, the emissions associated with remanufacturing (if applicable) and with consuming a unit of product is e_r and e_c, respectively, and the emissions associated with disposing the remains of a unit of product is e_d. Given this construct and the sizes of all customer segments ($d_{nn}, d_{nr}, d_{nu}, d_{on}$ and d_{or}), the total emissions of producing new products is $e_p\,(2 \cdot d_{nn} + d_{nr} + d_{nu} + d_{on})$ and the total emissions of producing remanufactured products is $e_r\,(d_{nr} + d_{or})$. Correspondingly, the total emissions associated with the consumption of those new and remanufactured products is $e_c\,(2 \cdot d_{nn} + 2 \cdot d_{nr} + d_{nu} + d_{on} + d_{or})$. Note that all products originally produced are eventually disposed, however the sources of disposal are twofold: on the one hand, consumers dispose the products in their possession at the end of the second period ($d_{nn}+d_{nr}+d_{nu}+d_{on}+d_{or}$), but they do not dispose any products at the end of the first period because, at that time, they either keep the product for another period of use or they return

Table 2.8: k^* vs. k^{EI}: Comparison of Profit and Emissions

$E = 0.2$	$k^{EI} = 0$	$k^{EI} = 1$
$k^* = 1$	15.1%	4.0%
$k^* = 0$	12.5%	68.4%

$E = 0.5$	$k^{EI} = 0$	$k^{EI} = 1$
$k^* = 1$	17.3%	1.9%
$k^* = 0$	16.5%	64.3%

$E = 0.8$	$k^{EI} = 0$	$k^{EI} = 1$
$k^* = 1$	19.0%	0.2%
$k^* = 0$	20.0%	60.8%

the product to the manufacturer for a trade-in allowance toward the purchase of a different one. On the other hand, the manufacturer disposes products at the end of the first period that it recollects from returns but does not remanufacture ($d_{nn}+d_{nr}-(d_{nr}+d_{or}) = d_{nn}-d_{or}$). Accordingly, the emissions associated with disposing product remains is $e_d\left(2 \cdot d_{nn} + d_{nr} + d_{nu} + d_{on}\right)$. Thus, all told, the total emissions for a given product design $EI\left(k\right)$ is as follows

$$EI\left(k\right) = 2e_1 \cdot d_{nn} + \left(e_1 + e_2\right) \cdot d_{nr} + e_1 \cdot d_{nu} + e_1 \cdot d_{on} + e_2 \cdot d_{or} \tag{2.6}$$

where $e_1 = e_p + e_c + e_d$ and $e_2 = e_r + e_c$ denote the life-cycle emissions per-unit (EPU) of a new and a remanufactured product, respectively, and $e_2 < e_1$ to reflect that remanufacturing is inherently environmentally efficient in the sense that remanufacturing a unit of product is more environmentally friendly than disposing a unit of product and then manufacturing a new one in its place (*i.e.*, $e_r < e_d + e_p$). This inherent efficiency, however, could potentially fuel an associated downside in the form of Jevons Paradox or the Rebound Effect (Owen 2010; Small and Van Dender 2007). The essence of these paradoxical phenomena is as follows: if technological advances enhance the efficiency of production, then profits would rise and investment in capacity expansion would occur as a result, thus driving prices down and pushing consumption higher (Goldberg 1998). Therefore, the end effect very well could be a higher total energy consumption than that before the efficiency improvements. Accordingly, we focus attention on total emissions $EI\left(k\right)$ rather than EPU.

Given (2.6), let k^{EI} be defined such that $k^{EI} = 1$ if and only if $EI(k = 1) \leq EI(k = 0)$ so that $k^{EI} \in \{0, 1\}$ denotes the product design that is more environmentally friendly in terms of total emissions. Then, by comparing k^*

and k^{EI} for each of the 18,720 problem instances from Table 2.3, we obtain Table 2.8, where each subtable corresponds to a different value of $E := \frac{e_2}{e_1}$. According to Table 2.8, for example, if $E = 0.5$, then it means that although a remanufacturable product design is environmentally friendly ($k^{EI} = 1$) in 66.20% of the 18,720 problem instances considered, that design is also optimal ($k^* = k^{EI} = 1$) in only 1.86% of the 18,720 instances.

We make several observations from Table 2.8. First, although a remanufacturable product design generally results in lower emissions as compared to a non-remanufacturable product design (in the sense that $k^{EI} = 1$ in approximately 60%-70% of the problem instances), a remanufacturable product design in and of itself is not necessarily synonymous with environmental friendliness (in the sense that $k^{EI} = 0$ in approximately 30%-40% of the problem instances). Second, by and large, the optimal product design k^* is not particularly environmentally friendly in terms of total emissions (in the sense that $k^* \neq k^{EI}$ in approximately 79%-83% of the the problem instances). Third, as E increases, although the proportion of cases for which $k^* = 0 \neq k^{EI}$ decreases, the proportion for which $k^* = 1 \neq k^{EI}$ increases. Thus, all told, Table 2.8 suggests that maximizing profit typically comes at the expense of increased total emissions. And by extrapolation, this means that one potential drawback of a purely regulatory approach to limiting total emissions is that it could force manufacturers to reduce its production level to the point that it fails to meet customer needs (James 1994). For this reason, government and industry alike often consider metrics of emissions efficiency in lieu of total emissions, where emissions efficiency accounts for the economic benefits generated in exchange for a unit of emissions. In other words, as an alternative to total emissions, environmental impact can be measured by $\frac{Emissions}{Economic\ Benefits}$, where *Economic Benefits* can refer either to manufacturer benefits (such as revenue or profit) or to societal benefits (such as consumer surplus or social welfare). Accordingly, we next introduce four such measures before proceeding to assess their relative significance in Section 2.5.2.

Emissions Per Revenue (ER). ER is an important environmental efficiency metric that manufacturers not only strive to reduce, but also publish voluntarily to communicate their environmental stewarding. See, for example, Apple (2013), Cummins (2012) and Dell (2013). Introduced by Klassen and McLaughlin (1996), ER gauges environmental impact by comparing a manufacturer's total emissions associated with the sales of its products to the total revenue derived from those sales. Thus, in our context, $ER(k) = \frac{EI(k)}{R(k)}$, where

$$R(k) = \begin{cases} p_1(d_{nn} + d_{nr} + d_{nu}) + p_2(d_{nn} + d_{on}) + p_r(d_{nr} + d_{or}) - s(d_{nn} + d_{nr}) & k = 1 \\ p_1(d_{nn} + d_{nu}) + p_2(d_{nn} + d_{on}) & k = 0 \end{cases} \quad (2.7)$$

Accordingly, let k^{ER} be defined such that $k^{ER} = 1$ if and only if $ER(k=1) \leq ER(k=0)$ so that $k^{ER} \in \{0,1\}$ denotes the product design that is more environmentally friendly in terms of the emissions per revenue efficiency ratio.

Emissions Per Profit (EP). EP is a related environmental efficiency metric that focuses on value added in lieu of total revenue (see, for example, Bosch 2012). Specifically, in our context, $EP(k) = \frac{EI(k)}{\Pi^k}$, where Π^k is given by (2.1) and (2.2), depending on whether $k = 0$ or $k = 1$, respectively. Accordingly, let k^{EP} be defined such that $k^{EP} = 1$ if and only if $EP(k=1) \leq EP(k=0)$ so that $k^{EP} \in \{0,1\}$ denotes the product design that is more environmentally friendly in terms of the emissions per profit efficiency ratio.

Emissions Per Consumer Surplus (EC). EC is an environmental efficiency metric that relates emissions to the net economic benefits derived directly from the consumption rather than the sales of the manufacturer's products. Given that overregulation of reuse and recycling rates has been shown to have potentially deleterious effects on consumer surplus under certain circumstances (Karakayali et al. 2012), EC has particular relevance to social planners. In our context, $EC(k) = \frac{EI(k)}{CS(k)}$, where $CS(k)$ is derived in detail in Appendix A. Accordingly, let k^{EC} be defined such that $k^{EC} = 1$ if and only if $EC(k=1) \leq EC(k=0)$ so that $k^{EC} \in \{0,1\}$ denotes the product design that is more environmentally friendly in terms of the emissions per consumer surplus efficiency ratio.

Emissions Per Social Welfare (EW). EW is an environmental efficiency metric similar to EC except that it relates emissions to the combined net economic benefits derived from both the consumption and the sales of the manufacturer's products (Örsdemir et al. 2014). In our context, $EW(k) = \frac{EI(k)}{SW(k)}$, where $SW(k)$ is derived in detail in Appendix A. Accordingly, let k^{EW} be defined such that $k^{EW} = 1$ if and only if $EW(k=1) \leq EW(k=0)$ so that $k^{EW} \in \{0,1\}$ denotes the product design that is more environmentally

Table 2.9: Environmental Efficiency Metrics

$E = 0.5$	k^{EI}		k^{ER}		k^{EP}	
	0	1	0	1	0	1
$k^* = 1$	17.27%	1.86%	11.56%	7.57%	9.61%	9.52%
$k^* = 0$	16.53%	64.34%	17.86%	63.01%	77.06%	3.81%
Total	33.80%	66.20%	29.42%	70.58%	86.67%	13.33%

$E = 0.5$	k^{EC}		k^{EW}	
	0	1	0	1
$k^* = 1$	15.68%	3.45%	16.05%	3.08%
$k^* = 0$	80.27%	0.60%	24.72%	56.15%
Total	95.95%	4.05%	40.77%	59.23%

friendly in terms of the emissions per consumer surplus efficiency ratio.

2.5.2 Assessment of Environmental Impact and Optimal Product Design

In this section, to assess the relative merits of the various environmental efficiency metrics and their potential significance to industry and government, we systematically compare k^* to k^{ef} for the four ef ratios defined in Section 2.5.1 in the same spirit that we compared k^* to k^{EI} in Table 2.8. Toward that end, we focus on the same 18,720 problem instances previously compiled, and we present our results in Table 2.9 for the representative case in which $E = 0.5$. Recall that, for any given metric $ef(k)$, $k^{ef} = 1$ if and only if $ef(k=1) \leq ef(k=0)$. Thus, in this section, if $k^{ef} = x$ for metric ef, then we say that x is the product design that is more environmentally friendly in terms of ef.

According to Table 2.9, EP is the environmental efficiency metric that is most consistent with a manufacturer's optimal product design in the sense that $k^* = k^{ef}$ is true for the highest percentage of problem instance (86.58%) when $ef = EP$ as compared to when $ef \in \{\text{ER,EC,EW}\}$. This can be explained intuitively because $EP(k)$ includes profit in its denominator, which means that, everything else being equal, EP decreases as profit increases. In this sense, environmental efficiency metric EP is particularly well aligned with profit maximization, thus it stands to reason that $k^* = k^{EP}$ would be true as a general rule. By contrast, it is the closely related environmental efficiency metric ER that is most aligned with the reduction of total emissions in the sense that the percentage of problem instances in which $k^{EI} = 1$ (66.20%) is closer in magnitude to the percentage of problem instances in which $k^{ER} = 1$ (70.58%) than it is to the percentage of problem instances in which $k^{ef} = 1$ for $ef \in$ {EP,EC,EW}. Indeed, the percentage of cases for which $k^{ef} = 1$ is greatest for $ef = ER$ among all environmental impact measures ef considered here. Intuitively, this makes sense because a production cost premium is required to produce a unit of a remanufacturable product as compared to producing a unit of a non-remanufacturable product (*i.e.*, $c_1 > c_0$), which in turn means that $k = 1$ typically corresponds to a higher associated per-unit revenue as compared to $k = 0$, everything else being equal. Correspondingly, $ER(k = 1)$ typically will be lower than $ER(k = 0)$ because $ER(k)$ is a metric that explicitly includes revenue in its denominator.

On the opposite end the spectrum relative to ER, environmental efficiency metric EC results in the lowest percentage of cases in which $k^{ef} = 1$ among all environmental impact measures ef considered here. In particular, $k^{EC} = 1$ in only 4.05% of the problem instances (as compared to $k^{ER} = 1$ in 70.58% of problem instances). Nevertheless, given that metric EC includes consumer surplus, as opposed to manufacturer surplus in its denominator, and given that it is natural for consumer surplus to decrease when the breadth of a product line increases, it makes sense that, everything else being equal, the consumer surplus associated with $k = 1$ typically would be lower than the consumer surplus associated with $k = 0$ because, in our context, $k = 0$ reflects a lower product line breadth as compared to $k = 1$. By comparison, environmental efficiency metric EW appears to be similar to metric ER in the sense that, like metric ER, metric EW is predominately aligned with the reduction of total emissions as measured by EI. In particular, according to Table 9, $k^{EW} = 1$ for a percentage of problem instances (59.23%) that is relatively close in magnitude to the percentage of problem instances for which $k^{EI} = 1$ (66.20%). Nevertheless, unlike metric ER, metric EW is unlikely to gain wide-spread adoption in practice because of the computational difficulty associated with measuring social welfare accurately.

Thus, all told, we conclude that among the four available environmental efficiency ratios defined in Section 2.5.1, ER can serve as the best proxy for EI as a metric for measuring overall environmental stewardship. In addition, interestingly, $k^* = k^{ER}$ in a higher percentage of cases (25.43%) than $k^* =$

k^{EI} (18.39%). Thus, this helps explain in part why some manufacturers might be more inclined to publish their overall environmental stewarding performance with respect to ER in lieu of publishing their performance with respect to EI.

2.6 Conclusion

Introducing a remanufacturable product to its market not only increases a manufacturer's profits by attracting a new customer segment to its product offerings, but also provides spillover benefits to the environment by consuming less resources. Yet, despite these noted benefits of remanufacturing, many manufacturers have yet to expand their operations to enter the remanufactured-goods industry. Therefore, in this chapter, we analyze this apparent dichotomy by formulating and studying a remanufacturable design problem when consumers are vertically heterogeneous with respect to their willingness to pay. Toward that end, we develop a stylized economic model in which a price-setting manufacturer can choose whether or not to enter into remanufacturing by designing its product to be either remanufacturable or non-remanufacturable, respectively, and then designing a corresponding pricing policy and trade-in program accordingly. Given this construct, we specifically explore and draw implications from the market segmentation strategy that results. Upon doing so, we find that as a general rule of thumb it is optimal for a manufacturer to design a remanufacturable product when the value-added from remanufacturing is relatively high, when product durability is relatively low, and when innovation is nominal. In a similar vein, remanufacturability typically is justified when the production cost of a remanufacturable product is comparatively low relative to the production cost of a non-remanufacturable product or when the cost to remanufacture a returned product is relatively low. Otherwise, however, it is not optimal for the manufacturer to design a remanufacturable product, which helps explain in part the documented evidence that reflects some manufacturer reluctance to expand into the remanufactured-goods industry.

In addition, we find that a remanufacturable product design is not synonymous with high return and remanufacturing rates. Indeed, we find that even if it is optimal for the manufacturer to design a remanufacturable product and to establish a trade-in program to induce a high return rate, a high level of remanufacturing activity is not a foregone conclusion. A high return rate but low remanufacturing rate would be the case, for example, if the production cost of a remanufacturable product is low while product innovation is high. This phenomenon suggests that regulating return rates in the name of environmental stewardship could potentially result in ineffective or even counterproductive policy. In a similar vein, we find that despite remanufacturing's inherent environmental benefits per unit of production, its associated countereffect is an increase in overall production volume to meet demand from an expanded market. Moreover, we find that, as a result, the manufacturer's increased profit potential very well could come at the net expense of environmental deterioration because of increased total GHG emissions. Thus, regulatory restrictions focused solely on overall emission totals run the risk of a social cost if they essentially force manufacturers to reduce production levels to the point at which they cannot affordably meet customer needs. Nevertheless, if environmental cost efficiency is taken into account, which in this context means emissions produced per unit of economic benefit extracted in return for the manufacturer, society, or both, then we find a happy middle ground. In particular, we find that the efficiency ratio ER (emissions per revenue) is a metric that can serve as an especially good proxy for monitoring and controlling environmentally responsible manufacturing operations.

We note that our results and insights are based in part on the modeling stipulation that the manufacturer allows its trade-in allowance for a returned product to be applied toward the purchase of either a new or a remanufactured product. Nevertheless, we also considered as a modeling extension if, instead, the manufacturer restricted trade-ins to be applied only toward the purchase of a new product (but not a remanufactured one). For this extension, we found that, by and large, our qualitative results and insights continue to apply. However, one notable difference is that the resulting optimal market segmentation strategy would be such that sales of remanufactured products would decrease and thus, cannibalization actually would decrease, thereby leading to an increase in the overall sales of new products (relative to the baseline situation in which trade-ins may be applied toward the purchase of either new or remanufactured products). Yet, interestingly, the manufacturer's profit would decrease as a result. One explanation of this somewhat counterintuitive implication is as follows: When trade-ins are not restricted such that they may be applied either toward the purchase of a new product or toward the purchase of a remanufactured product, some consumers who otherwise would opt for continued use of a previously purchased product over trading in that used product for a new product become willing to trade in the used product for a less expensive (but, often, more profitable) remanufactured product. In fact, given that remanufactured product sales often contribute as much as two-to-three times more earnings before interest and taxes than new product sales contribute (Giuntini 2008), the profits generated from the increase in the sales of remanufactured products more than offset the opportunity cost of losing profits from the cannibalization of new product sales.

In closing, we acknowledge the following limitations of our two-period model. First, it implicitly assumes that the manufacturer commits in the first period to a set of prices for the second period, which by definition means that our model does not account for the possibility of time inconsistency. In a similar vein, our model does not explicitly account for discounting of second period profits or utilities. In principle, both of these limitations could be addressed by reformulating the two-period model studied here as an infinite-horizon steady state model. Although we would expect that with such a reformulation many of our qualitative results will continue to hold, we also would expect quantitative differences to emerge. Thus, we view this direction as a potentially viable path for continued and extended research.

CHAPTER 3

THE INTER-DIVISIONAL COORDINATION OF MANUFACTURING AND REMANUFACTURING OPERATIONS IN A CLOSED-LOOP SUPPLY CHAIN

"If there's reason for hope, it lies in man's occasional binges of cooperation. To save our planet, we'll need that kind of heroic effort, in which all types of people join forces for the common good."

– George A. Meyer.

3.1 Introduction

Remanufacturing has become a significant, albeit largely hidden industry worldwide. The economic value of U.S. remanufactured production was over US$43 billion in 2011 (U.S. International Trade Commission 2012). The Ellen MacArthur Foundation and McKinsey & Company (2014) estimate that the net material cost savings of recycling, reuse and remanufacturing in relevant fast-moving consumer goods sectors could reach US$700 billion annually at the global level.

A manufacturing firm can undertake remanufacturing in-house (*e.g.,* Robert Bosch Tool, Black & Decker, and General Electric Transportation), by contracting with suppliers (*e.g.,* Hewlett-Packard), or using a mix of both in-house and contracting (*e.g.,* Pitney-Bowes) (Martin et al. 2010). Some manufacturing firms choose in-house remanufacturing to maintain sufficient control over the entire product life cycle and mitigate the effects of external remanufacturing competition (Majumder and Groenevelt 2001, Ferguson and Toktay 2006, Li et al. 2011), because consumers are willing to pay more for the remanufactured products made by the original manufacturing firms or authorized contractors than by the third parties (Subramanian 2012). Manufacturing firms that undertake in-house remanufacturing typically have separate divisions to produce new and remanufactured products (Toktay and

Wei 2011). For instance, Caterpillar established a remanufacturing division which had over $2 billion in sales in 2007 and has grown into a global leader in remanufacturing with 17 remanufacturing facilities in 7 countries (Ferguson and Souza 2010, Caterpillar 2012).

Despite the popularity and profitability of remanufacturing, the actual practice of such form of recovery is still very limited. From 2009 to 2011, remanufactured goods only accounts for 2% total sales of all manufactured products by US firms (USITC 2012) and remanufacturing just accounted for 1% of UK manufacturing sector turnover in 2011 (Lavery et al. 2013). Lavery et al. (2013) estimated that the full potential value of remanufacturing in UK could amount to US$9-13 billion for the three key remanufacturing sectors (electrical, electronic and optical products; machinery and equipment; transport equipment).

This research is motivated by the inter-divisional coordination issues faced by a Fortune 500 manufacturing company that has both manufacturing and remanufacturing operations. The two operations are conducted in dedicated in-house facilities and managed by new and remanufacturing divisions, respectively. Both new and remanufactured products reach customers through authorized dealers. Dealers are price-takers, which means that they sell new and remanufactured products at the prices dictated by the firm. Customers can return worn or broken products to the dealers who either 1) rebuild parts if products can be functional with easy parts replacement and cleaning, 2) send products to the remanufacturing facility if sophisticated repair and replacement work is required, or 3) dispose of products if they are seriously worn or damaged. Products returned to the remanufacturing facility will be processed to reattain an "as-new" or even better condition; some returns will be disposed of if remanufacturing is not cost-effective. Figure 3.1 depicts the forward and reverse flow of the products and parts in the firm we studied.

Although the company has been engaged in remanufacturing for decades, the remanufacturing operation still receives little support, according to the manager we interviewed. To be specific, on the one hand, the existing pricing policy of the firm is to price both new and remanufactured products at the same level, making remanufactured products barely attractive to the customers (one exception is when a model is discontinued, and hence the remanufactured counterpart becomes the only choice). On the other hand, the remanufacturing division has very little control over the product design

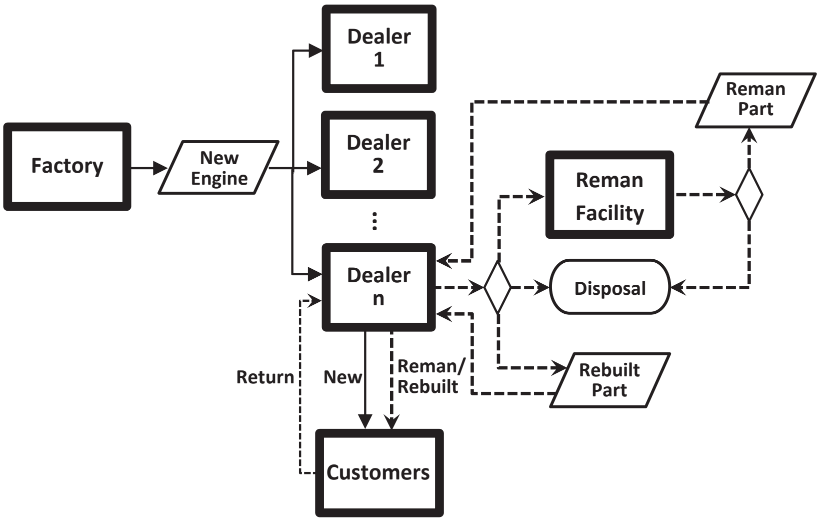

Figure 3.1: The Forward and Reverse Product Flow of the Studied Firm

that is normally incorporated into the manufacturing process. However, a remanufacturable product design may not be in the best interest of the manufacturing division for two primary reasons: 1) the manufacturing division is concerned with the remanufacturing operations because of the potential product cannibalization, meaning that the sales of lower-priced remanufactured products can steal from the sales of new products (Atasu et al. 2010); 2) the additional cost required to make new products remanufacturable prevents the manufacturing division from choosing a remanufacturable product design. Although it is not surprising to observe firm inefficiency based on the above discussion, it is still not clear as to what extent the divisional conflict between the manufacturing and remanufacturing divisions result in efficiency losses in terms of firm profits, product sales and product design change.

As an important observation from this case, a major obstacle to remanufacturing, albeit seldom discussed, is that the manufacturing division, who is responsible for the design decisions, is prone to choosing a non-remanufacturable product design to avoid product competition from the remanufacturing division as well as the additional cost associated with a remanufacturable product design. However, a remanufacturable product design is not always as harmful as it appears to the manufacturing division. In fact, remanufacturing operations can benefit the manufacturing division if the profit from the remanufactured products can be reallocated between the two divisions so that both divisions can reap an increase in profit. To achieve such a win-win situation, it is crucial for any firm that has potential intra-organizational conflicts to develop incentive alignment to coordinate the two divisions (Lebreton, 2007). Although many studies on cooperative optimization in a serial supply chain with independent firms currently exist, few have investigated independent agents within the firm that is involved in remanufacturing. A notable exception is Toktay and Wei (2011) who proposed a transfer pricing scheme that coordinates the manufacturing and remanufacturing divisions and induces the first-best result. Yet, does transfer pricing still guarantee the first-best design and profit when the manufacturing division has full control over the product design (remanufacturable or not)? If not, what mechanisms can be designed to achieve that goal?

To examine these questions, we consider a decentralized firm with one manufacturing division and one remanufacturing division. The firm sells both their new and remanufactured products through a retailer. In the decentralized firm, the manufacturing division can design new products to be non-remanufacturable and produce them at a base cost. Alternatively, it can design new products to be remanufacturable and produce them at a higher production cost while the remanufacturing division can produce remanufactured products at a lower cost than the base cost. Each division determines the optimal wholesale price of its products to maximize its divisional profit, as applicable. The retailer decides upon the retail prices of both products (if applicable) after knowing the wholesale prices.

Our results reveal that, compared with the centralized firm, the manufacturing division of the decentralized firm is more inclined to "shut down" the market for remanufacturable products by designing new products to be non-remanufacturable. Furthermore, although the centralized firm may find it optimal to design new products to be remanufacturable and remanufacture only part of returned products, it is never optimal for the decentralized firm to do so. The decentralized firm will either choose a non-remanufacturable product design or design products to be remanufacturable and remanufacture all returned products. Our findings also reveal that firm decentralization and divisional conflict could result in up to 50% loss in profits and sales.

Thus, we investigate transfer pricing, a single-parameter scheme to coordinate manufacturing and remanufacturing operations that commonly exist in practice (Toktay and Wei, 2011). We conclude that transfer pricing generally fails to induce the first-best result because the participation constraint of both divisions (*i.e.*, both divisions are better off under the scheme in question) cannot be satisfied simultaneously. We further illustrate that under certain circumstances, a two-part coordination scheme with a "transfer price" and a "single fixed payment" is required to motivate the manufacturing division to optimally design new products and to maximize the economic performance of the entire firm (*i.e.*, achieve the first-best outcome as of the benchmark model). We then demonstrate that by implementing the two-part coordination scheme, the decentralized firm can achieve the same total profit and sales as the centralized firm. In addition, both this incentive can increase the profit of both divisions. Interestingly, the per-unit transfer can flow from the manufacturing division to the remanufacturing division in certain cases. This result highlights the need for a more sophisticated (two-part) incentive mechanism to ensure coordination between the two divisions as well as the first-best firm-wide profit. In addition, compared to the transfer pricing, the two-part coordination scheme exhibits better robustness. Although the idea of coordinating the supply chain using a two-part incentive scheme is not new, in and of itself, our primary focus is to explore the impact of incentives on optimal product design, product cannibalization, and the direction in which fixed and variable payments flow.

The remainder of this chapter is organized as follows. The literature review is presented in Section 3.2. In Section 3.3, we specify our centralized and decentralized models and examine the impact of decentralization on optimal product architecture and pricing decisions. Then in Section 3.4, we discuss the limitations of a single transfer pricing scheme to coordinate the two divisions in a decentralized firm and then propose an inter-divisional incentive scheme with an examination of its effectiveness in our setting. We conclude with a summary of our findings in Section 3.5. Proofs of propositions and corollaries are provided in the online supplement.

3.2 Related Literature

This study is closely related to the literature on closed-loop supply chain management, as comprehensively reviewed by Guide Jr and Van Wassenhove (2009) and Souza (2013). There is a strand of papers that analyze profit maximization models to study the optimal design, pricing and production decisions associated with remanufacturing. In particular, Atasu et al. (2008) identified the major factors that affect the profitability of remanufacturing for a monopolist, which include cost savings from remanufacturing, the percentage of green consumers, the market growth rate, and consumer valuation discounts for remanufactured products. Debo et al. (2005) found that investment in remanufacturability is driven by the high production costs of a single-use product, low remanufacturing costs, and low additional costs to make a single-use product remanufacturable. Thus, firms need to analyze these factors prudently before deciding upon whether to design new products to be remanufacturable or not. Pricing new and remanufactured products is another critical issue in managing manufacturing and remanufacturing operations because it has been proven to be an effective strategy to control demand (Ferrer and Swaminathan 2006, 2010), segment the consumer market (Debo et al. 2005, Atasu et al. 2008) and limit competition (Majumder and Groenevelt 2001, Ferguson and Toktay 2006). A number of studies have also focused on the production quantity decision that basically answers how much can be remanufactured, which considers the availability of returned products or the acquisition of used products (Östlin et al. 2009, Galbreth and Blackburn 2010, Clottey et al. 2012) and how much should be remanufactured, which considers the optimal number of products to be remanufactured (Ferrer and Swaminathan 2006, Ferguson et al. 2011, Özdemir et al. 2014). We contribute to this literature by endogenizing a product design (*i.e.*, whether or not to design a product to be remanufactured), exploring the impacts of divisional conflict between a manufacturing division who designs and produces new products and a remanufacturing division who remanufactures used products and suggesting an inter-divisional coordination mechanism in a dual-division firm context. In addition, in a similar spirit as Desai et al. (2004), we consider the addition of a retailer in the distribution channel but in the framework of a closed-loop supply chain.

Examining the coordination issue between manufacturing and remanufacturing operations is relatively new in the remanufacturing literature. As mentioned in Section 3.1, there is a complicated interplay between the manufacturing division and the remanufacturing division in a decentralized firm, due to a lack of a common objective. Studies illustrate that contracts with a transfer payment scheme can help to optimize profit performance so that each entity's objective is consistent with that of the entire supply chain

(Cachon, 2003). Research on coordination contracts is rich in economic and accounting literature (see, Sengul et al. 2012, Ittner and Larcker 2001 for relevant reviews). Several recent avenues of work in the operations management literature investigate coordination problems in a supply chain setting. Jacobs and Subramanian (2012) studied the impact of collection and recycling targets under an extended producer responsibility (EPR) program and the impact of sharing responsibility for product recovery on profits in a supply chain with a supplier and a manufacturer. They suggest contract menus that can Pareto-improve the supply chain profits while social welfare may or may not improve. Cachon and Lariviere (2005) proposed a revenue-sharing contract with two parameters: the wholesale price the retailer pays per unit and the retailer's share of the revenue generated by each unit. This contract can coordinate a wider array of supply chains than buybacks do; it can divide the resulting total profit arbitrarily. However, most previous supply chain coordination studies focus on coordinating price/quantity decisions. In contrast, our analysis extends theirs in that we also incorporate the product design decision.

Although there is an extensive amount of literature on cooperative optimization in a serial supply chain with independent firms, few researchers have investigated independent agents within the same company in a remanufacturing setting. A notable exception is the paper by Toktay and Wei (2011); they addressed the question of how to set a coordinating transfer price to allocate the cost of input between a manufacturing division and a remanufacturing division. They suggest that a portion of the initial production cost should be assigned to the manufacturing division and that the compensation from the remanufacturing division to the manufacturing division should be a fixed cost allocation. This chapter not only studies the optimal pricing and inter-divisional coordination scheme for manufacturing and remanufacturing operations but also considers both the produce design and cannibalization effect. Firstly, the product design for remanufacturing is endogenous to our model; that is, the centralized firm or the manufacturing division in a decentralized firm decides whether or not to design its new products to be remanufacturable. This setting enables us to dive deeper into the impacts of divisional conflict on remanufacturing operations, as seen in the example of Caterpillar. If new products are designed to be remanufacturable, then they incur a higher production cost, due to the additional resource consumption and design change. Secondly, unlike Toktay and Wei (2011), we consider the case when product cannibalization exists because new and remanufactured products are sold in the same market. In other words, the demand of new and remanufactured products depends on the availability and price of both new and remanufactured products. Therefore, our model captures the demand reality in the majority of markets that have access to both new and remanufactured products. Lastly, we consider a supply chain with an independent retailer through which the firm sells new and remanufactured products. The retail distribution is a common practice in the remanufacturing industry.

Studies on remanufacturing with a profit-maximization approach have used single-period, two-period or infinite-horizon settings. In a two-period setting, it is assumed that only new products are manufactured in the first period. In the second period, used products are collected for remanufacturing and only remanufactured products (Toktay and Wei, 2011) or both new and remanufactured products (Majumder and Groenevelt 2001, Ferguson and Toktay 2006) are available in the consumer market. Other research considers the multi-period and infinite horizon time period (Debo et al. 2005, Ferrer and Swaminathan 2006). The single-period model can be applied to the cases in which similar products are introduced to the market repeatedly (Savaskan et al., 2004) or when a product's life cycle has reached its maturity stage, such that prices and recovery rates are stable (*e.g.,* Savaskan et al. 2004, Zikopoulos and Tagaras 2007, Atasu and Souza 2013). Along with the common assumption that remanufactured products have a one-period lifetime and that the returned product cannot be inventoried, we model the problem in such a way that products sold in the previous period can be returned for remanufacturing and pricing/production decisions are constant across periods.

3.3 The Models

3.3.1 Modeling Assumptions

The Firm. Consider a profit-maximizing firm with a manufacturing division and a remanufacturing division. The *manufacturing division* (denoted as

D1) designs and produces new products that are sold through the retailer; the *remanufacturing division* (denoted as D2) remanufactures the returned products and sells remanufactured products to the same retailer. D1 makes design decision k at the beginning of the time horizon. If $k = 0$, then new products are non-remanufacturable and can be produced at cost $c_1 > 0$ per unit by D1. In such a case, only new products are available in the market. Therefore, the production quantity of the remanufactured products and the divisional profit of D2 are both 0.

If $k = 1$, then new products are remanufacturable and are produced at cost $c_1 + \eta$ per unit, where the additional cost η is non-negative, to reflect the increased complexity required to make new products remanufacturable (Subramanian 2012). We assume $c_1 + \eta < 1$, where 1 represents the upper bound of consumer willingness-to-pay (WTP) for a new product, which will be discussed later. D2 can remanufacture the used remanufacturable products at cost $c_2 \geq 0$ per unit. Note that if producing one unit of remanufacturable product and one unit of remanufactured product costs no less than producing two units of non-remanufacturable products ($c_1+\eta+c_2 \geq 2c_1$ or equivalently $c_2 + \eta \geq c_1$), then the firm has no incentive to undertake remanufacturing. To avoid such a trivial case, we assume $c_2 + \eta < c_1$. We also assume that D1 has the production capacity to fulfill any demand for new products. However, D2 cannot remanufacture more than the past sales of new products. For simplicity, used products can all be returned and remanufactured. This assumption applies to products that require frequent replacement or updates and are not subject to significant wear and tear.

D1 and D2 decide the wholesale price w_1 and w_2 of new and remanufactured products, respectively, where $w_1, w_2 \in [0, 1]$ denote a consumer's WTP for a new or remanufactured product, which is assumed to be no more than 1. In a decentralized firm, each division maximizes its divisional profit because the divisional manager's performance is usually measured based on the divisional profit rather than on the total firm profit (Toktay and Wei 2011). A division only makes productions if its divisional profit, the net of revenue and the internal transfer (if it exists) minus the cost, is positive.

The Retailer. The retailer, denoted as R, sells both new and remanufactured products and decides upon the retail prices p_1 and p_2 of the new and remanufactured products, respectively, in order to maximize its own profit. Retailers play an important role in the remanufactured-goods market and are more efficient in undertaking product collection activity in terms of the return rate than the firm itself (Savaskan et al., 2004). Thus, we assume that the retailer is in charge of collecting used products and that all used products can be collected. A high collection rate can also be achieved through, but not limited to, leasing (Desai and Purohit 1998, Agrawal et al. 2012) and trade-in rebates (Ray et al. 2005, Oraiopoulos et al. 2012). Without loss of generality, the cost of collecting and handling returned products are normalized to zero for the retailer and all collected products will be returned to D2. These assumptions help us focus our analysis on issues that are important to this study.

Consumers. Customer WTP for a new product is heterogeneous and uniformly distributed in the interval $[0, 1]$. We assume a consumer's WTP to be independent of whether the product is remanufacturable or not, due to the distinction between consumers' consideration of product sustainability and conventional product characteristics (Galbreth and Ghosh, 2013). On the other hand, as demonstrated in Guide Jr and Li (2010), a consumer's WTP for a remanufactured product is generally less than her WTP for a new product. Thus, we assume that if a consumer is willing to pay θ for a new product in the first period, then her WTP for a remanufactured product in the second period is $\delta \cdot \theta$, where $\delta \in (c_2, 1)$ is the discount factor for a remanufactured product. Note that remanufactured products cannot be profitable if $\delta \leq c_2$. Each customer purchases at most one new unit. A consumer can choose between a new product and a remanufactured product, if applicable, depending on which one provides more customer surplus (the difference between WTP and the price). Note that consumers who would otherwise have a negative surplus do not purchase. In addition, the market size is normalized to 1. Under the above assumptions, the inverse demand functions for new and remanufactured products are (Desai and Purohit 1998; Ferguson and Toktay 2006) as follows:

$$p_1(d_1, d_2) = 1 - d_1 - \delta d_2, \text{ and} \tag{3.1}$$

$$p_2(d_1, d_2) = \delta(1 - d_1 - d_2), \tag{3.2}$$

where d_1 and d_2 are the demand for new and remanufactured products, respectively, and $d_2 \leq d_1$. If the new products are designed to be non-

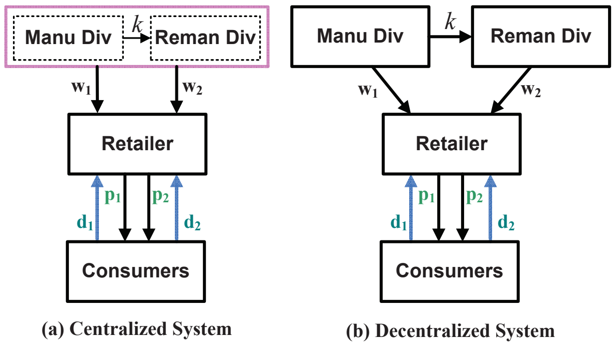

Figure 3.2: Channel Structures

remanufacturable, then $d_1 = 1 - p_1$ and $d_2 \equiv 0$. Note that we can formulate retail prices as functions of d_1 and d_2, because (d_1, d_2) uniquely determines (p_1, p_2), and vice versa. Therefore, the retailer's profit optimization problem on wholesale prices p_1 and p_2 is equivalent to the profit problem on demand d_1 and d_2 (see Section 3.3.2 for more detail). In all, our problem is defined on the parameter space $\Omega = \{(c_1, c_2, \delta, \eta) \,|c_2 + \eta < c_1 < 1 - \eta,\ c_2 < \delta < 1,\ 0 \leq c_1, c_2, \eta \leq 1\}$.

3.3.2 Benchmark: Centralized Scenario

In terms of the centralized scenario, we first establish the first-best benchmark by studying the centralized firm, the single decision maker for both the manufacturing and remanufacturing operations. The supply chain model of a centralized firm is illustrated in Figure 3.2(a). For the centralized scenario, we use superscript C to denote the optimal solutions. Let k^C and Π_F^C denote the optimal design decision and the firm profit, respectively, and let w_i^C and d_i^C denote Di's optimal wholesale price and sales quantity ($i = 1, 2$). The centralized firm chooses product design k and wholesale prices w_1 and w_2. Consequently, its problem is:

$$\Pi_F^C = \max_{w_1, w_2, k} d_1 [w_1 - (c_1 + k \cdot \eta)] + k \cdot d_2 \cdot (w_2 - c_2)$$

$$s.t. \quad 1 - d_1 - k \cdot d_2 \geq 0 \tag{3.3}$$

$$d_1 \geq k \cdot d_2 \geq 0 \tag{3.4}$$

After knowing the wholesale prices and product design, the retailer R decides upon retail price p_1 and p_2, as applicable, formulated as functions of d_1 and

Table 3.1: Optimal Solutions for the Centralized Scenario

Strategy	k^C	w_1^C	w_2^C	d_1^C	d_2^C
R1	1	$\frac{1+c_1+\eta}{2}$	$\frac{c_2+\delta}{2}$	$\frac{1-c_1-\eta-\delta+c_2}{4(1-\delta)}$	$\frac{\delta(c_1+\eta)-c_2}{4(1-\delta)\delta}$
R2	1	w_1*	$\frac{1+c_1+\eta+\delta+c_2}{2}-w_1$	$\frac{1-c_1-\eta+\delta-c_2}{4(1+3\delta)}$	d_1^C
NR	0	$\frac{1+c_1}{2}$	$-$	$\frac{1-c_1}{4}$	$-$

*: w_1 must satisfy $w_1 \in \left[\frac{1+4\delta-\delta^2+(c_1+\eta+c_2)(1+\delta)}{2(1+3\delta)}, \min\left\{\frac{1+\delta+c_1+\eta+c_2}{2}, 1\right\}\right]$

Strategy	Π_F^C	Π_R^C
R1	$\frac{(1-c_1-\eta-\delta+c_2)^2}{8(1-\delta)}+\frac{(\delta-c_2)^2}{8\delta}$	$\frac{\Pi_F^C}{2}$
R2	$\frac{(1-c_1-\eta+\delta-c_2)^2}{8(1+3\delta)}$	$\frac{\Pi_F^C}{2}$
NR	$\frac{(1-c_1)^2}{8}$	$\frac{\Pi_F^C}{2}$

d_2 by (3.1)-(3.2). Thus, the retailer's problem is:

$$\Pi_R = \max_{d_1,d_2} d_1 \cdot [p_1(d_1,d_2) - w_1] + k \cdot d_2 \cdot [p_2(d_1,d_2) - w_2] \quad (3.5)$$

subject to (3.3)-(3.4).

We solve the sequential decision problems by backward induction and classify the firm's strategy into three categories: 1) NR denotes the strategy that the firm chooses a non-remanufacturable product design ($k^C = 0$); 2) R1 denotes the strategy that the firm chooses a remanufacturable product design ($k^C = 1$), but the firm does not remanufacture all used products ($d_1^C > d_2^C$), and 3) R2 denotes the strategy that $k^C = 1$ and remanufactures all used products ($d_1^C = d_2^C$). The corresponding solutions for each strategy are derived in the online supplement and summarized in Table 3.1.

Proposition 3.3.1 *In a centralized firm,*
(i) if $\eta \le \frac{(\delta-c_2)\left(\sqrt{1+3\delta}-1-\delta\right)}{2\delta}$, *then*
strategy R2 is optimal when $c_1 \ge \frac{1-\delta-2\eta}{2}+\frac{(1+\delta)c_2}{2\delta}$;
strategy R1 is optimal when $\frac{\sqrt{(1-\delta)\eta(2\delta+\eta-2c_2)}+c_2-\eta}{\delta} < c_1 < \frac{1-\delta-2\eta}{2}+\frac{(1+\delta)c_2}{2\delta}$;
and strategy NR is optimal when $c_1 \le \frac{\sqrt{(1-\delta)\eta(2\delta+\eta-2c_2)}+c_2-\eta}{\delta}$.
(ii) if $\eta > \frac{(\delta-c_2)\left(\sqrt{1+3\delta}-1-\delta\right)}{2\delta}$, *then*
strategy R2 is optimal when $c_1 \ge \frac{2\delta+\eta+c_2-(\delta-c_2-\eta)\sqrt{1+3\delta}}{3\delta}$;
strategy NR is optimal when $c_1 < \frac{2\delta+\eta+c_2-(\delta-c_2-\eta)\sqrt{1+3\delta}}{3\delta}$;
and strategy R1 is not optimal.

Proposition 3.3.1 intuitively illustrates it is optimal for a centralized firm

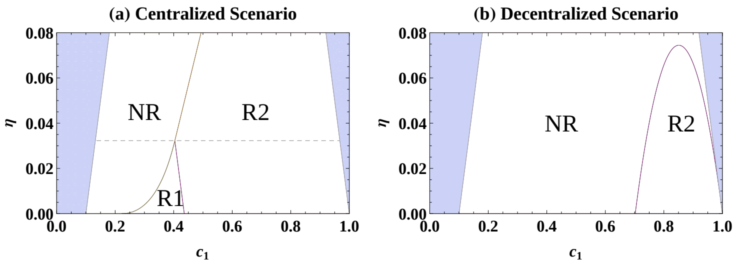

Figure 3.3: Optimal Strategy in Centralized and Decentralized Scenarios ($c_2 = 0.1$ and $\delta = 0.45$)
Note. Shaded area is outside the bounds of discussion which require that $c_2 + \eta < c_1 < 1 - \eta$ and $\delta > c_2$.

to sell remanufacturable products when the cost of producing new products c_1 is relatively large, the cost of remanufacturing products c_2 is relatively small, the added-value of remanufacturing δ is relatively large, and the cost of a remanufacturable product design η is relatively small, keeping all other parameters constant. We initially look at the effects of cost factors c_1 and c_2 on the product design. More specifically, when a firm can produce remanufactured products at low cost, it sells them at a low price to attract consumers who would otherwise not purchase. However, some customers who might have bought new products may instead purchase the remanufactured products for a lower price, leading to product cannibalization. If c_1 is small, then the cost-savings from the producing remanufactured product over the new product $(c_1 - c_2)$ is not significant. In all, product cannibalization dominates the cost-saving effect, resulting in lower total profits. For the same reason, which is also consistent with Atasu et al. (2008), we find that the firm only remanufactures when the remanufacturing cost c_2 is sufficiently low. Next, we examine how the value-added from the remanufacturing process affects the product design. To be specific, as δ increases, customers are willing to purchase remanufactured products at a higher price, which makes remanufactured products more profitable to produce. Hence, when δ is above a certain threshold, it is optimal for the firm to produce and sell remanufactured products. Finally, when the cost of the remanufacturable product design η is small, the additional cost of designing products to be remanufacturable is less than the additional profit from selling the remanufactured products. Therefore, it is more lucrative to design new products to be remanufacturable when η is small.

Figure 3.3(a) illustrates the optimal strategy of a centralized firm in the

(c_1, η) space for $c_2 = 0.1$ and $\delta = 0.45$. Note that (c_1, η) in the upper left and right corner does not satisfy our assumption; hence, it is beyond the scope of our discussion. In general, when the firm designs new products to be remanufacturable, it chooses strategy R2 over R1 when c_1 is relatively large, c_2 is relatively small and δ is relatively large, keeping all other parameters constant. This is because the unit profit of selling one new product decreases as c_1 increases and the unit profit of selling one remanufactured products increases as c_2 decreases or as δ increases, making it profitable to remanufacture as much as possible. As illustrated in Proposition 3.3.1(ii) and Figure 3.3(a), it is not optimal for a firm to only remanufacture part of the used products (strategy R1) when the cost of a remanufacturable product design is not nominal ($\eta > \frac{(\delta - c_2)\left(\sqrt{1+3\delta} - 1 - \delta\right)}{2\delta}$). In particular, it can be shown that $\frac{(\delta - c_2)\left(\sqrt{1+3\delta} - 1 - \delta\right)}{2\delta} \leq \frac{1}{24}$. Thus, if $\eta > \frac{1}{24}$, the firm should either design the new products to be non-remanufacturable (strategy NR) or design them to be remanufacturable and remanufacture all return products (strategy R2) for any c_1 and δ. Furthermore, the following corollary specifies the condition when strategy NR is a dominating strategy:

Corollary 3.3.2 *If $\eta > 0$ or $c_2 > 0$, then there exists a threshold for c_1 (δ) above (below) which strategy NR is optimal.*

According to Corollary 3.3.2, only when there is no extra cost to make new products remanufacturable ($\eta = 0$) and there is no cost to remanufacture ($c_2 = 0$) will the firm always design new products to be remanufacturable, irrespective of the value of c_1 and δ. This is because at "zero cost" ($\eta = c_2 = 0$), selling remanufactured products becomes so profitable that the loss in sales of new products is easily compensated by the increase in sales of remanufactured products. In fact, the firm is very likely to remanufacture as much as possible (strategy R2) in such a case. To see this, based on Proposition 3.3.1, strategy R2 is optimal when $c_1 \geq \frac{1-\delta}{2}$ and R1 is optimal when $c_1 < \frac{1-\delta}{2}$, where $\frac{1-\delta}{2} < \frac{1}{2}$ since $\delta > 0$. Nevertheless, as long as there is a cost to remanufacture or an additional cost to make new products remanufacturable, it is not always optimal for the firm to choose a remanufacturable product design.

In summary, a centralized firm chooses among three strategies: NR, R1 or R2. A remanufacturable product design (R1 or R2) is optimal when the unit production cost of new products (c_1) is high, unit cost of remanufacturing

(c_2) is low, value-added from remanufacturing (δ) is high and the cost of making new products remanufacturable (η) is low.

3.3.3 Decentralized Scenario

We now consider a decentralized firm in which the manufacturing division (D1) and remanufacturing division (D2) make decisions independently to maximize their own divisional profits. The supply chain model with a decentralized firm is illustrated in Figure 3.2(b). We use superscript D to denote the optimal solutions in the decentralized case. Let Π_1^D and Π_2^D denote D1's and D2's optimal profit, respectively. D1 first decides upon product design k and the wholesale price w_1 of the new products. D1's problem is:

$$\Pi_1^D = \max_{w_1,k} d_1 \left(w_1 - c_1 - k \cdot \eta\right)$$

subject to (3.3)-(3.4). If $k = 1$, then D2 decides upon the wholesale price w_2 of the remanufactured products and its problem is:

$$\begin{aligned} \Pi_2^D &= \max_{w_2} d_2 \cdot (w_2 - c_2) \\ s.t. &\quad 1 - d_1 - d_2 \geq 0 && (3.6) \\ &\quad d_1 \geq d_2 \geq 0 && (3.7) \end{aligned}$$

If $k = 0$, then D2 has no production and its divisional profit is 0. Finally, the retailer decides upon retailer prices based on problem (3.5).

We solve the sequential decision problems by backward induction, starting with the retailer's problem, followed by D2's problem and finally D1's problem. One may argue that the design decision is a strategic one and thus should be determined before the pricing decision (that is, D1 first decides k, then D1 and D2 decide the price of their products simultaneously). We acknowledge that different sequences of the game will result in quantitative differences. However, our numerical results indicate that qualitative results concerning the effects of decentralization and inter-divisional incentive continue to hold.

The optimal solutions for the decentralized scenario are derived in Appendix B and summarized in Table 3.2. Let Ω_{Re}^C and Ω_{Re}^D denote the set

Table 3.2: Optimal Strategy and Solutions for the Decentralized Scenario

Strategy	k^D	Condition	w_1^D	w_2^D	d_1^D	d_2^D
R2-1	1	Ω_{2-1}^D	$\frac{1+c_1+\eta+\delta-c_2}{2}$	$\frac{1-c_1-\eta+\delta+c_2}{4}$	$\frac{1-c_1-\eta+\delta-c_2}{8(1+3\delta)}$	d_1^D
R2-2	1	Ω_{2-2}^D	1	$\frac{\delta}{2}$	$\frac{\delta-c_2}{4(1+3\delta)}$	d_1^D
NR	0	Ω_{NR}^D	$\frac{1+c_1}{2}$	–	$\frac{1-c_1}{4}$	–

Strategy	Π_1^D	Π_2^D	Π_R^D
R2-1	$\frac{(1-c_1-\eta+\delta-c_2)^2}{16(1+3\delta)}$	$\frac{\Pi_1^D}{2}$	$\frac{(1-c_1-\eta+\delta+c_2)^2}{64(1+3\delta)}$
R2-2	$\frac{(\delta-c_2)(1-c_1-\eta)}{4(1+3\delta)}$	$\frac{(\delta-c_2)^2}{8(1+3\delta)}$	$\frac{\delta^2}{16(1+3\delta)}$
NR	$\frac{(1-c_1)^2}{8}$	–	$\frac{\Pi_1^D}{2}$

$$\Omega_{2-1}^D = \left\{(c_1, c_2, \delta, \eta) \left| \frac{1+5\delta+\eta+c_2-(\delta-\eta-c_2)\sqrt{2(1+3\delta)}}{1+6\delta} \le c_1 \le 1-\delta-\eta+c_2 \right.\right\}$$

$$\Omega_{2-2}^D = \{(c_1, c_2, \delta, \eta) \left| \max\left\{1-\delta-\eta+c_2, \frac{1+2\delta+c_2-\sqrt{(\delta-c_2)(\delta-2\eta-6\delta\eta-c_2)}}{1+3\delta}\right\} \le c_1 \right.$$
$$\le \frac{1+2\delta+c_2+\sqrt{(\delta-c_2)(\delta-2\eta-6\delta\eta-c_2)}}{1+3\delta} \;\&\; \eta \le \frac{\delta-c_2}{2(1+3\delta)}\}$$

$$\Omega_{NR}^D = \{(c_1, c_2, \delta, \eta) \left| (c_1, c_2, \delta, \eta) \in \Omega - \Omega_{2-1}^D - \Omega_{2-1}^D \right.\}$$

of (c_1, c_2, δ, η) such that a remanufacturable product design is optimal in the centralized scenario ($k^C = 1$) and the decentralized scenario ($k^D = 1$), respectively.

Proposition 3.3.3 *For the decentralized firm,*
(i) $\Omega_{Re}^D \subset \Omega_{Re}^C$*;*
(ii) $\Pi_1^D + \Pi_2^D \le \Pi_F^C$*, where the equality sign only holds when* $k^C = 0$*; and*
(iii) if $(c_1, c_2, \delta, \eta) \in \Omega_{Re}^D$*, then* $d_1^D = d_2^D < d_1^C$*,* $d_1^D + d_2^D < d_1^C + d_2^C$*.*

Proposition 3.3.3(i) indicates that a remanufacturable product design is less likely to be chosen in the decentralized scenario than in the centralized scenario. This is consistent with our intuition because although a remanufacturable product design benefits the remanufacturing division, it not only cannibalizes the sales of new products (as is illustrated in part (iii) of Proposition 3.3.3), but it also incurs an additional unit cost η to D1, both adversely affecting D1's profit. Another reason is that in a centralized firm, the design decision is optimized by comparing the firm's total profit with and without a remanufacturable product design. On the contrary, in a decentralized firm, the design decision is optimized by comparing D1's profit with and without a remanufacturable product design. Note that the firm's total profit without a remanufacturable product design in a centralized scenario equals D1's profit without a remanufacturable product design in the decentralized scenario while the firm's total profit with a remanufacturable product design is generally greater than D1's profit with a remanufacturable product design. Thus, it is not difficult to see that a remanufacturable design is less preferred in a decentralized firm than in a centralized firm.

Figure 3.3(b) illustrates the optimal strategy of a decentralized firm in the (c_1, η) space for $c_2 = 0.1$ and $\delta = 0.45$. The first observation is that the area of NR is larger while the area of R2 is smaller in Figure 3.3(b) than in Figure 3.3(a) for the same choice of parameters, indicating that non-remanufacturing is more desirable to a decentralized firm than to a centralized firm, which is consistent with Proposition 3.3.3(i). The second observation, according to Proposition 3.3.3 and as depicted in Figure 3.3(b), is that the optimal strategy does not include R1 ($d_1 > d_2 > 0$). This is because when the supply of returned products (originally new products) is not enough to meet the demand of remanufactured products, the retailer, who intends to maximize the retail profit, may increase the supply of the returned products (or equivalently, increase the demand of the originally new products) by decreasing the retail price of the new products and increasing the retail price of the remanufactured products, which, to some extent, relieves the cannibalization toward D1's new product. This explains why in the decentralized scenario, the remanufacturable product design is profitable for D1 only when the constraint $d_1 \geq d_2$ is binding. However, in the case when the supply of returned products is more than the demand of the remanufactured products ($d_1 > d_2$), the retailer's pricing scheme does not alleviate cannibalization. As a result, D1's profit with a remanufacturable product design will be less than that of a non-remanufacturable product design. The third observation is that, in the decentralized scenario, the change in the optimal strategy with respect to c_1 is not "monotone". To see this, in the centralized scenario, the optimal strategy switches from NR to R2 as c_1 increases, while in the decentralized scenario, the optimal strategy changes from NR to R2 and back to NR (Figure 3.3). This difference originates from the fact that when c_1 is sufficiently high, the firm can still generate enough profit from the remanufactured products by jointly pricing the wholesale prices of the new and remanufactured products, such that the demand for new products is not reduced significantly. However, in the decentralized scenario, D1 has to price w_1 high enough to cover its high cost, resulting in much less demand and a nominal profit. As a result, D1 finds it more profitable to choose a non-remanufacturable product design when c_1 is

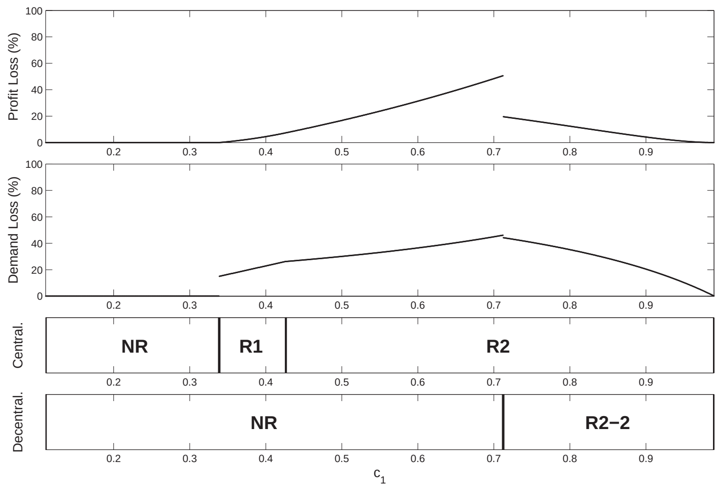

Figure 3.4: Centralized Firm vs. Decentralized Firm (c_2=0.1, $\delta = 0.45$ and $\eta = 0.01$)

relatively high.

Propositions 3.3.3(ii) and 3.3.3(iii) suggest that, even in the case when it is optimal for the manufacturing division to choose a remanufacturable product design, the total profit $\Pi_F^D = \Pi_1^D + \Pi_2^D$ and total demand $d_1^D + d_2^D$ of the decentralized firm are both strictly less than that of the centralized firm. As an outcome of decentralization, D1 increases w_1 and D2 decreases w_2 to maximize their own divisional profit, respectively, leading to a suboptimal profit and sales for the firm. Figure 3.4 depicts the effects of decentralization on total profit, total demand and the optimal strategy when $c_2 = 0.1$, $\delta = 0.45$ and $\eta = 0.01$. The first two subfigures in Figure 3.4 provide the ratio of profit loss $(1 - \frac{\Pi_F^D}{\Pi_F^C})$ and sales loss $(1 - \frac{d_1^D + d_2^D}{d_1^C + d_2^C})$ due to decentralization as c_1 varies, which can be as high as 51% and 46%, respectively. Such a drastic negative decentralization effect usually occurs when the optimal strategy changes from R2 to NR (see the last two subfigures, which illustrates the optimal strategies in the centralized and decentralized scenarios, respectively).

As illustrated in Proposition 3.3.3, cost ownership and product cannibalization foil D1's remanufacturable product design, and thus, result in a lower total profit than the firm-wide benchmark profit Π_F^C. Therefore, it is in a decentralized firm's best interest to introduce a coordination mechanism and to incentivize D1 to design new products to be remanufacturable. A natural conjecture would be that the firm achieves coordination by making D2 responsible for all or a portion of the cost associated with a remanufacturable product design (η). However, according to Propositions 3.3.3(ii) and 3.3.3(iii), $\Pi_1^D + \Pi_2^D < \Pi_F^C$ and $d_1^D = d_2^D < d_1^C$ both hold when $\eta = 0$. Then what if more than η is allocated to the remanufacturing division? Does transfer pricing enable the firm to achieve the first-best profit? If so, can such a coordination scheme induce the voluntary participation of both divisions? We answer these questions in the next section.

3.4 Inter-Divisional Coordination

3.4.1 Transfer Pricing

A firm is organized into responsibility centers (divisions) and a well-established "transfer pricing" is essential whenever goods or services are transferred among the divisions. If the transfer price fails to reflect the true value of resources, it becomes difficult to fairly measure the divisional performance. As a result, managers could make inappropriate decisions that reduce firm value (Zimmerman, 2005). Thus, we first consider a transfer pricing scheme similar to Toktay and Wei (2011), in the sense that D2 has to pay a fixed amount τ to D1 for each unit D1 produces, where τ can be any real value and is determined by the firm, who is a profit maximizer and is neutral toward a non-remanufacturable and remanufacturable product design. Note that $\tau \in (0, \eta]$ represents the cost allocation scheme and $\tau < 0$ means that D1 pays a per-unit transfer to D2. In Toktay and Wei (2011), the manufacturing division can only produce remanufacturable products and both divisions have to follow the transfer pricing scheme, which, in reality, may not be in the best interest of both divisions, and thus, such a coordination scheme is difficult to implement in a decentralized firm. To this end, we propose a transfer pricing scheme that distinguishes itself from Toktay and Wei's scheme in two ways: 1) D1 has the *option* of choosing a remanufacturable or non-remanufacturable product design; and 2) D2 has the *option* of participating in the coordination scheme. Thus, our transfer pricing scheme is essentially a voluntary scheme and is more realistic in a decentralized firm.

Under our transfer pricing scheme, if D1 chooses a remanufacturable product design, then D2 has the *option* to participate; that is denoted by j, where $j = 0$ represents when D2 does not follow the coordination scheme, no matter whether it remanufactures or not (note if D2 remanufactures but does not participate, then the problem is essentially equivalent to the decentralized problem without the incentive discussed in Section 3.3.3). In addition, $j = 1$ represents when D2 follows the coordination scheme and remanufactures the returned products. In the latter case, D2 pays a variable amount τ to D1 for each unit D1 produces. Note that if D1 designs new products to be non-remanufacturable ($k = 0$), then D2's profit is always 0 and hence no transfer occurs. We use the superscript V to denote the optimal solutions in the presence of the transfer pricing scheme. Given the transfer pricing scheme and the region Ω^C_{Re}, D1's problem becomes $\Pi^V_1 = \max\limits_{w_1,k} d_1(w_1 - c_1 - k \cdot \eta + j \cdot k \cdot \tau)$ subject to constraints (3.3)-(3.4). If $k = 1$, then D2's problem becomes $\Pi^V_2 = \max\limits_{w_2,j} d_2 \cdot (w_2 - c_2) - j \cdot d_1 \cdot \tau$ subject to constraints (3.6)-(3.7). The retailer's problem remains the same as formulated by (3.5).

Now, given the transfer pricing scheme, will both divisions voluntarily join the coordination program? The success of such an inter-divisional coordination requires the profit of both divisions to be greater than when in the absence of an incentive (the decentralized scenario in Section 3.3.3). That is, $\Pi^V_1 \geq \Pi^D_1$ and $\Pi^V_2 \geq \Pi^D_2$ (referred to as "participation constraints") whenever the coordination scheme exists, where Π^V_1 and Π^V_2 denote D1 and D2's profits with the option of design/coordination, respectively. Based on the numerical results, we make the following observations.

Observation 1 *Given $(c_1, c_2, \delta, \eta) \in \Omega^C_{R2}$, there exists a τ^V such that the first-best optimal firm profit can be achieved (i.e., $\Pi^V_1 + \Pi^V_2 = \Pi^C_F$) when $\tau = \tau^V$. Moreover, $\Pi^V_2 = \Pi^D_2$, $\Pi^V_1 > \Pi^D_2$, $d^V_i = d^C_i$ ($i = 1, 2$) and $\tau^V > 0$.*

Observation 1 reveals that under the transfer pricing scheme, the decentralized firm can always achieve the optimal total profit and optimal sales level of both new and remanufactured products (if applicable) as in the centralized scenario when $(c_1, c_2, \delta, \eta) \in \Omega^C_{R2}$, where Ω^C_{R2} is a subset of Ω^C_{Re}. Recall that decentralization can result in a lower profit and fewer sales, as stated in Propositions 3.3.3(ii) and (iii). Thus, the transfer pricing scheme benefits the firm in both aspects. Correspondingly, D2's profit is the same as in the decentralized scenario without incentive and D1's profit increases $\Pi^C_F - \Pi^V_2 - \Pi^V_1 > 0$. In other words, in the equilibrium, D2's participation constraint $\Pi^V_2 \geq \Pi^D_2$ is always binding while D1's participation constraint

$\Pi_1^V \geq \Pi_1^D$ is not binding. This finding can be explained by the fact that D1 has an advantage over D2 in the sense that D1 decides on the product design (to make the product remanufacturable or not) and can limit d_2, the production quantity of D2, by controlling its own production quantity d_1. As a result, D2 needs to incentivize D1 to choose the remanufacturable product design and increase the production quantity of new products.

Proposition 3.4.1 *Given the transfer pricing scheme,* $\Pi_1^V + \Pi_2^V < \Pi_F^C$ *for any* τ *when* $(c_1, c_2, \delta, \eta) \in \Omega_{R1}^C$.

Proposition 3.4.1 reveals that the transfer pricing does not always enable the firm to achieve the optimal total profit. In particular, when $(c_1, c_2, \delta, \eta) \in \Omega_{R1}^C$, the firm's total profit is always below the first-best for any τ. Note, in the centralized scenario, the firm chooses strategy R1 when remanufacturing is not sufficiently profitable, so that it is irrational to remanufacture all returned products. It is not hard to see that, ceteris paribus, D2 may not have much of an incentive to compensate D1 to enhance D2's profit in the decentralized scenario. To further evaluate the profit recovery performance of an incentive scheme, especially when $(c_1, c_2, \delta, \eta) \in \Omega_{R1}^C$, we introduce the notion of *effectiveness* (E), as defined by

$$E = \frac{\left(\Pi_1^S + \Pi_2^S\right) - \left(\Pi_1^D + \Pi_2^D\right)}{\Pi_F^C - \left(\Pi_1^D + \Pi_2^D\right)} \times 100\%$$

where S refers to the incentive scheme under consideration. The denominator of this ratio is the firm-level profit gap between the centralized scenario and the decentralized scenario, while the numerator is the firm profit gap between the scenario with the incentive scheme under consideration and the decentralized scenario. By definition, $E \in [0, 100\%]$. Higher effectiveness represents higher profit recovery, and thus, better performance of the given incentive scheme. An incentive scheme that can induce the first-best result has $E = 100\%$ while an inactive incentive scheme has $E = 0$. Figure 3.5 illustrates the effectiveness of the transfer pricing scheme as transfer price τ varies. Figure 3.5(a) depicts the effectiveness under two sets of parameters such that R1 is the optimal strategy in the centralized scenario while Figure 3.5(b) depicts the effectiveness under the two sets of parameters such that R2 is the optimal strategy in the centralized scenario. As shown in Figure 3.5(b), there always exists a τ such that the $E = 100\%$ can be achieved

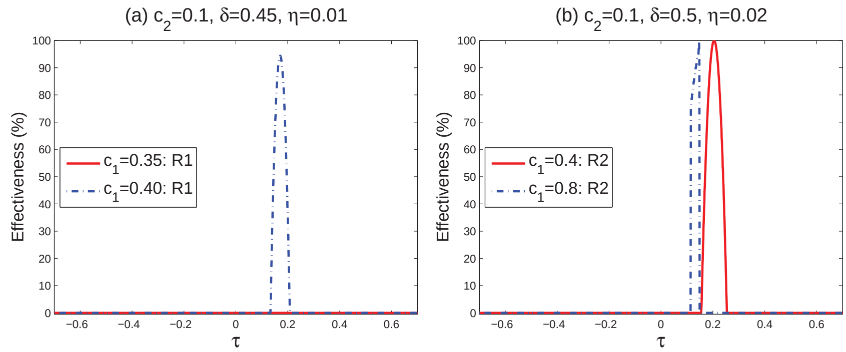

Figure 3.5: Effectiveness of Transfer Pricing Scheme

if $(c_1, c_2, \delta, \eta) \in \Omega^C_{R2}$. Note from Figure 3.5(a), when $(c_1, c_2, \delta, \eta) \in \Omega^C_{R1}$, the total firm profit may or may not increase as τ varies. For example, when $c_1 = 0.4, c_2 = 0.1, \delta = 0.4$ and $\eta = 0.01$ (the dashed line in Figure 3.5(a)), τ induces an increase in the total profit and high effectiveness, but the firm-wide benchmark profit Π^C_F is not attainable for any τ; when τ is too large, the potentially large cash outflow prevents the remanufacturing division from participating in the transfer pricing scheme; when τ is too small, the manufacturing division cannot benefit from the transfer pricing scheme, and hence, it will design new products to be non-remanufacturable. Even worse, when $c_1 = 0.35, c_2 = 0.1, \delta = 0.4$ and $\eta = 0.01$ (the solid line in Figure 3.5(a)), the transfer pricing scheme is not in effect in any case (*i.e.*, $E = 0$). This observation suggests that we need to explore other coordination schemes to overcome this problem.

3.4.2 Two-Part Coordination Scheme

Observation 1 shows that the firm-wide benchmark profit can always be achieved under the single transfer pricing scheme for any $(c_1, c_2, \delta, \eta) \in \Omega^C_{R2}$. Proposition 3.4.1, however, signifies that given any $(c_1, c_2, \delta, \eta) \in \Omega^C_{R1}$, the first-best total profit is not ensured when divisional participation and design decisions are both endogenous. This implies that, in addition to implementing transfer pricing, the decentralized firm should also redistribute the profit between the two divisions so that both divisions can benefit from the coordination. In this regard, we propose a two-part coordination scheme as follows. The participation constraints and the transfer price τ are defined as in the single transfer pricing scheme. Besides τ, D2 also pays D1 a fixed

Table 3.3: Comparison of Coordination Schemes

Scheme	Transfer Pricing		Fixed Lump-sum		Two-part Scheme	
Condition	Ω^C_{R1}	Ω^C_{R2}	Ω^C_{R1}	Ω^C_{R2}	Ω^C_{R1}	Ω^C_{R2}
Achieve Opt.?	No	Yes	No	Yes	Yes	Yes
Payer of τ^{opt}	n/a	D2	n/a	n/a	D1	D1/D2
Payer of f^{opt}	n/a	n/a	n/a	D2	D2	D1/D2
Robustness	n/a	Sensitive	n/a	Robust	Sensitive	Sensitive w.r.t τ Robust w.r.t f

$\tau^{opt}(f^{opt})$: optimal $\tau(f)$ that induces the first-best result.

amount f. f is determined by the firm and is independent of the sales of new or remanufactured products. Note that f can be any real value, where a negative f means that D1 pays a lump sum to D2. In addition, no transfer, variable or fixed, occurs should D1 design new products to be non-remanufacturable. We use superscript T to denote the optimal solutions in the presence of the two-part coordination scheme. As such, D1's problem is $\Pi_1^T = \max\limits_{w_1,k} d_1(w_1 - c_1 - k\cdot\eta + j\cdot k\cdot\tau) + k\cdot j\cdot f$ subject to constraints (3.3)-(3.4). If $k=1$, then D2's problem becomes $\Pi_2^T = \max\limits_{w_2,j} d_2\cdot(w_2-c_2) - j\cdot d_1\cdot\tau - j\cdot f$ subject to constraints (3.6)-(3.7).

Recall that the participation constraints are $\Pi_1^T \geq \Pi_1^D$ and $\Pi_2^T \geq \Pi_2^D$. However, the two-part coordination scheme allows for weaker "participation constraints" $\Pi_1^T + \Pi_2^T > \Pi_1^D + \Pi_2^D$ because the lump sum f reallocates the total profit and is allowed to be any value, positive or negative. The comparison of transfer pricing (τ), fixed lump-sum scheme (f) and two-part scheme (τ, f) is summarized in Table 3.3. We will discuss Table 3.3 in more detail below.

Proposition 3.4.2 *In the presence of the two-part coordination scheme,*

(i) $\tau^T = \frac{c_1+\eta-1}{2} < 0$, $\Pi_1^T = f^T > 0$ *and total transfer* $d_1^T\cdot\tau^T + f^T \geq 0$ *when* $(c_1, c_2, \delta, \eta) \in \Omega^C_{R1}$*;*

(ii) there exists some $f^T > 0$ *such that* $\tau^T = 0$ *when* $(c_1, c_2, \delta, \eta) \in \Omega^C_{R2}$*; and*

(iii) $\Pi_F^T = \Pi_F^C$, $\Omega^T_{Ri} = \Omega^C_{Ri}$ *and* $d_i^T = d_i^C$ *(*$i = 1, 2$*) for any* (c_1, c_2, δ, η)*.*

Proposition 3.4.2 indicates that the benefits of our proposed internal incentive to a decentralized firm are twofold. On the one hand, the incentive can always enable the firm to achieve the optimal firm-wide profit and sales level as in the centralized scenario for any parameter set (c_1, c_2, δ, η). By contrast, as is illustrated in the first row of Table 3.3, the single-parameter scheme cannot guarantee the first-best result. On the other hand, the internal incentive motivates D1 to choose a remanufacturable product design as if it were the planner in a centralized firm. Recall that new products are designed to be remanufacturable in fewer cases due to decentralization, as stated in Proposition 3.3.3(i). Therefore, the two-part coordination scheme encourages the manufacturing division in a decentralized firm to choose a remanufacturable product design.

Moreover, Proposition 3.4.2 has two interesting implications. First, one would expect τ to be positive, because D1, who determines design decision k, has more "power" over D2, and thus, D2 would have to compensate D1 for choosing a remanufacturable product design. However, when $(c_1, c_2, \delta, \eta) \in \Omega_{R1}^C$, it is actually optimal for D1 to "compensate" D2 in the amount of τ^T for each new unit D1 produces ($\tau^T < 0$). Note that product cannibalization is prominent when $(c_1, c_2, \delta, \eta) \in \Omega_{R1}^C$. Under such a circumstance, the per-unit transfer τ^T from D1 to D2 motivates D2 to raise the wholesale prices of the remanufactured products ($w_2 = \frac{\delta(w_1-\tau)+c_2}{2}$, as shown in the proof of Proposition 3.4.2), and thus, alleviates the side effects of cannibalization on the sales of new products, which is beneficial to D1. Proposition 3.4.2(i) highlights that if τ is restricted to be non-negative, then the first-best firm profit cannot always be achieved. In particular, a fixed lump-sum scheme without a transfer price (*i.e.,* $\tau = 0$) generally fails to induce the first-best result, because f cannot affect the optimal wholesale prices. In addition, D2 has to pay D1 a lump sum $f^T > 0$, because $\Pi_1^T = f^T$ when $(c_1, c_2, \delta, \eta) \in \Omega_{R1}^C$. To determine f^T, recall that the participation constraint $\Pi_1^T \geq \Pi_1^D$, or equivalently $f^T \geq \Pi_1^D$, needs to be satisfied while $\Pi_1^D \geq \frac{(1-c_1)^2}{8} > 0$, according to Table 3.2. Thus, D2 will have to make a fixed transfer $f^T > 0$ to motivate D1 to voluntarily design new products to be remanufacturable. Also note that $w_1^T + \tau^T = c_1 + \eta$ and $f^T \geq 0$ are consistent with the literature on franchising that suggests selling at the marginal cost and charging franchise fees to achieve channel coordination (Cachon and Lariviere 2005). In our context, although D1 does not literally sell new products to D2, a portion of D1's products will be collected by D2 and becomes D2's production input. In some sense, D1 "sells" new products to D2, who later sells them in the form of remanufactured products. Therefore, franchising theory can still be applied. In particular, the total transfer should be positive so that the manufacturing division has the incentive to voluntarily choose a remanufacturable product design.

As stated in Proposition 3.6(ii), the second implication is that a fixed lump sum is sufficient to ensure a firm-wide benchmark profit and sales level when c_1 is relatively large (the same condition for R2 to be optimal in the centralized scenario). To help explain this, recall that transfer price τ serves as an instrument to control product cannibalization. When $(c_1, c_2, \delta, \eta) \in \Omega^C_{R2}$, however, D1 can also manipulate its production quantity d_1 to restrict D2's production quantity d_2, which serves the same purpose as τ, and thus, τ can be replaced. The total transfer $\tau^T \cdot d_1^T + f^T$, which equals f^T when $\tau^T = 0$, must be positive to induce D1's voluntary participation because $\Pi_1^T \geq \Pi_1^D$ needs to be satisfied. Note that the direction of τ and f can be positive or negative if the firm simultaneously employs both τ and f to coordinate the two divisions. Table 3.3 summarizes the direction of the variable and fixed payment under different schemes.

Similar to Figure 3.5, in Figure 3.6, we depict the effectiveness of the two-part coordination scheme as transfer price τ varies and f is optimized given each τ. When the set of parameters is such that R1 is optimal in the benchmark setting (Figure 3.6(a)), 100% effectiveness can be achieved at a particular point ($\tau^T = \frac{c_1+\eta-1}{2}$ and f set to the corresponding optimal quantity). In addition, according to Figure 3.5(a), when $c_1 = 0.40, c_2 = 0.45, \delta = 0.5, \eta = 0.01$, the effectiveness loss is more than 5% for any τ under the transfer pricing scheme. By contrast, Figure 3.6(a) indicates that, for the same set of parameters, the two-part coordination scheme can help the firm to control the effectiveness loss to less than 5% for a wide range of τ, provided f is appropriately chosen. When the set of parameters is such that R2 is optimal in the benchmark setting (Figure 3.6(b)), 100% effectiveness can be achieved if τ falls within a certain range. In the example of Figure 3.6(b), τ must be no less than -0.57 (-0.18) when $c_2 = 0.1, \delta = 0.5, \eta = 0.02$ and $c_1 = 0.4$ ($c_1 = 0.8$) to ensure 100% effectiveness. In fact, when τ falls into the above range, a multiple of f can induce the first-best result. To better capture such characteristics, in our context, a scheme is called robust with respect to the scheme variable τ (f) if the effectiveness only gradually decreases when τ (f) deviates from τ^{opt} (f^{opt}) within a small neighborhood. Otherwise, the scheme is sensitive with respect to that scheme variable. By the above definition, we do not need to discuss the robustness of a scheme in

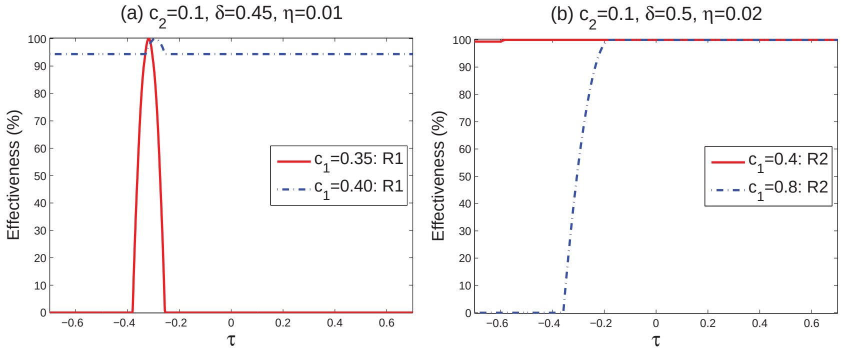

Figure 3.6: The Effectiveness of Two-part Coordination Scheme with Optimized f

the regions where the coordination scheme cannot induce the first-best result for any τ or f. As shown in Table 3.3, a coordination scheme is generally robust with respect to the fixed lump-sum while being sensitive with respect to the transfer price. This is because, for any f within a small neighborhood of f^{opt}, the participation constraints of both divisions are still satisfied while the wholesale prices, demand, the firm profit remain unchanged. Thus, all such f's are associated with 100% effectiveness. In contrast to the fixed lump sum, the transfer pricing generally affects wholesale prices, demand and total profit. Thus, a small deviation from τ^{opt} may result in less of a firm profit or non-participation of one division.

In summary, we demonstrate that the two-part coordination scheme can always result in the firm-wide benchmark profit. The primary reason for this is that transfer pricing does not always work in the presence of participation constraints, stemmed from firm decentralization and the manufacturing division's control over product design. While there may be multiple mechanisms by which two divisions can be coordinated, we have provided one scheme which is simple and effective.

3.5 Conclusions

In this chapter, we seek out insights for firms who face divisional conflict and are concerned with the cannibalization from remanufactured products, as well as for firms who wish to increase profits by coordinating their manufacturing and remanufacturing operations. Motivated by examples from industry, we consider a firm consisting of a manufacturing division and a remanufacturing division, and a retailer through whom the firm sells all of its products. Given this construct, we explore the optimal strategy with respect to design architecture and pricing in centralized and decentralized scenarios. We find that it is optimal for the centralized firm to undertake remanufacturing with a high production cost of new products, a low remanufacturing cost, a high value-added from remanufacturing, and a low cost of the remanufacturable product design. However, the manufacturing division of the decentralized firm would be more likely to choose a non-remanufacturing design to avoid a potential increase in production cost and competition from the remanufactured products. By comparing the two scenarios, we demonstrate that firm decentralization and divisional conflict reduce both profits and total sales; in addition, they prevent the firm from offering a remanufacturable product design. Therefore, it is to the firm's advantage to implement inter-divisional coordination mechanism to improve overall performance.

Thus, we investigate several incentive mechanisms that coordinate a firm's manufacturing and remanufacturing divisions. Motivated by Toktay and Wei (2011), we first examine the effectiveness of transfer pricing. We show that transfer pricing cannot always induce the remanufacturable product design or the first-best profits because the participation constraints of the manufacturing and remanufacturing divisions cannot be satisfied simultaneously. In fact, this occurs when it is optimal for a firm to remanufacture only a fraction of the returned products in the centralized scenario. Thus, the decentralized firm should not only use the transfer price to achieve the highest profit. To probe deeper, we propose an inter-divisional coordination scheme, with a transfer price for each unit the manufacturing division produces and a fixed lump sum payment that is independent of the sales of new or remanufactured products. We prove that this two-part coordination scheme always enables the firm to invariably achieve the first-best total profit and sales level and can effectively promote a remanufacturable product design. An interesting finding is that the inter-divisional transfer is not always from the remanufacturing division to the manufacturing division. We illustrate that, in the case when it is optimal to remanufacture only a fraction of the used products in the centralized scenario, a two-parameter inter-divisional coordination scheme with a per-unit transfer from the manufacturing division to the remanufacturing division and a lump sum payment from the remanufacturing division to the manufacturing division is required to achieve the first-best outcome. However, in the case when remanufacturing is sufficiently profitable so that it is optimal to remanufacture all used products in the centralized scenario, a one-parameter incentive with either a lump sum or a transfer price paid by the remanufacturing division to the manufacturing division is sufficient. The reason is that product cannibalization can be managed through production quantity control. Finally, we find that the fixed lump-sum scheme performs more robustly than the transfer price.

Our results and discussions are based, in part, on the modeling stipulation that the wholesale prices of new and remanufactured products must be no more than the maximum customer WTP (*i.e.*, $w_1, w_2 \leq 1$). Although this assumption seems plausible, we find that it is not always optimal for the firm to price new products below the maximum customer WTP. We considered, as a modeling extension, the case when wholesale prices are allowed to exceed the maximum customer WTP. The most noticeable observation is that the decentralized firm is more likely to choose a remanufacturable product design without a price constraint than with a price constraint, which implies that under certain circumstance, the manufacturing division can increase its profit by designing new products to be remanufacturable and selling them to the retailer at a price that is higher than the maximum customer WTPs. The explanation is that, in some cases, selling remanufactured products is so profitable that the retailer is willing to adjust the retail price of new products to be less than the maximum customer WTP (and bear the loss from the new products) in order to guarantee enough returns for remanufacturing. Essentially, the manufacturing division extracts profit from the retailer and the remanufacturing division by optimally pricing new products, even if the price is above the maximum customer WTP.

So far, our discussion is limited to the case of a firm selling all products to its end-users through a retailer. In practice, some companies integrate retailing (vertical integration) and sell both new and remanufactured products directly to their end-users. Therefore, we also study the role of a retailer in a closed-loop supply chain by comparing the firm's optimal pricing, product design for remanufacturing and profitability with and without an independent retailer. We find that in the centralized scenario, the firm's profit and the demand for new and remanufactured products (if applicable) doubles when the firm integrates retailing because vertical integration completely eliminates double marginalization. By contrast, in the decentralized scenario, vertical disintegration benefits the firm in terms of both sales quantity and profit and encourages the manufacturing division to undertake a remanufacturable product design, which is because the retailer's optimal pricing scheme alleviates product cannibalization and the manufacturing division can extract additional surplus from the retailer. Therefore, in the absence of an independent retailer, the manufacturing division will always design new products to be non-remanufacturable in order to avoid product cannibalization, the production cost increase, and potential profit loss. In all, to maximize profit and boost sales, the centralized firm should consider retail integration while the decentralized firm should strategically disintegrate retailing.

In closing, we acknowledge that our discussion is restricted to the situation of when all used products can be returned and remanufactured and when the collection cost is negligible. Considering that lower return and remanufacturing rates and a higher collection cost should lead to less of a cannibalization risk for the decentralized firm, our model focuses on the most unfavorable conditions for remanufacturing operations.

CHAPTER 4

THE EFFECTS OF PATENT TERM EXTENSION AND PHARMACEUTICAL STEWARDSHIP PROGRAM ON GREEN PHARMACY

"The future will be green, or not at all."

– Jonathon Espie Porritt.

4.1 Introduction

The issue of potential environmental impact by pharmaceuticals has gained increasing attention in the last two decades. Since the 1980s, a number of studies have examined the origin, occurrence and consequence of pharmaceuticals and personal care products (PPCPs) in surface, subsurface, and drinking waters (see reviews by Halling-Sørensen et al. 1998, Daughton 2001 and Tong et al. 2011). For example, the studies by Kidd et al. (2007) and Vajda et al. (2008) showed the feminization of male fish and female-biased sex ratio as the result of freshwater exposure to synthetic estrogenic substances (source of female sex hormones) in Ontario, Canada and Colorado, U.S., respectively. Another example is the veterinary use of the nonsteroidal anti-inflammatory drug diclofenac, which resulted in catastrophic decline of three vulture species of *Gyps* in Southeast Asia (Oaks et al. 2004). Kolpin et al. (2002) found that pharmaceuticals, hormones, and other organic wastewater contaminants were present in over 80% of the streams sampled across the United States. The occurrence of PPCPs as trace environmental pollutants is primarily originated from consumer use and actions rather than leaks in the manufacturing process (Daughton 2003a). The U.S. Centers for Medicare & Medicaid Services (CMS) and the Department of Health and Human Services (DHHS) estimate that $406.1 billion will be spent on prescription drugs in 2020 (CMS/DHHS 2014), among which 10 to 33 percent will be unused (Grasso et al. 2009). Another survey by Trueman et al. (2010) suggested that the annual primary and community care prescription medicines wastage in England costs about GB£300 million, accounting for 4% of the medication cost.

The main causes for waste include, among other things, early recovery before all dispensed medicines are taken, ineffectiveness or unwanted side effects, prescription change by the physicians, non-adherence and non-compliance with drug treatment. (Morgan 2001, Ruhoy and Daughton 2008, Trueman et al. 2010). Unwanted pharmaceuticals can reach the environment when disposed in the garbage, toilet or sink. In fact, in a study conducted by Kotchen et al. (2009), 73.2% of 1005 households in the central coast of California threw unused medications in the rubbish or flushed them down the toilet or sink. Only 11% of the sampled households returned unused medications to a pharmacy or dropped them off at a hazardous waste center.

With the deteriorating situation of eco-toxicity of pharmaceuticals and mixtures of medicines, the U.S. Environmental Protection Agency (U.S. EPA), the European Environment Agency (EEA), and many other organizations are advancing the practice of *"green pharmacy"* (Daughton 2003a, 2003c, EEA 2010). According to EEA, *green pharmacy* is the design of pharmaceutical products and processes that eliminates or reduces the use and generation of hazardous substances (EEA 2010). In other words, *green pharmacy* focuses on the innovation of "benign by design" drugs while keeping the safety and efficacy of the drug unaffected by the innovation.

Pharmaceutical companies are now taking steps to pursue green pharmacy. For instance, Schering-Plough Pharmaceuticals, LLC modified its birth control products by using natural estrogens paired with a biodegradable progesterone (Lubick, 2008). Major pharmaceutical companies, as well as policymakers and scientists, are gathering to discuss how to make drugs more environmentally friendly at conventions such as the International Conference on Sustainable Pharmacy and the American Chemical Society's Green Institute Pharmaceutical Roundtable (Knoblauch 2009).

A major obstacle in achieving green pharmacy is the high R&D expense of inventing green pharmaceuticals or redesigning existing products to be greener by identifying or using biodegradable ingredients or agents. To alleviate this, one possible incentive is to offer patent term extension to pharmaceutical companies that formulate greener drugs. The award of a patent allows an inventor to temporarily and exclusively use its invention, and the importance of patents is significant to the pharmaceutical sector (Mansfield et al. 1981, Competition DG, 2009). Currently, pharmaceutical companies may obtain patent extension with new formulation, new routes of administration for known drugs, stereoselectivity or chiral switches, new uses, fixed-dose combinations, polymorphism (Kvesic 2008, Gupta et al. 2010). But none of these reasons is related to green pharmacy. EEA, however, has proposed the idea of implementing patent extension to encourage pharmaceutical companies to develop substances with less environmental impact (EEA 2010). Given the ever-growing costs of drug development, such incentive can encourage the consideration of degradable green drugs (Shah 2010), foster stewardship programs that tie both environmental and human health together (Daughton 2003b), and help make *green pharmacy* a part of the company's strategic plan (Clark et al. 2010), especially for the innovative company. In addition, the patent system not only helps to stimulate innovation, but also encourages technical information disclosure (Merges 1988). If patent extension can be awarded to advance green pharmacy, then green technology can be easily and widely implemented after the patent expiration.

As highlighted above, patent incentives could stimulate pharmaceutical companies to invest in green pharmacy. Thus, in this chapter, we answer the following questions: Under what conditions can the implementation of a pharmaceutical patent term extension induce green pharmacy? What are the impacts of the patent term extension on environmental performance, the availability of pharmaceutics, and the profitability of the firms? What is the optimal length of patent extension? To this end, we consider an innovative company who collects monopoly profits for its patented medicine and faces competition from a generic rival after the patent expires. Both the innovative company and the generic company maximize their own profits. Their products, if not appropriately disposed of, could exert negative impact on the environment. Both firms can achieve green pharmacy and thus reduce adverse environmental impact by investing a fixed amount. In the case when the innovative company obtains patent extension by investing in green pharmacy, the generic rival can take a free-ride after the extended patent expired. To determine the optimal extended patent term, we assume that the regulator considers two stakeholders: the number of patients who cannot afford the pharmaceutical products, and the potential contamination of unwanted pharmaceuticals to the surface, subsurface, and drinking waters.

We demonstrate that a patent term extension can encourage the innovative company to invest in green pharmacy. In particular, the patent incentive is effective when fixed investment cost is low, the extended term of the patent is long or competition intensity is high. In fact, the more competitive is the market, the more is the innovative company willing to invest in green pharmacy, even under shorter extended terms of the patent. As a result, the regulator can induce green pharmacy with a short extended term when market competition is intensive. Specifically, the optimal extended term is finite when the regulator is seeking the balance of the affordability of medicine and the environmental protection; in general, a longer extended term is needed to induce green pharmacy when the fixed investment cost increases. Nevertheless, we also show that implementing the patent term extension can be suboptimal, especially when the regulator values the affordability of medicines over environmental stewardship.

Another possible approach for the regulator to promote green pharmacy is to impose a pharmaceutical take-back program. Similar to the product stewardship programs for items such as electronics and beverage containers, residents would be able to deliver their unused medicines to appropriate entities for safe and effective disposal; and drug manufacturers would be required to run and pay for the program. Pharmaceutical take-back programs exist in many countries, such as Canada (Health Products Stewardship Association), Australia (Return Unwanted Medicines Project), and most countries in Europe (EEA 2010). In the U.S., the Alameda County Safe Drug Disposal Ordinance, first adopted in June, 2012, is a first-in-the-nation pharmaceutical extended producer responsibility program, and was upheld by the U.S. Court of Appeals for the Ninth Circuit in September, 2014. Heidi Sanborn of the California Product Stewardship Council pointed out that shifting responsibility for drug waste to manufacturers could lead to greener design in terms of "what it's made out of, how it works, (and) how long it lasts" (Bartolone 2014).

Thus, in this chapter, we also address the following questions: which environmental policy is more effective in inducing green pharmacy, the patent term extension, the take-back regulation, or the combination of both? Intuitively, when both companies are subject to the take-back regulation and the compliance cost associated with the take-back regulation is independent of the choice of green pharmacy, pharmaceutical companies will neither go green nor bear all the compliance cost; some of the environmental cost will eventually be transferred to the consumers. Furthermore, we demonstrate that adding the take-back regulation on top of the patent term extension can potentially reduce firm profit and generally require a longer extended patent term. Yet, we also conclude that the combined policy outperforms the patent term extension when the compliance cost is relatively small, the fixed investment cost and the collection rate are relatively large, the competition is either nominal or sufficiently intensive, and the environmental issue is rather urgent.

To address the issue that the take-back regulation alone cannot promote green pharmacy, we propose a modified take-back policy such that companies with green pharmacy pay a lower compliance cost per unit than if without green pharmacy. Compared with the patent term extension that can only motivate the innovative company to invest in green pharmacy, the modified take-back regulation can sometimes encourage both companies to invest. Also, the modified take-back regulation is better than the patent extension when the competition intensity is relatively high. Last, when implementing a combined policy of both patent term extension and take-back regulation, using the modified cost structure is typically superior to the traditional cost structure. Interestingly, under this modified combined policy, the innovative company may find it profitable to go green without requesting patent extension. The intuition here is that company is not obliged to reveal the ingredients or process of green pharmacy, which alleviates competition from the generics by exclusively enjoying the benefits of green pharmacy it invents. However, implementing only the patent term extension can generate less social and environmental impact than a combined policy when the needs of pharmaceuticals are compelling or when the compliance cost is relatively large.

The rest of this chapter is organized as follows. We first review related literature in Section 4.2. In Section 4.3, we formally define the green pharmacy, patent term extension and pharmaceuticals take-back regulations, and introduce some main assumptions. In Section 4.4, we study the patent term extension by developing the decision model and establishing properties of its optimal solution. Then, in Section 4.5, we explore implications of the take-back regulation. In Section 4.6, we study how compliance cost structure affects the optimal strategy of the pharmaceutical companies and the regulator. Section 4.7 concludes this chapter and discusses the scope and limitation of this study. The proofs of propositions, lemmas, and the corollary are provided in Appendix C.

4.2 Relation to Literature

Our study is related to three streams of literature. First, a fast-growing stream of works in operations management addresses the issues related to product take-back regulations (*e.g.*, Toyasaki et al. 2011, Atasu and Subramanian 2012, Atasu et al. 2013, Gui et al. 2013). In particular, a number of researchers studied how the take-back regulation affects product design decisions of manufacturers (*e.g.*, Zuidwijk and Krikke 2008, Plambeck and Wang 2009, Esenduran and Kemahlıoğlu-Ziya 2015). However, a pharmaceutical stewardship program is different from traditional product stewardship programs in several ways. First, the goal of a pharmaceutical stewardship program is not only to reduce pharmaceuticals in the environment but to reduce drug abuse and accidental poisoning as well. The second difference is that the reverse channel of pharmaceutical products is still strictly regulated, especially for controlled substances. For example, the Disposal of Controlled Substances Final Rule by the U. S. Drug Enforcement Administration (DEA) stated that a person may not dispose pharmaceutical controlled substances for a non-member of her household and that controlled substance can only be returned to a DEA authorized collector (DEA 2014). The third difference is that a pharmaceutical stewardship program can hardly bring any economic benefit to the participating pharmaceutical companies because pharmaceutical products have almost no end-of-life value. In fact, such a program usually requires that pharmaceutical products be safely disposed of through certified incineration. As a result, regulations or incentives are needed to ensure the implementation of a pharmaceuticals take-back program. We contribute to this literature by extending the analysis of the take-back regulation to pharmaceuticals.

The second stream of literature explores the interactions between patent, price and innovation (*e.g.*, Kitch 1977, Gilbert and Shapiro 1990, Jaffe 2000). In the pharmaceutical industry, relevant studies surged after the Drug Price Competition and Patent Term Restoration Act of 1984 (known as the "Hatch-

Waxman Act") was implemented (*e.g.*, Grabowski and Vernon 1992, Bottazzi et al. 2001, Lee 2003). In this study, we focus on the role of patent term extension in the investment and development of environmentally friendly pharmaceutical substances, as suggested by EEA (2010). We believe that no study has been conducted to validate this proposal. Hence, there is a clear need for research to analyze and compare the patent term extension with other existing regulatory policy. In this study, we make the first attempt and obtain guidelines for choosing the optimal length of the patent extension.

Finally, our study is related to the literature that examines the choice of the policy instruments and the efficiency implication of regulatory policies on the environment (*e.g.*, Palmer and Walls 1997, Calcott and Walls 2000, Walls 2006, Krass et al. 2013). Our study differs from theirs in several ways. First, we consider patent term extension as a policy instrument to induce environmentally friendly design, which has rarely been studied before. Patent protection is critical to the pharmaceutical industry, and thus has a high potential for realizing the goal of environmental protection. Second, in this chapter, the availability of pharmaceuticals is an important consideration for the regulators. Pharmaceuticals differ from other commodities in that consumer surplus or producer surplus is not as crucial as the number of people who cannot afford the drug. Therefore, we incorporate the affordability rather than consumer surplus into the model of the regulator. Third, we also propose a new compliance cost structure that relates the unit compliance cost to the choice of green pharmacy. The traditional compliance cost structure fails to promote sustainable product design because it is independent of the greenness of products. We conclude that our proposed cost scheme typically achieves better performance than the traditional one.

To the best of our knowledge, the only other study that employs operations approaches to analyze extended producer responsibility (EPR) for pharmaceuticals is the working paper by Alev et al. (2013), who investigate the effectiveness of EPR policies by considering the interactions between doctors, patients, manufacturers and insurance companies; however, they do not explore patent term extension as a regulatory tool nor do they examine the role of green pharmacy in product design.

4.3 Green Pharmacy, Patent Term Extension, and Take-back Regulation Defined

In this section, we define the terms, notation, and assumptions that lay the groundwork for our models. Specifically, we first formalize our notions of green pharmacy, patent term extension, and take-back regulations. Then, we specify several assumptions regarding the market segments, cost structure, and the goals of pharmaceutical companies and regulator. Table 4.1 summarizes the technical notation and assumptions discussed in this chapter. And Figure 4.1 illustrates the decisions of the innovative and generic pharmaceutical companies under different policies.

4.3.1 Defining Green Pharmacy

Consistent with the concept proposed by the U.S. EPA and EEA (Daughton 2003a, 2003c, EEA 2010), we mean for *green pharmacy* to represent the redesign of a pharmaceutical product such that the generation of hazardous substances is reduced while the two fundamental traits of the pharmaceutical product, *i.e.*, safety and efficacy, remain unchanged. Thus, the environmental impact of one unit of the green product per period is only α fraction of the environmental impact of one unit of the non-green counterpart per period, where $\alpha \in [0, 1)$ reflects the degree of non-greenness. A small α denotes green pharmacy that results in little environmental impact.

The definition of *green pharmacy* implicitly assumes that the customer demand is independent of the greenness of pharmacy because the two essential traits of the pharmaceutical product remain constant. Moreover, in reality, customers have little access to the environmental hazard assessments of each pharmaceutical product. One exception is the database of regional environmental classification system for pharmaceuticals set up by the Stockholm County Council, Sweden in 2003 (http://www.janusinfo.se/Beslutsstod/Miljo-och-lakemedel/About-the-environment-and-pharmaceuticals/Environmentially-classified-pharmaceuticals/). Unfortunately, such database is not available in the global sense.

4.3.2 Defining Patent and Patent Term Extension

In our model, the innovative company is granted a patent for a limited period of time for its invention of the brand name drug, and the invention is subject to public disclosure after the expiration of the patent. For simplicity, we do not differentiate "patent" with "exclusivity". For detailed difference, readers can refer to `http://www.fda.gov/Drugs/DevelopmentApprovalProcess/ucm079031.htm`. Therefore, in our setting, the innovative company is the monopoly, and the brand name drug is the only available drug in the market as long as the patent protection is active. However, after the patent expires, a generic company will immediately enter the market and produce the generic version of the brand name drug based on the public disclosure.

The patent term extension is used restrictively in this chapter to refer to the extended term of a granted patent for the development of green pharmacy by the innovative company. According to our assumption, only the innovative company may be granted patent term extension. The regulator has the option of implementing patent term extension, which is known to both the innovative and generic companies before they make decisions. If patent term extension exists and the innovative company develops green pharmacy, then the innovative company is granted an n-period patent extension. Thus, within the extended n periods, the innovative company can still charge the monopoly price. Note the generic company can obtain the ingredients of green drug, free of charge, after the patent expires if the innovative company develops a green drug and receives patent extension. However, we assume that the generic company cannot obtain green pharmacy, free of charge, if the innovative company develops a green drug without applying for patent extension. We will relax this assumption and discuss its implication in the conclusion section.

4.3.3 Defining Take-back Regulations

To encourage pharmaceutical companies to take responsibility for pharmaceutical waste, the regulator may consider adopting pharmaceuticals take-back regulations. The pharmaceuticals take-back regulations require that pharmaceutical producers create and finance a collection and disposal program for unused/wasted medicines. Existing pharmaceutical companies pay for all administrative and operational expenses of running the program based on their market share. In fact, collection and disposal operations are funded in part by manufacturers based on prior year's sales volumes in France (Wisconsin DNR 2012) and on market share in Canada (Product Stewardship Institute 2011). In the presence of the take-back regulation, the compliance cost for a pharmaceutical company is $c_t \cdot d$, where d is the sales of that company.

4.3.4 Key Assumptions

Assumption 1: The regulator chooses environmental policy by weighting two considerations: the non-affordability of pharmaceuticals (social impact) and the generation of hazardous substances (environmental impact).

The regulator decides whether to implement an environmental policy by taking two stakeholders into consideration. First, the number of patients who cannot afford the pharmaceutical products. Expensive medicines could jeopardize lives and result in adverse social impact. We assume that the social impact associated with unaffordable pharmaceutical products is $e_1(1-d_1-d_2)$ per period, where the market size is normalized to 1; d_1 and d_2 are the sales of the brand name and generic name drugs, respectively. Second, unused and expired pharmaceuticals products that are not collected could contaminate surface, subsurface, and drinking waters (Daughton 2003a). We assume that $\tau \times 100\%$ of sales will be unused, of which $(1-\eta) \times 100\%$ can be collected and safely disposed of if the take-back regulation exists, where $\tau, \eta \in [0, 1]$. Assume that environmental impact per period is E per unit of non-green product (in monetary terms) and αE per unit of green products (in monetary terms). Thus, the total environmental impact of unsafe disposal per period is $\alpha^l \cdot e_2 d$ if the take-back regulation does not exist and $\eta\alpha^l e_2 d$ if the regulation exists, where d is the sales of a pharmaceutical company, $e_2 = E\tau$, $l = 1$ if the pharmaceutical product is green, and $l = 0$ if the pharmaceutical product is not green. We acknowledge that collection and disposal of unused and wasted medicine result in at least some greenhouse gas (GHG) emissions (Wisconsin DNR 2012) and that active pharmaceutical ingredients (APIs) can be introduced to sewage as a result of excretion and bathing (Ruhoy and Daughton 2008). However, we ignore these two impacts to help us focus on the two major stakeholders.

Assumption 2: The green pharmacy is achievable no earlier than T_0, the time when the original patent expires.

Both companies can obtain green pharmacy (and thus produce green drugs) for a one-time R&D fixed cost of A at T_0 is assumed to be A. In practice, the effective period of patent protection can hardly be more than 8 years because, in general, manufacturers start applying for patent protection before they perform clinical trials on a compound (Gassmann et al. 2008). Considering that few manufacturers would want to develop greener version of the drug before they can market and sell the original version, we assume that green drugs become available at T_0. As a result, we only need to consider the cumulative payoff for all periods after the original patent expires (referred to hereafter as T_0).

Assumption 3: The demand curve slopes down. Generic drugs can cannibalize the sales of brand name drugs but brand name awareness/brand loyalty exists.

A number of empirical studies indicate that a 1 percent increase in the price of prescription drugs will lead to a 0.15-0.33 percent decrease in the number of prescriptions in the United Kingdom (O'Brien 1989, Lavers 1989). In the presence of a cost-sharing prescription drug plan, the price elasticity of demand is still negative though the absolute value decreases (Harris et al. 1990, Smith 1993). In addition, innovator brand loyalty in pharmaceuticals has been observed and analyzed in many previous studies (Scherer and Ross 1990, Grabowski and Vernon 1992, Frank and Salkever 1992). This can be explained by the fact that brand name companies spend more on advertisements (Hurwitz and Caves 1988) and that patients have the experience or perception of low risk and high efficacy of brand name medicines (Denoth et al. 2011, Meredith 2003). The empirical study by Kjoenniksen et al. (2006) found that 41% of the patients would not switch to generic drugs should they have no personal economic incentives.

As a result, we assume that the pharmaceutical product market is cross-price-sensitive. If a customer's willing-to-pay (wtp) for the brand name drug is θ, then her wtp for the generic product is $\delta \cdot \theta$, where $\delta \in [0, 1)$ and θ is distributed uniformly between 0 and 1. $\delta < 1$ not only reflects the fact that patients are willing to pay more for brand name drugs, but also captures the intensity of the market competition. δ close to 0 represents no competition (brand name medicine dominates the market) while δ close to 1 represents an extremely intensive competition. Assume that a customer maximizes her customer surplus (wtp less the price) and makes a purchase only if her customer surplus is positive. In the same spirit as Moorthy (1984), the demand for the brand name and generic drug per period is $d_1 = 1 - \frac{p_1 - p_2}{1-\delta}$ and $d_2 = \frac{\delta p_1 - p_2}{(1-\delta)\delta}$, respectively when both drugs are available in the market. It is not hard to derive that before patent expiration, the monopoly demand (demand for the brand name drug) per period is $d_m = 1 - p_m$.

Assumption 4: The per unit cost to produce brand name drug or generic drug is $c_0 = 0$.

We normalize the manufacturing cost to zero because the unit production cost usually has marginal impact on the pricing of drugs and, therefore, is sometimes negligible. For example, a hepatitis C drug called Sovaldi is priced at \$84,000 but the manufacturing cost is only \$150 (Jogalekar, 2014).

Assumption 5**:** The per unit compliance cost of the take-back regulations c_t is less than $\frac{\delta}{2}$ and is independent of whether a company adopts green pharmacy.

We restrict our discussion to the case when $c_t \leq \frac{\delta}{2}$ for two reasons. First, the administrative and operational expenses of running the program must be within a reasonable and affordable range for both the innovative company and the generic company. In particular, it is not profitable for the generic companies to enter the market when $c_t \geq \delta$. Second, this assumption allows us to focus on the interior optimal solutions and to avoid discussing the boundary condition.

4.4 Patent Term Extension and Model Solutions

Based on the terms, notations and assumptions introduced in Section 4.3, we use this section to formulate the models of the pharmaceutical companies in response to the given environmental policy (policy N or E), and the model of the regulator given the optimal response of the companies.

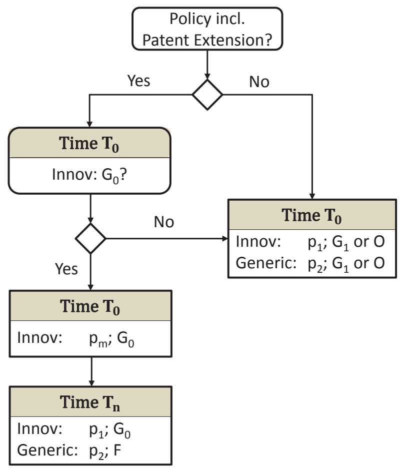

Figure 4.1: Decisions of Pharmaceutical Companies under Different policies

4.4.1 The Model of the Pharmaceutical Companies

4.4.1.1 Benchmark Model: No Regulatory Policy (Policy N)

Given policy N, the innovative company decides whether to pursue green pharmacy and the price of its brand name drug p_1 at time T_0. The profit of the innovative company is $\Pi_1 = \max\limits_{p_1} \frac{1}{1-r} \cdot \frac{1-\delta-p_1+p_2}{1-\delta} \cdot p_1 - A$ if it goes green (denoted as strategy G_1) and $\Pi_1 = \max\limits_{p_1} \frac{1}{1-r} \cdot \frac{1-\delta-p_1+p_2}{1-\delta} \cdot p_1$ if it does not go green (denoted as strategy O). Meanwhile, the generic company decides whether to invest in green pharmacy and the price of the generic drug p_2. The profit of the generic company is $\Pi_2 = \max\limits_{p_2} \frac{1}{1-r} \cdot \frac{\delta p_1 - p_2}{(1-\delta)\delta} \cdot p_2 - A$ if it goes green (strategy G_1) and $\Pi_2 = \max\limits_{p_2} \frac{1}{1-r} \cdot \frac{\delta p_1 - p_2}{(1-\delta)\delta} \cdot p_2$ if it does not go green (strategy O). It is not hard to see that neither company has an incentive to invest in green pharmacy under this policy. By solving the simultaneous game, we have the following results:

Lemma 4.4.1 *In the absence of the patent term extension (policy N), (O, O) is the equilibrium. Moreover,* $\Pi_1^N = \frac{4(1-\delta)}{(1-r)(4-\delta)^2}$, $\Pi_2^N = \frac{(1-\delta)\delta}{(1-r)(4-\delta)^2}$, $p_1^N = \frac{2(1-\delta)}{4-\delta}$, $p_2^N = \frac{(1-\delta)\delta}{4-\delta}$, $d_1^N = \frac{2}{4-\delta}$, *and* $d_2^N = \frac{1}{4-\delta}$.

Lemma 4.4.1 is consistent with intuition because by choosing green pharmacy, pharmaceutical companies incur a fixed cost without any benefits under policy N. Thus, in the absence of any regulatory policy, pharmaceutical companies will not invest to go green. Also, due to the brand loyalty, the innovative company can charge a higher price, sell more products and earn greater profit than the generic company.

4.4.1.2 Patent Term Extension (Policy E)

Given policy E, the innovative company first decides whether to pursue green pharmacy at time T_0. If the innovative company decides to go green (denoted as strategy G_0), then it chooses the monopoly price of its brand name drug p_m for the next n periods. After the extended patent expires (n periods later, denoted as T_n), the generic company enters the markets. At time T_n the innovative company decides p_1 and the generic company decides p_2 simultaneously. Therefore, the profit of the innovative company is $\Pi_1 = \max_{p_m,p_1} \frac{1-r^n}{1-r} \cdot (1-p_m)\, p_m + \frac{r^n}{1-r} \cdot \frac{1-\delta-p_1+p_2}{1-\delta} p_1 - A$ and the profit of generic company is $\Pi_2 = \max_{p_2} \frac{r^n}{1-r} \cdot \frac{\delta p_1 - p_2}{(1-\delta)\delta} \cdot p_2$. Note, in this case, the generic company obtains free access to the green technology after the extended patent term expires (denoted as strategy F). If the innovative company decides not to go green (strategy O) and, therefore, is not qualified for patent term extension, then the problem is essentially the same as that under policy N. Let $A^E = \frac{(1-r^n)\delta(8+\delta)}{4(1-r)(4-\delta)^2}$.

Lemma 4.4.2 *In the presence of policy E,*

(a) If $A \leq A^E$, then (G_0, F) is the equilibrium. $\Pi_1^E = \frac{16-8(1+r^n)\delta+(1-r^n)\delta^2}{4(1-r)(4-\delta)^2} - A$, $\Pi_2^E = r^n \Pi_2^N$, $p_m^E = \frac{1}{2}$, $d_m^E = \frac{1}{2}$; $p_i^E = p_i^N$ and $d_i^E = d_i^N$ for $i = 1, 2$;

(b) If $A > A^E$, then (O, O) is the equilibrium. $\Pi_i^E = \Pi_i^N$, $p_i^E = p_i^N$, and $d_i^E = d_i^N$ for $i = 1, 2$.

Intuitively, Lemma 4.4.2 is true because the patent extension can only benefit the innovative company but not the generic company. Therefore, if it is profitable for the generic company to choose green pharmacy, it would also be profitable for the innovative company to do so and thus obtain the patent. In such a case, the generic company can only enter the market at time T_n but obtain green technology for free. Accordingly, either strategy (O, O) or (G_0, F) can be the equilibrium.

Figure 4.2 illustrates the effects of exogenous parameters (fixed investment cost A, extended term of the patent n, and competition intensity δ) on the strategy equilibrium. The strategy space is separated by the solid lines when

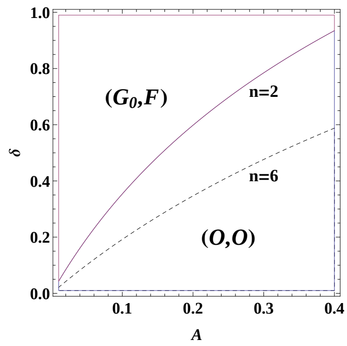

Figure 4.2: Equilibrium under Policy E ($r = 0.8$)

$n = 2$ and by the dashed lines when $n = 6$. First, when fixed investment cost A is sufficiently small, the innovative company chooses to invest in green pharmacy to prolong the patent and monopoly; when A is sufficiently large, the innovative company will not go green because the benefit of extended patent cannot justify the cost of investment. Second, a longer extended term of the patent (larger n) makes investment in green pharmacy more attractive for the innovative company because innovative company can charge monopoly price and earns monopoly profit for a longer time. Last, a high degree of competition intensity encourages investment in green pharmacy, which is intuitive because green pharmacy allows the innovative company to exclusively possess the market for an additional n periods. In a similar vein, as the competition becomes more intensive, the innovative company is willing to go green in order to take advantage of the patent extension even with higher investment cost A or shorter extended term of the patent n.

4.4.2 The Model of the Regulator – Implement the Patent Term Extension (E) or Not (N)?

To decide whether it is optimal for the regulator to implement the patent term extension, we need to compare the resulting social and environmental impacts under policy N with those under policy E. Recall that (O, O) is the equilibrium for any A under policy N (see Lemma 4.4.1) and for $A > A^E$ under policy E (see Lemma 4.4.2), which indicates that patent term extension cannot induce green pharmacy and, therefore, does not change the social and environmental impact when $A > A^E$. Consequently, we only need to focus on the case when $A \leq A^E$.

The regulator's objective is to minimize the negative social and environmental impact, which can be modeled as

$$e_1\Sigma_{k=1}^{\infty}r^{k-1}\left(1-d_{1,k}-d_{2,k}\right)+e_2\Sigma_{k=1}^{\infty}r^{k-1}\left(\alpha^{l_{1,k}}d_{1,k}+\alpha^{l_{2,k}}d_{1,k}\right) \tag{4.1}$$

where $d_{1,k}(d_{2,k})$ are the sales of the brand (generic) name drugs during the k^{th}-period after the original patent expires; $l_{1,k}(l_{2,k}) = 1$ if the brand name (generic) drug is green, and $l_{1,k}(l_{2,k}) = 0$ if otherwise. Denote impact ratio as $e = \frac{e_1}{e_2}$. A large impact ratio represents when the major concern of the regulator is the social impact (non-affordability of medicines), and a small impact ratio represents when the primary concern is the environmental impact of medicine. Let $e^E = \alpha + \frac{6(1-\alpha)}{(1-r^n)(2+\delta)}$.

Proposition 4.4.3 *When $A \leq A^E$, it is optimal for the regulator to implement the patent term extension if and only if $e < e^E$.*

Given $A \leq A^E$, it is possible for the regulator to induce green pharmacy by implementing policy E. However, Proposition 4.4.3 establishes that the regulator should only do so when the environment protection requires close attention ($e < e^E$). This is because patent extension can reduce the availability of medicines and, consequently, should not be implemented when the social impact is the primary concern of the regulator ($e \geq e^E$). Note that e^E decreases in α and δ. In other words, given e, the regulator is less likely to implement patent extension when α and δ are relatively large. First, the regulator has little incentive to carry out patent term extension if green pharmacy only alleviates environmental impact by a small margin (*i.e.*, large α). Second, given the fact that more patients are willing to buy generic drugs when δ is relatively large, the regulator will be conservative in implementing the patent extension because such incentive may result in the situation that more patients cannot afford the medicine. Figure 4.3 further illustrates the results of Proposition 4.4.3. In Figure 4.3, $(G_0, F)^+$ represents when the patent term extension can induce green pharmacy and it is optimal for the regulator to implement the incentive of patent term extension, while $(G_0, F)^-$ represents when the patent term extension can induce green pharmacy but the regulator should not further encourage monopoly after the original patent expires. (O, O) represents when the incentive has no impact on the social and environmental welfare because no company will go green.

If the regulator decides to implement the patent term extension, what is the optimal n? According to Proposition 4.4.3, everything else being equal, n increases as e^E decreases, which is intuitive because when e is small, the regulator is more determined to induce green pharmacy by providing longer extending patent term. Let n^E denote the optimal extension of the term. Given that the regulator optimizes the decision of whether or not to implement the patent term extension, Proposition 4.4.4 provides the optimal extended patent term n^E. Note $n^E = 0$ represents the situation when it is not optimal for the regulator to provide the incentive in the form of patent term extension.

Proposition 4.4.4 *If the regulator implements policy E, then*
(a) $n^E = log_r \left[1 - \frac{4A(4-\delta)^2(1-r)}{\delta(8+\delta)}\right]$ *when* $\alpha \leq e < \alpha + \frac{3(1-\alpha)\delta(8+\delta)}{2A(1-r)(2+\delta)(4-\delta)^2}$ *and* $A < \frac{\delta(8+\delta)}{4(1-r)(4-\delta)^2}$*;*
(b) $n^E = \infty$ *when* $e < \alpha$ *and* $A < \frac{\delta(8+\delta)}{4(1-r)(4-\delta)^2}$*;*
(c) $n^E = 0$ *when* $e \geq \alpha + \frac{3(1-\alpha)\delta(\delta+8)}{2A(1-r)(2+\delta)(4-\delta)^2}$ *or* $A \geq \frac{\delta(8+\delta)}{4(1-r)(4-\delta)^2}$.

According to Proposition 4.4.4(a), if $\alpha < e < \alpha + \frac{3(1-\alpha)\delta(8+\delta)}{2A(1-r)(2+\delta)(4-\delta)^2}$ and $A < \frac{\delta(8+\delta)}{4(4-\delta)^2(1-r)}$, then the optimal extension term n^E is finite. It is not hard to show that n^E increases in A and decreases in δ. As the one-time fixed R&D investment amount increases (large A), the regulator should provide more incentive to induce green pharmacy. As customers becomes more interested in generic drugs (large δ), the innovative company is more motivated to take advantage of the patent extension by choosing green pharmacy, which means that the regulator can induce green pharmacy with a smaller n.

The optimal extension term n^E is not always finite. On the one hand, if the regulator places more emphasis on the environmental issues (relatively small e) and the fixed investment A is relatively small, then the regulator would set the extended term to be as long as possible because by doing so, the innovative company will choose green pharmacy and the total sales volume is less than if the market is competitive. On the other hand, if the social issues is the top priority (relatively large e) or if the fixed investment A is sufficiently large, then it is not in the best interest of the regulator to implement the patent term extension because the policy either significantly impairs affordability of drugs (when e is sufficiently large) or fails to induce green pharmacy (when A is sufficiently large).

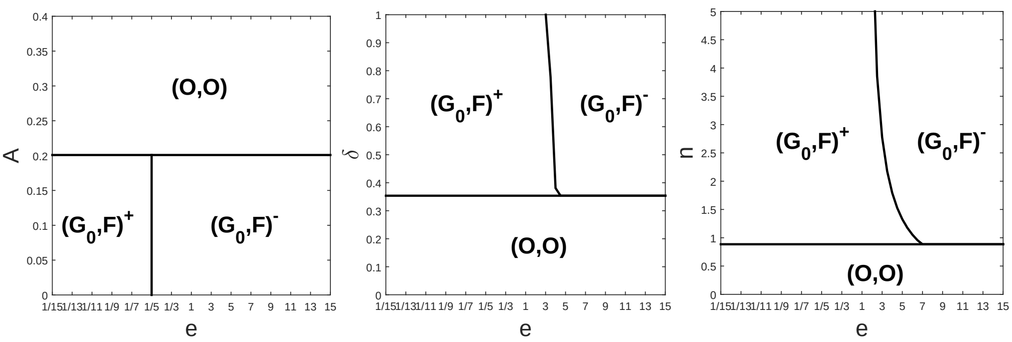

Figure 4.3: Optimal Regulatory Policy: Policy N or E
$r = 0.8$, and (L) $n = 2$, $\alpha = 0.5$ and $\delta = 0.6$; (M) $A = 0.1$, $\alpha = 0.5$ and $n = 2$; (R) $A = 0.1$, $\alpha = 0.5$ and $\delta = 0.6$.

4.5 The Role of Take-back Regulations

In the previous section, we demonstrated that the patent term extension fails to encourage companies to invest in green pharmacy when $A \geq A^E$, no matter how long the extended patent term n is. Therefore, in this section, we consider another regulatory policy, take-back regulation, and evaluate its impact on company strategy in Section 4.5.1. Intuitively, pharmaceutical companies will not choose green pharmacy because the compliance cost associated with the take-back regulation is usually independent of the choice of green pharmacy. Thus, in Section 4.5.2, we compare the patent term extension with and without the presence of the take-back regulation, and discuss the optimal policy, optimal extended term and the resulting overall social and environmental performance.

4.5.1 Pharmaceutical Take-back Regulations (Policy T)

As mentioned earlier, pharmaceutical take-back programs can help to reduce environmental pollution by collecting and incinerating unwanted medicines. However, it is unclear whether pharmaceutical take-back programs can induce green pharmacy. One central issue in implementing this policy is deciding how to pay for the cost of running the take-back program. In the countries where the cost is financed by all participating pharmaceutical companies, a common cost allocation scheme is based on the market size. Thus, we model the problem as follows: In the presence of the take-back regulation, each company has to pay the compliance cost c_t per unit of sales.

The innovative company will invest in green pharmacy only if its profit of going green ($\Pi_1^T = \max_{p_1} \frac{1}{1-r} \cdot \frac{1-\delta-p_1+p_2}{1-\delta} \cdot (p_1 - c_t) - A$) is higher than its profit of not going green ($\Pi_1^T = \max_{p_1} \frac{1}{1-r} \cdot \frac{1-\delta-p_1+p_2}{1-\delta} \cdot (p_1 - c_t)$). Similarly, the generic company will invest in green pharmacy only if its profit of going green ($\Pi_2^T = \max_{p_2} \frac{1}{1-r} \cdot \frac{1-\delta-p_1+p_2}{1-\delta} \cdot (p_2 - c_t) - A$) is higher than its profit of not going green ($\Pi_2^T = \max_{p_2} \frac{1}{1-r} \cdot \frac{\delta p_1 - p_2}{(1-\delta)\delta} \cdot (p_2 - c_t)$). It is not hard to see that neither company would invest because there is no financial benefit of going green. As a result, we have $\Pi_1^T = \frac{(1-\delta)(2-c_t)^2}{(1-r)(4-\delta)^2}$, $\Pi_2^T = \frac{(1-\delta)(\delta-2c_t)^2}{(1-r)(4-\delta)^2\delta}$, $p_1^T = \frac{2(1-\delta)+3c_t}{4-\delta}$, $p_2^T = \frac{(1-\delta)\delta+c_t(2+\delta)}{4-\delta}$, $d_1^T = \frac{2-c_t}{4-\delta}$, and $d_2^T = \frac{\delta-2c_t}{(4-\delta)\delta}$. Furthermore, compared with the benchmark (Lemma 4.4.1 in Section 4.4.1.1), both companies charge higher prices under policy T; consequently, they sell fewer products and earn lower profit due to the compliance cost associated with the take-back regulation. These results indicate that by only implementing the take-back regulation, pharmaceutical companies will neither go green nor will they bear all the clean-up cost; consumers will inevitably absorb some of the compliance costs. The outcome is also consistent with the existing literature on environmental economics which state that producer take-back regulation may not promote environmentally-friendly product designs (*e.g.*, Walls 2006).

From the perspective of the regulator, the take-back regulation has both environmental and social impacts. On the one hand, the increased prices means a low level of affordability because it prevents customers with low willingness-to-pay from obtaining the medicines. On the other hand, pharmaceutical stewardship program reduces the environmental impact because a fraction of unwanted medicines will be collected and safely disposed of and the sales volume ($d_1^T + d_2^T$) decreases. Thus, the regulator should consider choosing the take-back-only policy when the environmental concern is acute, the compliance cost is sufficiently low, and the recovery rate is sufficiently high ($e < \eta + \frac{3\delta(1-\eta)}{c_t(2+\delta)}$). Figure 4.4 depicts the above results.

4.5.2 Patent Term Extension and Take-back Regulations (Policy ET)

Section 4.5.1 highlights that the take-back regulation alone cannot induce companies to pursue green pharmacy. We now examine the take-back regu-

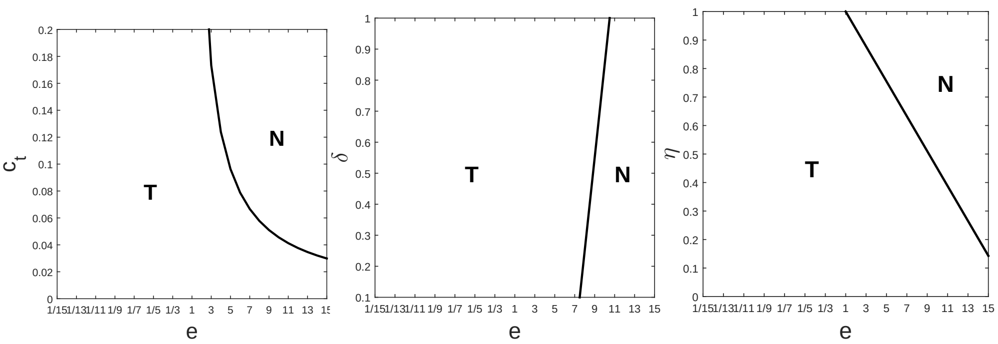

Figure 4.4: Optimal Regulatory Policy: Policy N or T
(L) $\delta = 0.6$ and $\eta = 0.5$; (M) $c_t = 0.05$ and $\eta = 0.5$; (R) $c_t = 0.05$ and $\delta = 0.6$.

lation in conjunction with the patent term extension? The research question we ask is how would the optimal extended patent term be affected when both policies are implemented?

To answer the above question, we first specify our models: the innovative company decides whether to invest at time T_0. If the innovative company plans to invest, then it decides the monopoly price p_m for the next n periods. At time T_n, the generic company enters the market; the innovative company decides p_1 and the generic company decides p_2 simultaneously. Therefore, the profit of the innovative company is $\Pi_1^{ET} = \max\limits_{p_m, p_1} \frac{1-r^n}{1-r} \cdot (1 - p_m) \cdot (p_m - c_t) + \frac{r^n}{1-r} \cdot \frac{1-\delta-p_1+p_2}{1-\delta} \cdot (p_1 - c_t) - A$ and the profit of generic company is $\Pi_2^{ET} = \max\limits_{p_2} \frac{r^n}{1-r} \cdot \frac{\delta p_1 - p_2}{(1-\delta)\delta} \cdot (p_2 - c_t)$. Note, in this case, the generic company can obtain free access to the green pharmacy after T_n. If the innovative company decides not to invest and, therefore, does not obtain patent term extension, then the problem is essentially the same as that under policy T. Let $A^{ET} = \frac{1-r^n}{1-r}\left[\frac{(1-c_t)^2}{4} - \frac{(2-c_t)^2(1-\delta)}{(4-\delta)^2}\right]$. Similar to Lemma 4.4.2, we have

Lemma 4.5.1 *In the presence of policy ET,*

(a) If $A \leq A^{ET}$, then (G_0, F) is the equilibrium. $\Pi_1^{ET} = \frac{(2-c_t)^2(1-\delta)r^n}{(4-\delta)^2(1-r)} + \frac{(1-c_t)^2(1-r^n)}{4(1-r)} - A$, $\Pi_2^{ET} = \frac{(1-\delta)(\delta-2c_t)^2 r^n}{(4-\delta)^2(1-r)}$. *Moreover,* $p_m^{ET} = \frac{1+c_t}{2}$ $d_m^{ET} = \frac{1-c_t}{2}$; $p_i^{ET} = p_i^T$ *and* $d_i^{ET} = d_i^T$ *for* $i = 1, 2$;

(b) If $A > A^{ET}$, then (O, O) is the equilibrium. $\Pi_i^{ET} = \Pi_i^T$, $p_i^{ET} = p_i^T$, *and* $d_i^{ET} = d_i^T$ *for* $i = 1, 2$.

(c) $\Pi_i^{ET} \leq \Pi_i^E$ *for* $i = 1, 2$.

It is not hard to show that, everything else being equal, the threshold of A below which the innovative company will go green is lower under policy ET

than under policy E ($A^{ET} \leq A^{E}$) when $c_t \leq \frac{\delta}{2}$. This is because the decrease in demand due to the compliance cost has a greater impact (in terms of profit reduction) on the innovative company's monopoly profit than on its profit under the competition, which makes patent term extension less attractive. In addition, as Lemma 4.5.1 states, in the presence of patent term extension, both companies have less profit with the take-back regulation than without it.

Nevertheless, policy ET can induce green pharmacy in cases where policy T can never achieve it; also, policy ET can result in less negative impact than policy E in some cases. Recall that the regulator aims to minimize the following social and environmental impacts

$$e_1 \Sigma_{k=1}^{\infty} r^{k-1} \left(1 - d_{1,k} - d_{2,k}\right) + \eta^t e_2 \Sigma_{k=1}^{\infty} r^{k-1} \left(\alpha^{l_{1,k}} d_{1,k} + \alpha^{l_{2,k}} d_{1,k}\right)$$

where $t = 1$ if the take-back regulation exists and $t = 0$ if otherwise; $d_{1,k}, d_{2,k}, l_{1,k}, l_{2,k}$ are defined in Section 4.4.2. Given the choice of implementing both the patent term extension and the take-back regulation (policy ET) or nothing (policy N), which one is the better strategy for the regulator? If implementing both regulations, what is the optimal extended patent term? Letting $e_{ET}^{u} = \frac{(2+\delta)(1-\alpha\eta)\left[c_t^2\left(12-4\delta+\delta^2\right)-2c_t\left(8+\delta^2\right)+\delta(8+\delta)\right]}{2A(4-\delta)^2(1-r)[3\delta - c_t(\delta+2)]+3c_t\left[c_t^2(12-4\delta+\delta^2)-2c_t(8+\delta^2)+\delta(8+\delta)\right]}$, Proposition 4.5.2 specifies the optimal extended patent term n^{ET}.

Proposition 4.5.2 *If the regulator implements policy ET, then*
(a) $n^{ET} = log_r\left[1 - \frac{4A(4-\delta)^2(1-r)}{\delta(8+\delta)-2c_t(8+\delta^2)+c_t^2(12-4\delta+\delta^2)}\right]$ *when* $\alpha\eta \leq e < \max\left\{\alpha\eta + \frac{2(1-\alpha)(2+\delta)}{3\delta}, \alpha\eta + e_{ET}^{u}\right\}$ *and* $A < \frac{\delta(8+\delta)-2c_t\left(8+\delta^2\right)+c_t^2\left(12-4\delta+\delta^2\right)}{4(4-\delta)^2(1-r)}$*;*
(b) $n^{ET} = \infty$ *when* $e < \alpha\eta$ *and* $A < \frac{\delta(8+\delta)-2c_t\left(8+\delta^2\right)+c_t^2\left(12-4\delta+\delta^2\right)}{4(1-r)(4-\delta)^2}$*;*
(c) $n^{ET} = 0$ *when* $e \geq \max\left\{\alpha\eta + \frac{2(1-\alpha)(2+\delta)}{3\delta}, \alpha\eta + e_{ET}^{u}\right\}$ *or* $A > \frac{\delta(8+\delta)-2c_t\left(8+\delta^2\right)+c_t^2\left(12-4\delta+\delta^2\right)}{4(1-r)(4-\delta)^2}$.

Similar to Proposition 4.4.4, Proposition 4.5.2 reveals that the optimal extension term n^{ET} is finite when the environmental and social impacts are to be balanced. By comparing Propositions 4.4.4 with 4.5.2, we have the following corollary:

Corollary 4.5.3 $n^{ET} \geq n^{E}$ *when* $A < \frac{\delta(8+\delta)-2c_t\left(8+\delta^2\right)+c_t^2\left(12-4\delta+\delta^2\right)}{4(1-r)(4-\delta)^2}$ *and* $\alpha < e < \min\left\{\alpha + \frac{3(1-\alpha)\delta(8+\delta)}{2A(1-r)(2+\delta)(4-\delta)^2}, \max\left\{\alpha\eta + \frac{2(1-\alpha)(2+\delta)}{3\delta}, \alpha\eta + e_{ET}^{u}\right\}\right\}$.

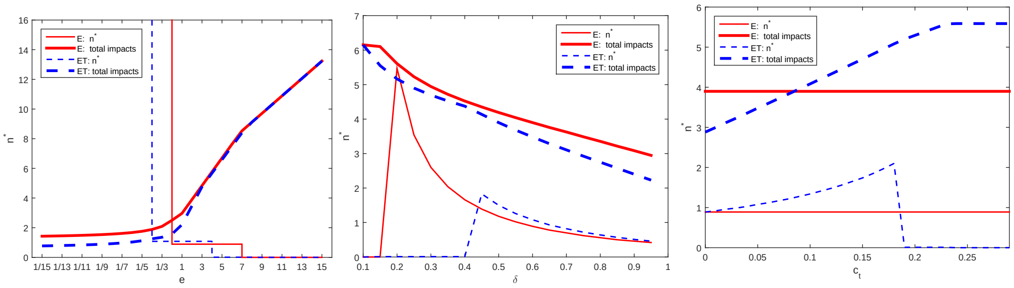

Figure 4.5: Optimal Length of Patent Extension and Total Impacts under Different Policies

$A = 0.1, \alpha = 0.5, r = 0.8, \eta = 0.5$. (L) $c_t = 0.05, \delta = 0.6$; (M) $c_t = 0.05, e = 2$; (R) $\delta = 0.6, e = 2$.

According to Corollary 4.5.3 and Figure 4.5, the optimal patent term extension is longer under policy ET than under policy E when n^E and n^{ET} are both finite, which means that more incentive must be provided to induce green pharmacy with the take-back regulation than without such regulation. This is because the innovative company's monopoly profit is reduced from $\frac{1}{4}$ to $\frac{(1-c_1)^2}{4}$ per period due to the take-back regulation. Therefore, everything else being equal, in order to encourage green pharmacy, the regulation has to offer a longer patent term extension under policy ET.

In terms of the total impact, numerical results indicate that adding the take-back regulation to the existing patent term extension could increase or decrease the total impact, depending on the system parameters. First of all, if the regulator aims to reduce the environmental impact (small e), then in most cases, it is optimal for the regulator to adopt policy ET rather than policy E because the take-back regulation helps to further reduce the environmental impact. If the social impact is the main concern (large e), then the regulator should only implement E rather than policy ET because the take-back regulation increases the price of pharmaceutical products and reduces the affordability of medicines. Second, when e is relatively small, policy ET is more likely to outperform policy E as A increases. When A is relatively large, companies have little motivation to invest in green pharmacy, which means that policy ET (E) is essentially policy T (N). Thus, the analysis in Section 4.5.1 follows. Third, adding the take-back regulation to the existing patent term extension could decrease the total impact when the compliance cost c_t is relatively small. This is because policy ET with small c_t encourages safe disposal but merely changes the social impact. Fourth, it is generally optimal for the regulator to adopt policy ET rather than policy E when δ is sufficiently small or sufficiently large. When δ is sufficiently small, the patent extension regulation can hardly induce green pharmacy because the innovative company dominates the market. In fact, n^E and n^{ET} generally equal zero in such a case. However, the take-back regulation can help achieve a lower environmental impact by collecting some of the unused pharmaceutical products. When δ is sufficiently large, the regulator can induce green pharmacy with small n because innovative company wants to take advantage of the patent term extension in face of fierce competition. As a result, the environmental impact is reduced while the social impact does not significantly increase. Last, the total impact is typically lower under policy ET than under policy E when η is relatively small, which is intuitive because smaller η means a higher fraction of unused products can be safely disposed of. Overall, similar to Section 4.5.1, we conclude that the environmental impact is generally reduced because of the decreased sales and safe disposal; however, the negative social impact is usually exaggerated due to the higher price and the low level of affordability. In addition, policy ET excels policy E when A is relatively large, when e, c_t, and η are relatively small, and when δ is either sufficiently small or sufficiently large.

4.6 Effects of Green Pharmacy on the Compliance Cost

According to Section 4.5.1, the take-back regulation alone will not induce green pharmacy because the program does not provide financial incentive to the pharmaceutical company for engaging in green technology. This result relies on the assumption that the compliance cost is independent of whether a company adopts green pharmacy. In this section, we consider the case that the compliance cost of the take-back regulation is related to the greenness of the pharmaceutical products: companies without green pharmacy have the base compliance cost c_t per unit; however, companies with green pharmacy have lower compliance cost $\alpha \cdot c_t$ per unit, where α is the degree of non-greenness as we discussed before. This is a reasonable assumption because a more green design (smaller α) should receive more discount than a less green design (larger α). We first evaluate the impact of the take-back regulation on the strategies of the two companies, and on the overall social and environmental performance in Section 4.6.1. Next, we compare the proposed scheme with the regulatory policies analyzed before and present the results in Section 4.6.2. To avoid discussing the boundary solutions, we assume that $c_t \leq \frac{(1-\delta)\delta}{2-\alpha\delta-\delta}$.

4.6.1 The Modified Take-back Regulation (Policy $\bar{T}$)

4.6.1.1 The Model of the Pharmaceutical Companies

Given policy $\bar{T}$, the innovative company decides whether to invest in green pharmacy and the price p_1 at time T_0. The profit of the innovative company is $\Pi_1^{\bar{T}} = \max_{p_1} \frac{1}{1-r} \cdot \frac{1-\delta-p_1+p_2}{1-\delta} \cdot (p_1 - \alpha \cdot c_t) - A$ if it goes green and $\Pi_1^{\bar{T}} = \max_{p_1} \frac{1}{1-r} \cdot \frac{1-\delta-p_1+p_2}{1-\delta} \cdot (p_1 - c_t)$ if it does not go green. Meanwhile, the generic company decides whether to go green and p_2. The profit of the generic company is $\Pi_2^{\bar{T}} = \max_{p_2} \frac{1}{1-r} \cdot \frac{\delta p_1 - p_2}{(1-\delta)\delta} \cdot (p_2 - \alpha \cdot c_t) - A$ if it goes green and $\Pi_2^{\bar{T}} = \max_{p_2} \frac{1}{1-r} \cdot \frac{\delta p_1 - p_2}{(1-\delta)\delta} \cdot (p_2 - c_t)$ if it does not go green. Note under this policy, when one company decides to go green, the other company cannot free-ride because the former company has no obligation to disclose its green technology. Let $A_1^{\bar{T}} = \frac{(1-\alpha)(2-\delta)c_t[2\delta(1-\delta)-c_t(2-\delta+\alpha(2-3\delta))]}{(1-r)(1-\delta)(4-\delta)^2}$ and $A_2^{\bar{T}} = \frac{(1-\alpha)(2-\delta)c_t[4(1-\delta)-c_t(\alpha(2-\delta)-\delta)]}{(1-r)(1-\delta)(4-\delta)^2\delta}$.

Lemma 4.6.1 *In the presence of policy $\bar{T}$,*

(a) If $A \leq A_1^{\bar{T}}$, then (G_1, G_1) is the equilibrium. $\Pi_1^{\bar{T}} = \frac{(1-\delta)(2-\alpha c_t)^2}{(1-r)(4-\delta)^2} - A$, $\Pi_2^{\bar{T}} = \frac{(1-\delta)(\delta-2\alpha c_t)^2}{(1-r)(4-\delta)^2\delta} - A$, $p_1^{\bar{T}} = \frac{2(1-\delta)+3\alpha c_t}{4-\delta}$, $p_2^{\bar{T}} = \frac{(1-\delta)\delta+\alpha c_t(2+\delta)}{4-\delta}$, $d_1^{\bar{T}} = \frac{2-\alpha c_t}{4-\delta}$, *and* $d_2^{\bar{T}} = \frac{\delta-2\alpha c_t}{(4-\delta)\delta}$;

(b) If $A_1^{\bar{T}} \leq A \leq A_2^{\bar{T}}$, then (G_1, O) is the equilibrium. $\Pi_1^{\bar{T}} = \frac{[2(1-\delta)+c_t(1-\alpha(2-\delta))]^2}{(1-r)(1-\delta)(4-\delta)^2} - A$, $\Pi_2^{\bar{T}} = \frac{[(1-\delta)\delta-c_t(2-\delta-\alpha\delta)]^2}{(1-r)(1-\delta)(4-\delta)^2\delta}$, $p_1^{\bar{T}} = \frac{2(1-\delta)+c_t(1+2\alpha)}{4-\delta}$, $p_2^{\bar{T}} = \frac{(1-\delta)\delta+c_t(2+\alpha\delta)}{4-\delta}$, $d_1^{\bar{T}} = \frac{2(1-\delta)-\alpha c_t(2-\delta)}{(4-\delta)(1-\delta)}$, *and* $d_2^{\bar{T}} = \frac{(1-\delta)\delta-c_t(2-\delta-\alpha\delta)}{(4-\delta)(1-\delta)\delta}$;

(c) If $A > A_2^{\bar{T}}$, then (O, O) is the equilibrium. $\Pi_1^{\bar{T}} = \frac{(1-\delta)(2-c_t)^2}{(1-r)(4-\delta)^2}$, $\Pi_2^{\bar{T}} = \frac{(1-\delta)(\delta-2c_t)^2}{(1-r)(4-\delta)^2\delta}$, $p_1^{\bar{T}} = \frac{2(1-\delta)+3c_t}{4-\delta}$, $p_2^{\bar{T}} = \frac{(1-\delta)\delta+c_t(2+\delta)}{4-\delta}$, $d_1^{\bar{T}} = \frac{2-c_t}{4-\delta}$, *and* $d_2^{\bar{T}} = \frac{\delta-2c_t}{(4-\delta)\delta}$.

Compared with the take-back regulation in Section 4.5.1, the modified take-back regulation can induce green pharmacy. In fact, under certain circumstances, both companies will invest to obtain green pharmacy. Moreover, according to Lemma 4.6.1, if it is profitable for the generic company to invest in green pharmacy, then it is also profitable for the innovative company to invest. This is because the innovation company usually generates higher profit and demand than the generic company due to the brand loyalty advantage. Therefore, if green pharmacy allows the generic company to lower unit cost while maintain or increase its profit, then the green pharmacy will benefit the innovative company to a greater extent. Consequently, strategy (O, G_1) cannot be an equilibrium.

Figure 4.6 illustrates the effects of exogenous parameters (fixed investment cost A, base compliance cost c_t, degree of non-greenness α, and competition intensity δ) on the strategy equilibrium. The strategy space is separated by the solid lines when $\alpha = 0.3$ and separated by the dashed lines when $\alpha = 0.5$. First, when fixed investment cost A is sufficiently small or the base compliance cost c_t is sufficiently large, both companies choose to invest in green pharmacy to reduce the compliance cost; when A is sufficiently large or c_t is sufficiently small, no company would go green because the compliance cost saving cannot cover the cost of investment. Second, a high degree of non-greenness α is associated with less compliance cost saving of going green. Thus, a large α discourages green pharmacy. Last, when A is sufficiently small, higher competition intensity δ can generally induce the generic company to go green because in such a case, the company has to compete on price by reducing the cost; note the innovative company always goes green with a very small A. Interestingly, when A is relatively large, the innovative company chooses green pharmacy only when competition intensity δ is either sufficiently low or sufficiently high. Little competitive rivalry allows the innovative company to earn great profit by exclusively enjoying the low compliance cost; a sufficiently high competition intensity drives the innovative company to lower the compliance cost by going green.

4.6.1.2 The Model of the Regulator: Implement the Modified Take-back Regulation ($\bar{T}$) or Not (N)?

Given the choice of implementing the modified take-back regulation or nothing, Proposition 4.6.2 provides the guideline for the optimal regulatory policy.

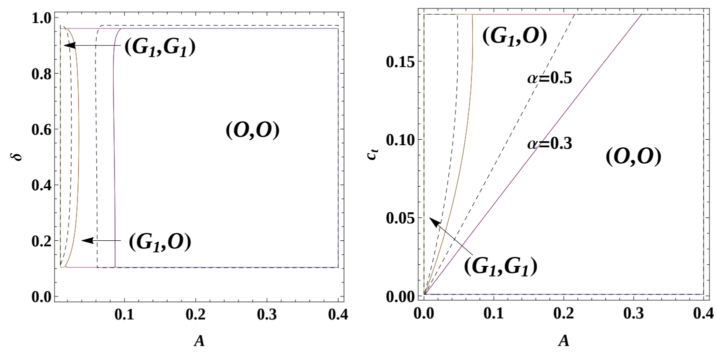

Figure 4.6: Equilibrium under Policy $\bar{T}$

(L) $c_t = 0.05$, $r = 0.8$; (R) $\delta = 0.6$, $r = 0.8$. $c_t \leq \frac{(1-\delta)\delta}{2-\alpha\delta-\delta}$ based on our assumption

Proposition 4.6.2 *Given a parameter set* $(A, \alpha, c_t, \delta, \eta, r)$*, there exists* $e^{\bar{T}}$ *such that it is optimal for the regulator to implement policy* $\bar{T}$ *if and only if* $e < e^{\bar{T}}$*.*

Figure 4.7 depicts how exogenous parameters affect the optimal regulatory decision. $(S_1, S_2)^+$ represents when it is optimal for the regulator to implement the modified take-back regulation, where (S_1, S_2) is the resulting strategy choice by the two firms; $(S_1, S_2)^-$ represents when the regulator should not implement the modified take-back regulation and if it does, (S_1, S_2) is the strategy equilibrium.

One observation from Figure 4.7 is that keeping other parameters constant, $e^{\bar{T}}$ increases in δ. This can be explained by two reasons. On the one hand, more patients switch from the brand name drug to the generic drug when δ increases, while the generic company is less likely to adopt green pharmacy than the innovative company (see Lemma 4.6.1). On the other hand, the total number of medicine sold in each period increases in δ, which imposes more pressures on the environment. For both changes, the regulator is more likely to implement the take-back regulation. Thus, along with the discussion in Section 4.4.2, the regulator should implement the modified take-back regulation rather than the patent extension when δ is relatively large.

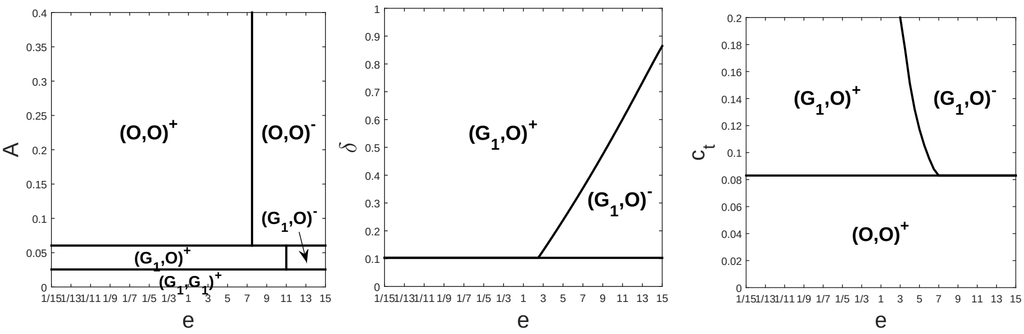

Figure 4.7: Optimal Regulatory Policy: Policy N or $\bar{T}$
$r = 0.8$, $\alpha = 0.5$, $\eta = 0.5$. (L) $c_t = 0.05$ and $\delta = 0.6$; (M) $c_t = 0.05$ and $A = 0.1$; (R) $\delta = 0.6$ and $A = 0.1$. Note $c_t \leq \frac{(1-\delta)\delta}{2-\alpha\delta-\delta}$ based on our assumption.

4.6.2 Patent Term Extension and Modified Take-back Regulation (Policy $\overline{ET}$)

In Section 4.6.1.1, we have shown that the strategy equilibrium can only be (G_1, G_1), (G_1, O) or (O, O) in the presence of the modified take-back regulation. What is the strategy equilibrium if the regulatory policy is the combination of the patent term extension and the modified take-back regulation (policy $\overline{ET}$)? It is not hard to conclude that strategy equilibrium becomes either (G_0, F), (G_1, O) or (O, O).

We make three observations regarding policy $\overline{ET}$. First, given n and a parameter set $(A, \alpha, c_t, \delta, \eta, r)$, if (G_1, G_1) is the equilibrium under policy $\bar{T}$, then (G_0, F) is the equilibrium under policy $\overline{ET}$. This result is intuitive because the innovative company can reduce both competition and compliance cost by choosing green pharmacy and obtaining patent term extension under policy $\overline{ET}$. Second, interestingly, strategy (G_1, O) can be an equilibrium for some $(A, \alpha, c_t, \delta, \eta, r, n)$, meaning that under certain conditions, the innovative company would not extend the patent so that the company has no obligation to reveal the ingredients or process of green pharmacy and thus can exclusively enjoy the benefits of green pharmacy it invests. By contrast, if the innovative company obtains patent extension, then after the extended patent expires, the generic company will enter the market with lower compliance cost without investment, which intensifies the competition. (G_1, O) is an equilibrium when A is large enough such that it is not profitable for the generic company to go green but is still small enough for the innovative company to go green. Third, if (G_1, O) is the equilibrium under policy $\bar{T}$, then either (G_0, F) or (G_1, O) is the equilibrium under policy $\overline{ET}$; if (O, O) is the equilibrium under policy $\bar{T}$, then either (G_0, F) or (O, O) is the equilibrium under policy $\overline{ET}$. By adding the patent term extension to the modified take-back regulation, the regulatory policy is more like to induce green pharmacy.

However, it is still not clear whether policy $\overline{ET}$ can lower the social and environmental impacts. To answer this question, similar to Section 4.5.2, we can define and evaluate the optimal solutions to the problem of the regulator. Figure 4.8 illustrates the overall impact and the optimal patent term extension under different policies. Based on the numerical results, we have the following observations. First, if the regulator aims to reduce the environmental impact (sufficiently small e), then it is generally optimal for the regulator to adopt policy ET rather than policy E or $\overline{ET}$ because policy ET helps to further reduce the environmental impact as compared to policy E, and results in lower sale volume as compared to policy $\overline{ET}$. If the social impact is the primary concern (sufficiently large e), then the regulator should only implement E rather than policy ET or $\overline{ET}$ because the take-back regulation further increases the price of pharmaceutical products and reduces the affordability of medicines. In fact, the optimal extended term is zero for any of these three policy when e is sufficiently large. If the regulator is seeking the balance between social and environmental impacts, then policy $\overline{ET}$ is generally the best policy among the three. Second, policy $\overline{ET}$ is more likely to outperform policies E and ET when α is relatively small. A smaller α means that the pharmaceutical products are much greener and that companies can have lower compliance cost per unit. As a result, the regulator has more incentive to induce green pharmacy and the innovative company is more willing to invest in green pharmacy to achieve lower cost under policy $\overline{ET}$ as compared to policies E and ET. When α is relatively large, the regulator prefers the take-back regulation to the patent term extension in achieving lower environmental impact, making ET a better policy than E or $\overline{ET}$. Third, in general, policy $\overline{ET}$ is optimal when c_t is relatively small, and policy E is optimal when c_t is relatively large. This is because with small low compliance cost c_t, policy $\overline{ET}$ can best reduce the environmental impact while control the social impact by choosing relatively small n among all three policies. However, policies ET and $\overline{ET}$ significantly increases the negative social impact when c_t is relatively large. Fourth, it is generally optimal for the regulator to adopt policy $\overline{ET}$, especially when δ is small. Similar to the analysis in Section 4.5.2, when δ is sufficiently small, on the one hand, unless n is sufficiently large, the patent extension regulation can hardly induce green pharmacy because the brand name product already dominates the market; on the other hand, the take-back regulation can help achieve a lower environmental impact by having some of the unused pharmaceutical products safely disposed. Thus, the regulator can collect unused products and induce green pharmacy with smaller n under policy $\overline{ET}$ than under other policies. Last, the total impact is generally lower under policy $\overline{ET}$ than under policy E or ET when η is relatively small because a relatively high proportion of unused products can be safely disposed of under policy $\overline{ET}$ with small η. Overall, policy $\overline{ET}$ is more favorable than policies E and ET, especially when α, c_t, δ, and η are relatively small. However, policy ET can excel policies E and $\overline{ET}$ when e is relatively small and α is relatively large; policy E can excel polices ET and $\overline{ET}$ when e and c_t are relatively large.

4.7 Conclusion

Unused pharmaceuticals are disposed of unsafely in increasingly large volumes every year. The eco-toxicity arising from unused pharmaceuticals has drawn considerable attention of policy makers, such as the EPA in the U.S and EEA in Europe, who are now advocating the concept of *"green pharmacy"*. The key element of green pharmacy is "benign by design", which aims to eliminate or reduce the use and generation of hazardous substances. However, the major obstacles to the achievement of green pharmacy are high R&D expenses and the lack of incentives and regulations. One possible incentive, as proposed by EEA, is to offer a patent term extension to pharmaceutical companies that formulate greener drugs. Such incentive can encourage both the development of degradable green drugs and technical information disclosure. Yet, it is still unclear how effective the pharmaceutical patent term extension is in inducing green pharmacy and the implication of patent term extension for the social and environmental impacts. Toward that end, we consider an innovative company who collects monopoly profits for its patented medicine and faces competition from a generic rival after the patent expires. Each company can achieve green pharmacy by investing a fixed amount. However, the generic rival can acquire green pharmacy, free of charge, after the expiry of the extended patent that is granted to the innovative company for its development of green pharmacy. Both the social impact (the affordability of pharmaceutical products) and environmental impact (contamination of unwanted pharmaceuticals in the environment) are considered by the regulator when determining the optimal extended patent term. We demonstrate that in the presence of the patent term extension, the innovative company will invest in green pharmacy when the fixed investment cost is low, the extended term of the patent is long and the competition intensity is high. However, patent term extension can result in a lack of affordability. As a result, the regulator should implement the patent extension only with a sufficiently high level of environmental concern. Specifically, the optimal extended term is finite when the regulator is seeking the balance of controlling both social and environmental impacts; the extended term should increase as the fixed investment cost increases or the market competition becomes less competitive.

Pharmaceutical stewardship program is another possible approach to promoting green pharmacy. However, pharmaceutical companies will not choose green pharmacy in the presence of the take-back regulation because the unit compliance cost is typically independent of the choice of green pharmacy; worse still, companies will raise the price so that the consumers partly pay the cost incurred due to the pharmaceutical stewardship program. Nevertheless, we conclude that implementing both the take-back regulation and the patent term extension dominates the single policy of the patent term extension when the compliance cost is relatively small, the fixed investment cost and the collection rate are relatively large, the competition is either nominal or sufficiently intensive, and the environmental issue is relatively urgent. In addition, we propose a modified take-back regulation such that the unit compliance cost is lower for companies with green pharmacy than without green pharmacy. Such regulation can encourage both companies to invest in green pharmacy and is better than the patent extension when the competition intensity is relatively high. Numerical results indicate that the modified take-back regulation is generally superior to the traditional take-back regulation when the regulator considers adding the take-back regulation to the patent term extension. An interesting observation is that the innovative company would sometimes go green without requesting patent extension under the modified joint policy. The reason is that the generic company cannot take a free-ride after the patent expires, which helps the innovative company to lessen the competition from the generics. However, a single policy of patent term extension can still outperform a combined policy when the needs of pharmaceuticals are compelling or when the compliance cost is relatively large.

We note that our results are based in part on the assumption that a company can obtain green pharmacy either by its R&D investment or by waiting for the technical disclosure of its competitor after patent expires. Nevertheless, we also consider, as a modeling extension, the possibility that it takes sufficiently short time for the generic company to duplicate an unpatented green technology without enabling disclosure. For this extension, we find that the previous analysis for policies N and E remains unchanged. However, this extension can change the equilibria under policy T or $\bar{T}$. Assuming that when the innovative or generic company invests in green technology, the probability that the green technology is hard to duplicate is p, and the probability that it is easy to duplicate is $1 - p$. We consider $p < 1$ because $p = 1$ represents the case we have already discussed before. We find that, in general, our qualitative results and insights continue to apply. However, compared with Lemma 4.6.1, (G_1, G_1) is less likely to be the equilibrium while (O, O) is more likely to be the equilibrium. This is because companies are hesitant to invest in green pharmacy when facing a potential imitation risk by its competitor and a potential opportunity of free-ride. Interestingly, when p is sufficiently small, the equilibria are not unique under certain circumstance: the fact that (G_1, O) and (O, G_1) are both equilibria indicates that it is profitable for a company to take a free ride if its competitor invests in green pharmacy while it is still profitable to invest if its competitor does not. From the perspective of the regulator, implementing policy T or $\bar{T}$ can be more effective with $p < 1$ than $p = 1$ because the possibility of easy duplication of green pharmacy could lead to the reduction in environmental impact.

In closing, we acknowledge the following limitations of our model. First, it implicitly assumes that the GHG emissions associated with the collection and disposal of unused and wasted medicine are nominal, and the APIs introduced to sewage as a result of excretion are negligible. In fact, these impacts can sometimes be remarkable. For example, Bound and Voulvoulis (2005) estimated that a total of 34% of metabolic products was excreted in active forms though "active" may not necessarily be interpreted as "eco-toxic". In principle, the relaxation of these two assumptions will lead to a greater emphasis by the regulator on the promotion of green pharmacy because green pharmacy reduces the requirement for collection and lowers the risk of eco-toxicity caused by excretion or bathing. Second, the demand of pharmaceuticals is assumed to be price-sensitive, which generally holds for over-the-counter products. For prescribed medicines, recommendations by the doctors and the third-party payment make the price elasticity of demand relatively small, which can favor the small innovations (Ganuza et al. 2009).

Table 4.1: Model Notation

Decision Variables of the Pharmaceutical Companies	
p_m, d_m	the monopoly price and demand of brand name drugs, respectively, before the patent expires
$p_1(p_2), d_1(d_2)$	the price and demand of brand name drugs (generic drugs), respectively, after the patent expires
$S_1(S_2)$	the strategies of the innovative (generic) company, where $S_1 \in \{G_0, G_1, O\}$ and $S_2 \in \{F, G_1, O\}$
	G_0: the strategy of investing green pharmacy and obtaining patent extension
	G_1: the strategy of investing green pharmacy but not gaining patent extension
	O: the strategy of not going green
	F: the strategy of going green for free after patent expires
Decision Variables of the Regulator	
S_r	the environmental policy implemented by the regulator, where $S_r \in \{N, E, T, ET\}$
	Policy N: no environmental policy
	Policy E: patent term extension
	Policy T: take-back regulation
	Policy ET: patent term extension and take-back regulation
n	the length of extended term
Parameters	
α	degree of non-greenness
A	one-time fixed R&D investment in green pharmacy
c_t	base compliance cost of the take-back regulation per unit
δ	valuation factor of generic drugs
e_1	social impact of unaffordable medicine per person per period (in monetary terms)
e_2	environmental impact per unit per period (in monetary terms)
e	impact ratio. $e = \frac{e_1}{e_2}$
η	proportion of unwanted drugs that are unsafely disposed (without being taken back)
r	discount factor
T_0	the time when the original patent expires

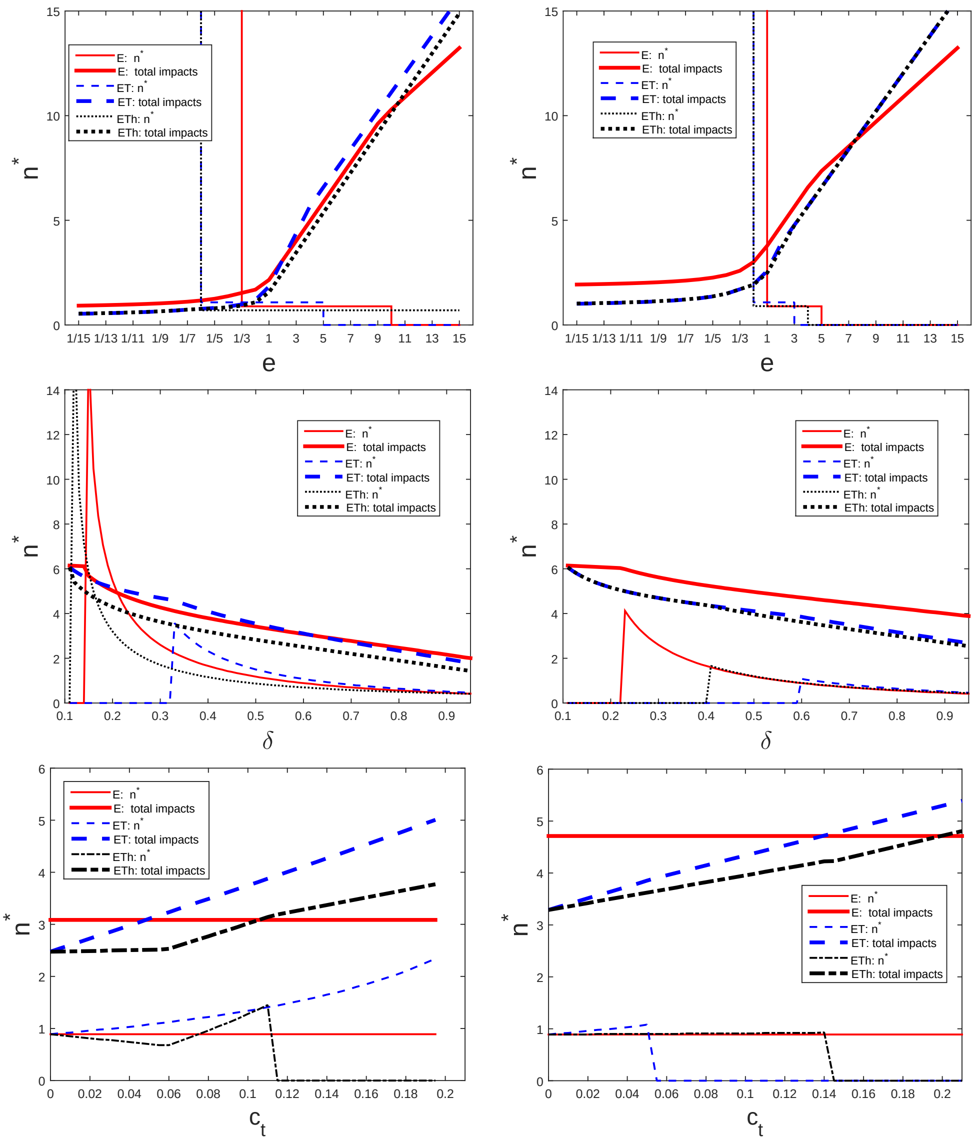

Figure 4.8: Optimal Length of Patent Extension and Total Impacts under Different Policies

(1^{st} Row) $A = 0.1$, $c_t = 0.05$, $\delta = 0.6$, $\eta = 0.5$, $r = 0.8$; (2^{nd} Row) $A = 0.1$, $c_t = 0.05$, $e = 2$, $\eta = 0.5$, $r = 0.8$; (3^{rd} Row) $A = 0.1$, $\delta = 0.6$, $e = 2$, $\eta = 0.5$, $r = 0.8$. (1^{st} Col.) $\alpha = 0.3$; (2^{nd} Col.) $\alpha = 0.7$. Note $c_t \leq \frac{(1-\delta)\delta}{2-\alpha\delta-\delta}$ based on our assumption.

CHAPTER 5

CONCLUSION

"There is no Plan B because we do not have a Planet B."

– Ban Ki-moon.

In 2014, U.S. EPA published the third edition of *Climate Change Indicators in the United States*. According to the report, average U.S. and global temperatures are rising, snow and rainfall patterns are changing, extreme weather and climate events are increasing, ragweed pollen season and growing season for crops are lengthening, and the oceans are becoming more acidic. Scientific evidence shows that many of these climate changes are linked to the increase in greenhouse gases emissions as a result of human activities (U.S. EPA 2014). To reduce the greenhouse gasses emissions, a large number of research endeavors have been made in the past several decades; however, more efforts are needed to help us live sustainable lives and save our planet.

Eco-friendly design has been one of the key topics studied in sustainable operations management. Growing research attention has been shifting from an end-of-pipe-control approach to a benign-by-design approach (Angell and Klassen 1999). Eco-friendly design is motivated by the potential economic benefits, stringent environmental legislation, and growing public awareness, among others. In the remanufacturing industry, Design for the Environment (DfE) has proven to be a key to the success of product recovery operations. DfE helps bring full potential of product recovery into play in the context of different firm or market structures. DfE is also equally applied to the products that have little end-of-life value. It enables companies to use fewer harmful components during manufacturing and to minimize pollutant releases to the environment after disposal.

This dissertation discusses the mechanisms to promote DfE and the consequences of implementing DfE, as illustrated in Figure 5.1. DfE is not always

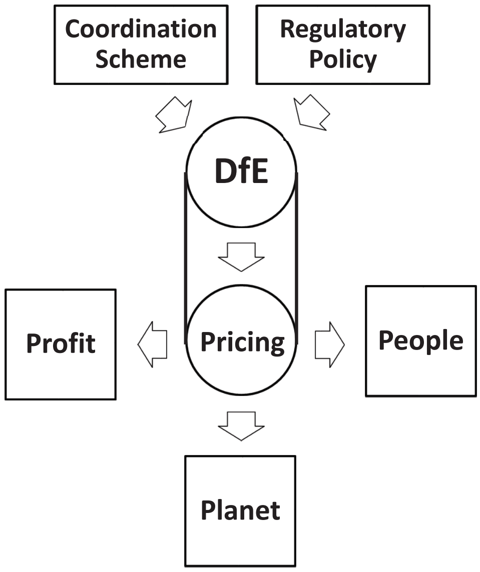

Figure 5.1: Research Focus of This Dissertation

a natural choice by the producers and sometimes external incentives or regulations are needed to induce DfE. Two regulatory policies are analyzed in the setting of the pharmaceutical industry: patent extension and take-back regulation. Another approach to achieving DfE is through inter-organizational coordination. This dissertation examines the effectiveness of imposing single-parameter schemes (transfer price or fixed lump sum transfer) and two-part tariff to pursue DfE.

DfE facilitates product end-of-life recovery and can reduce adverse environmental impacts. However, DfE can also increase the production cost and result in higher product prices. Understanding the impact of design decisions on profit, people, and planet is critical in analyzing DfE. Therefore, in this dissertation, a firm or a division maximizes its profit by deciding product design and prices; demand can be characterized by consumer's vertical differentiation and price; and decisions made by firms and consumers influence the environmental impact.

This dissertation makes the following contributions: It extends the analysis of take-back regulation to pharmaceuticals and makes the first attempt to validate the proposal of implementing patent extension in achieving DfE. It also extends supply chain coordination studies by incorporating DfE decisions. In addition, the study develops guidelines for optimal pricing to companies that embrace the idea of DfE. To probe deeper into the consequences of DfE, this dissertation defines and evaluates different stakeholders and environmental measures, and it relates environmental stewardship to other outcomes such as profit, revenue and social welfare.

There are still many open questions regarding the promotion, implementation, and consequences of DfE. The work presented in this dissertation can be extended in several ways.

One line of future research might be to study DfE in the context of service operations. The current DfE tools are mainly applied to physical merchandises, such as heavy-duty and off-road equipment, motor vehicle parts, IT products and medical devices. However, a recent transition is from selling physical products to offering a service-based package (Corbett and Klassen 2006). Researchers have demonstrated that the adoption of green practices is related to better firm performance in some service industries (*e.g.*, Goodman 2000, Kassinis and Soteriou 2003). Unfortunately, little attention has been paid to the DfE approach for service systems and the examination of potential economic and environmental benefits of DfE in the service industry.

Another direction for future research is to develop and evaluate a more comprehensive DfE that deals with the recovery of heterogeneous end-of-life products of the same generation and the upgradeability of a product over multiple generations. Optimizing the design of a product portfolio can offer more practical applications than an all-in-one approach; however, considering a product portfolio design can potentially increase the complexity of the target system. Thus, a comprehensive DfE analysis along with large-scale optimization methods, such as a hierarchical approach or a decomposition approach, need to be developed in the future.

Additionally, data-driven analysis that encodes system parameters is another potential to advance the study of DfE. Encouraged by emerging big data applications, researchers can build more sophisticated models in which dynamics and uncertainty embedded in DfE can be addressed in a joint manner. For example, the demand or the willingness-to-pay for an eco-friendly product can be estimated using a data-driven tool before the product is launched or reintroduced. Another application of data-driven analysis techniques is DEA-based energy and environmental efficiency measurement and monitoring (Zhou et al. 2008). The DEA models and its extensions can be employed to analyze the environmental performance of DfE.

The topic of DfE in the pharmaceutical industry is relatively new in the field of operations management. Many other operational questions related to pharmaceutical stewardship remain unanswered. For example, what is the best approach to collect unwanted medical products: the mail-back program, the permanent disposal program, or the periodically scheduled collection program? The method of collection may significantly influence the participation rate, the ease of operations, cost, and greenhouse gas emissions. Another question is how to allocate cost and resources (*e.g.*, reverse logistics networks) when collecting unused and expired medical products? The collection and disposal costs are sometimes funded in part by manufacturers based on prior year's sales volumes (*e.g.*, in France and Canada). However, such an allocation mechanism does not consider the synergies inherent in resource sharing among participating companies. Thus, it is critical to develop a cost allocation mechanism that not only induces resource sharing in the collective system, but also maximizes cost efficiency or increases return rate.

APPENDIX A

APPENDIX FOR CHAPTER 2

APPENDIX A.1 PROOF OF PROPOSITIONS

Proof of Proposition 2.3.1. Part (i) follows directly from the constraint that the manufacturer cannot remanufacture more products than returned products as follows: $d_{or}+d_{nr} \leq d_{nn}+d_{nr} \Rightarrow d_{or} \leq d_{nn}$. Thus, $d_{or} > 0$ implies that $d_{nn} > 0$.

Part (ii) is by contradiction. From Table 2.1, $d_{nr} > 0 \Rightarrow \exists\, \theta_1$ such that $S_{nr}(\theta_1) \geq S_{nn}(\theta_1) \Leftrightarrow \theta_1 \leq \frac{p_2-p_r}{\alpha-\delta_r}$ and $S_{nr}(\theta_1) \geq S_{or}(\theta_1) \Leftrightarrow \theta_1 \geq p_1-s$. Thus, the existence of θ_1 requires that $p_1-s \leq \frac{p_2-p_r}{\alpha-\delta_r}$. Note $p_1-s = \frac{p_2-p_r}{\alpha-\delta_r} \Rightarrow d_{nr} = 0$. Thus, $d_{nr} > 0$ requires that $p_1 - s < \frac{p_2-p_r}{\alpha-\delta_r}$. Similarly, $d_{on} > 0 \Rightarrow \exists\, \theta_2$ such that $S_{on}(\theta_2) \geq S_{nn}(\theta_2) \Leftrightarrow \theta_2 \leq p_1 - s$ and $S_{on}(\theta_2) \geq S_{or}(\theta_2) \Leftrightarrow \theta_2 \geq \frac{p_2-p_r}{\alpha-\delta_r}$. Thus, the existence of θ_2 requires that $\frac{p_2-p_r}{\alpha-\delta_r} \leq p_1-s$, which is a contradiction.

To prove part (iii), we use Table 2.2(a) because $d_{nr} = d_{or} = 0$, by assumption. Assume $d_{nn} > 0$. If $d_{on} = 0$, then $d_{nu} = 0$ only when $\frac{p_2}{\alpha-\delta} - \frac{p_1}{1+\delta} \leq 0$; if $d_{nu} = 0$, then $d_{on} = 0$ only when $p_1 - \frac{p_2}{\alpha} \leq 0$. Therefore, after some algebra, we must have $\alpha p_1 \leq p_2 \leq \frac{\alpha-\delta}{1+\delta} p_1$, which is impossible if $p_1 \neq 0$ or $p_2 \neq 0$ because $\alpha > \frac{\alpha-\delta}{1+\delta} > 0$. ⊠

Proof of Proposition 2.3.2. Part (i). In both cases, customers either buy the only offered product or do not purchase. We first consider when the offered product is available only in the second period. The object function can be written as $\Pi_{00010} = \max_{p_2}(p_2 - c_0) \cdot d_{on}$ subject to $d_{on} > 0, p_2 \geq 0$. Since $d_{nr} = d_{or} = 0$, $s = 0$ and $d_{on} = 1 - \frac{p_2}{\alpha}$. It is easy to show that $p_2^* = \frac{\alpha+c_0}{2}$ and $\Pi^*_{00010} = \frac{(\alpha-c_0)^2}{4\alpha}$ when $c_0 < \alpha$ and $\Pi^*_{00010} = 0$ (no production) when $c_0 \geq \alpha$. Similarly, when the offered new product is available only in the first period. It is straightforward to show that $p_1^* = \frac{1+\delta+c_0}{2}$ and $\Pi^*_{00100} = \frac{(1+\delta-c_0)^2}{4(1+\delta)}$ when $c_0 < 1 + \delta$ and $\Pi^*_{00100} = 0$ (no production) when $c_0 \geq 1 + \delta$.

When $c_0 < \alpha$, we must have $c_0 < 1+\delta$ because $\alpha < 1+\delta$. Thus, $\Pi^*_{00100} > 0$ whenever $\Pi^*_{00010} > 0$. Moreover, $\Pi^*_{00010} = \frac{(\alpha-c_0)^2}{4\alpha} > \Pi^*_{00100} = \frac{(1+\delta-c_0)^2}{4(1+\delta)}$ only when $\alpha(1+\delta) > c_0^2$, which is impossible as $c_0 < \alpha, c_0 < 1+\delta$. When $c_0 \geq \alpha$, $\Pi^*_{00010} = 0$ and $\Pi^*_{00100} \geq 0$. Therefore, the statement follows.

Part (ii). We first solve the manufacturer's problem when M=(0,0,1,1,0):

$$\begin{aligned}\Pi_{01010} &= \max_{p_1,p_2} (p_1 - c_0)\cdot d_{nu} + (p_2 - c_0)\cdot d_{on}\\ s.t \quad & d_{nn} = 0\\ & d_{nu}, d_{on} > 0\\ & p_1, p_2 \geq 0\end{aligned}$$

Since $d_{nr} = d_{or} = 0$, $s = 0$. Note $d_{nn} = 0$ if $\frac{p_2}{\alpha-\delta} \geq 1$. The problem can be further expressed as

$$\begin{aligned}\Pi_{00110} &= \max_{p_1,p_2} (p_1 - c_0)\cdot\left(1 - \frac{p_1-p_2}{1+\delta-\alpha}\right) + (p_2 - c_0)\cdot\left(\frac{p_1-p_2}{1+\delta-\alpha} - \frac{p_2}{\alpha}\right)\\ s.t. \quad & \frac{p_2}{\alpha-\delta} - 1 \geq 0 && \text{(A.1)}\\ & 1 - \frac{p_1-p_2}{1+\delta-\alpha} > 0, \frac{p_1-p_2}{1+\delta-\alpha} - \frac{p_2}{\alpha} > 0 && \text{(A.2)}\\ & p_1 \geq 0, p_2 \geq 0 && \text{(A.3)}\end{aligned}$$

Consider the relaxed problem where (A.2) is replaced by $1 - \frac{p_1-p_2}{1+\delta-\alpha} \geq 0$, $\frac{p_1-p_2}{1+\delta-\alpha} - \frac{p_2}{\alpha} \geq 0$ and denote the corresponding optimal profit as $\tilde{\Pi}^*_{00110}$. Thus, the Lagrangian function of the relaxed problem can be written as

$$\begin{aligned}L &= (p_1 - c_0)\cdot\left(1 - \frac{p_1-p_2}{1+\delta-\alpha}\right) + (p_2 - c_0)\cdot\left(\frac{p_1-p_2}{1+\delta-\alpha} - \frac{p_2}{\alpha}\right)\\ &\quad +\mu_1\left(\frac{p_2}{\alpha-\delta} - 1\right) + \mu_2\left(1 - \frac{p_1-p_2}{1+\delta-\alpha}\right) + \mu_3\left(\frac{p_1-p_2}{1+\delta-\alpha} - \frac{p_2}{\alpha}\right)\end{aligned}$$

Based on the KKT conditions, we obtain two KKT points:

Case 1: if $a \geq \frac{2\delta(1+\delta)}{1+\delta-c_0}$, then $p_1^* = \frac{(\alpha-\delta)(1+\delta)}{\alpha}$ and $p_2^* = \alpha - \delta$ and $\tilde{\Pi}^*_{00110} = \frac{\delta[(\alpha-\delta)(1+\delta)-\alpha c_0]}{\alpha^2}$. Note when $c_0 \geq \frac{(\alpha-\delta)(1+\delta)}{\alpha}$, the profit is negative and hence we assume no production. We can further prove that $\tilde{\Pi}^*_{00110} \leq \Pi^*_{00100} = \frac{(1+\delta-c_0)^2}{4(1+\delta)}$ when $c_0 < \frac{(\alpha-\delta)(1+\delta)}{\alpha}$ and $2\delta < \alpha < 1+\delta$.

Case 2: if $a < \frac{2\delta(1+\delta)}{1+\delta-c_0}$, then $p_1^* = \frac{1+\delta+c_0}{2}$ and $p_2^* = \frac{\alpha(1+\delta+c_0)}{2(1+\delta)}$ and $\tilde{\Pi}^*_{00110} = \frac{(1+\delta-c_0)^2}{4(1+\delta)}$. In such a case $\tilde{\Pi}^*_{00110} = \Pi^*_{00100}$.

The proposition thus follows because $\Pi^*_{00110} \leq \tilde{\Pi}^*_{00110}$.$\boxtimes$

APPENDIX A.2 DERIVATIONS OF $CS\,(k)$ AND $SW(k)$

Derivation of $CS\,(k)$. Given $d_{nn}, d_{nr}, d_{nu}, d_{on}, d_{or}$, first consider the case in which $k = 1$. Let $\theta_1 = 1 - d_{nn}, \theta_2 = \theta_1 - d_{nr}, \theta_3 = \theta_2 - d_{nu}, \theta_2 = \theta_3 - d_{on}, \theta_5 = \theta_4 - d_{or}$. Then, by definition of consumer surplus, $CS\,(k = 1)$ can be expressed as follows:

$$
\begin{aligned}
CS\,(k=1) &= \int_{\theta_1}^{1} \theta\,(1+\alpha) - (p_1 + p_2 - s)\,d\theta + \int_{\theta_2}^{\theta_1} \theta\,(1+\delta_r) - (p_1 + p_r - s)\,d\theta \\
&\quad + \int_{\theta_3}^{\theta_2} \theta\,(1+\delta) - p_1 d\theta + \int_{\theta_4}^{\theta_3} (\theta\alpha - p_2)\,d\theta + \int_{\theta_5}^{\theta_4} (\theta\delta_r - p_r)\,d\theta \\
&= \frac{(1-\theta_1^2)\,(1+\alpha)}{2} - (p_1 + p_2 - s)\,(1-\theta_1) + \frac{(\theta_1^2 - \theta_2^2)\,(1+\delta_r)}{2} \\
&\quad - (p_1 + p_r - s)\,(\theta_1 - \theta_2) + \frac{(\theta_2^2 - \theta_3^2)\,(1+\delta)}{2} - p_1\,(\theta_2 - \theta_3) \\
&\quad + \frac{(\theta_3^2 - \theta_4^2)\,\alpha}{2} - p_2\,(\theta_3 - \theta_4) + \frac{(\theta_4^2 - \theta_5^2)\,\delta_r}{2} - p_r\,(\theta_4 - \theta_5)
\end{aligned}
$$

Next, for the case in which $k = 0$, let $\theta_1 = 1 - d_{nn}, \theta_2 = \theta_1 - d_{nu}, \theta_3 = \theta_2 - d_{on}$. Then

$$
\begin{aligned}
CS\,(k=0) &= \int_{\theta_1}^{1} \theta\,(1+\alpha) - (p_1 + p_2)\,d\theta + \int_{\theta_2}^{\theta_1} \theta\,(1+\delta) - p_1 d\theta \\
&\quad + \int_{\theta_3}^{\theta_2} (\theta\alpha - p_2)\,d\theta \\
&= \frac{(1-\theta_1^2)\,(1+\alpha)}{2} - (p_1 + p_2)\,(1-\theta_1) + \frac{(\theta_1^2 - \theta_2^2)\,(1+\delta)}{2} \\
&\quad - p_1\,(\theta_1 - \theta_2) + \frac{(\theta_2^2 - \theta_3^2)\,\alpha}{2} - p_2\,(\theta_2 - \theta_3)
\end{aligned}
$$

Derivation of $SW(k)$. Given $d_{nn}, d_{nr}, d_{nu}, d_{on}, d_{or}$, first consider the case in which $k = 1$. Let $\theta_1 = 1 - d_{nn}, \theta_2 = \theta_1 - d_{nr}, \theta_3 = \theta_2 - d_{nu}, \theta_2 = \theta_3 - d_{on}, \theta_5 = \theta_4 - d_{or}$. Then $SW\,(k = 1)$ is defined as the sum of manufacturer profit and consumer surplus as follows:

$$\begin{aligned}
SW\left(k=1\right) &= \int_{\theta_1}^{1}\theta\left(1+\alpha\right)d\theta+\int_{\theta_2}^{\theta_1}\theta\left(1+\delta_r\right)d\theta+\int_{\theta_3}^{\theta_2}\theta\left(1+\delta\right)d\theta \\
&\quad +\int_{\theta_4}^{\theta_3}\theta\alpha d\theta+\int_{\theta_5}^{\theta_4}\theta\delta_r d\theta \\
&= \frac{\left(1-\theta_1^2\right)\left(1+\alpha\right)}{2}+\frac{\left(\theta_1^2-\theta_2^2\right)\left(1+\delta_r\right)}{2}+\frac{\left(\theta_2^2-\theta_3^2\right)\left(1+\delta\right)}{2} \\
&\quad +\frac{\left(\theta_3^2-\theta_4^2\right)\alpha}{2}+\frac{\left(\theta_4^2-\theta_5^2\right)\delta_r}{2}
\end{aligned}$$

Similarly, for the case in which $k=0$, let $\theta_1=1-d_{nn}, \theta_2=\theta_1-d_{nu}, \theta_3=\theta_2-d_{on}$. Then

$$\begin{aligned}
SW\left(k=0\right) &= \int_{\theta_1}^{1}\theta\left(1+\alpha\right)d\theta+\int_{\theta_2}^{\theta_1}\theta\left(1+\delta\right)d\theta+\int_{\theta_3}^{\theta_2}\theta\alpha d\theta \\
&= \frac{\left(1-\theta_1^2\right)\left(1+\alpha\right)}{2}+\frac{\left(\theta_1^2-\theta_2^2\right)\left(1+\delta\right)}{2}+\frac{\left(\theta_2^2-\theta_3^2\right)\alpha}{2}
\end{aligned}$$

APPENDIX B

APPENDIX FOR CHAPTER 3

Proofs are restricted to the parameter space Ω and $w_1, w_2 \in [0,1]$ (referred to as "the assumption"), as described in detail in Section 3.3.1. Profit maximizing problems are solved using the method of Lagrange multipliers unless stated otherwise.

Proof of Proposition 3.3.1 and the Optimal Solution. Firstly, given w_1, w_2 (if applicable) and k, we solve the retailer's optimization problem (3.5) subject to constraints (3.3)-(3.4). Table B.1 summarizes the retailer's optimal strategy.

Secondly, we solve the firm's optimization problem. Let superscript NR (R) denote the optimal solution when $k = 0$ ($k = 1$). If $k = 0$, then $\Pi_F^{NR} = \max_{w_1} \frac{1-w_1}{2} \cdot (w_1 - c_1)$ $s.t.$ $0 \leq d_1 = \frac{1-w_1}{2} \leq 1$. One can show that $w_1^{NR} = \frac{1+c_1}{2}$, $\Pi_F^{NR} = \frac{(1-c_1)^2}{8}$ and $\Pi_R^{NR} = \frac{(1-c_1)^2}{16}$. Note that a centralized firm can always make new products non-remanufacturable so that its profit is at least Π_F^{NR}. If $k = 1$, then $\Pi_F^R = \max_{w_1, w_2} d_1 \left[w_1 - (c_1 + \eta)\right] + d_2 \left(w_2 - c_2\right)$, where d_1 and d_2 are given in Table B.1 and $w_1, w_2 \in [0,1]$. Note that it is not optimal for the firm to undertake remanufacturing when $w_2 > \delta w_1$ because given such (w_1, w_2), a remanufacturable product design will not increase sale but only increase the cost. Therefore, we restrict our discussion to case 1 and case 3 in Table B.1 when $k = 1$.

Case 1: Solve $\Pi_F^1 = \max_{w_1, w_2} \frac{1-\delta-w_1+w_2}{2(1-\delta)} \left[w_1 - (c_1 + \eta)\right] + \frac{\delta w_1 - w_2}{2(1-\delta)\delta} \left(w_2 - c_2\right)$ $s.t.$

Table B.1: The Retailer's Opt. Strategy in the Centralized or Decentralized Scenario

Case	Condition	d_1^*	d_2^*
1	$k = 1$ & $\max\left\{\frac{(2w_1-1+\delta)\delta}{1+\delta}, 0\right\} \leq w_2 \leq \delta w_1$	$\frac{1-\delta-w_1+w_2}{2(1-\delta)}$	$\frac{\delta w_1 - w_2}{2(1-\delta)\delta}$
2	$k = 0$ or $k = 1$ & $w_2 > \delta w_1$	$\frac{1-w_1}{2}$	0
3	$k = 1$ & $0 \leq w_2 \leq \frac{(2w_1-1+\delta)\delta}{1+\delta}$	$\frac{1+\delta-w_1-w_2}{2(1+3\delta)}$	$\frac{1+\delta-w_1-w_2}{2(1+3\delta)}$

$\max\left\{\frac{(2w_1-1+\delta)\delta}{1+\delta},0\right\} \le w_2 \le \delta w_1$ and $0 \le w_1 \le 1$. We obtain the following solution:

(1-1) if $\frac{c_2}{\delta}-\eta \le c_1 \le \frac{1-\delta-2\eta}{2}+\frac{(1+\delta)c_2}{2\delta}$, then $w_1^*=\frac{1+c_1+\eta}{2}$, $w_2^*=\frac{c_2+\delta}{2}$, $\Pi_F^{1-1}=\frac{[(1-c_1-\eta)-(\delta-c_2)]^2}{8(1-\delta)}+\frac{(\delta-c_2)^2}{8\delta}$.

(1-2) if $c_1 \le \frac{c_2}{\delta}-\eta$, then $w_1^*=\frac{1+c_1+\eta}{2}$, $w_2^*=\frac{\delta(1+c_1+\eta)}{2}$, $\Pi_F^{1-2}=\frac{(1-c_1-\eta)^2}{8}<\Pi_F^{NR}$. This subcase is dominated by strategy NR.

(1-3) if $c_1 \ge \frac{1-\delta-2\eta}{2}+\frac{(1+\delta)c_2}{2\delta}$, then $w_1^*=1-\frac{(1+\delta)[(1-c_1-\eta)+(\delta-c_2)]}{2(1+3\delta)}$, $w_2^*=\frac{\delta(c_1+c_2+2\delta+\eta)}{1+3\delta}$, $\Pi_F^{1-3}=\frac{(1+\delta-c_1-c_2-\eta)^2}{8(1+3\delta)}$.

Case 3: Solve $\Pi_F^3=\max\limits_{w_1,w_2}\frac{1+\delta-w_1-w_2}{2(1+3\delta)}\left[w_1-(c_1+\eta)\right]+\frac{1+\delta-w_1-w_2}{2(1+3\delta)}(w_2-c_2)$ *s.t.* $0 \le w_2 \le \frac{(2w_1-1+\delta)\delta}{1+\delta}$ and $0 \le w_1 \le 1$,. We obtain the following solution under the assumption:

(3) If $\frac{1+4\delta-\delta^2+(c_1+\eta+c_2)(1+\delta)}{2(1+3\delta)} \le w_1 \le \min\{1,\frac{1+c_1+\eta+\delta+c_2}{2}\}$, then $w_2^*=\frac{1}{2}(1+\delta+c_1+c_2+\eta)-w_1^*$, $\Pi_F^3=\frac{(1+\delta-c_1-c_2-\eta)^2}{8(1+3\delta)}$. Note that (1-3) is a special case of (3). In addition, (3) indicates that for any c_1,c_2,δ,η under the assumption, a centralized firm can always make new products remanufacturable so that its profit is at least Π_F^3 by choosing a proper w_1 and w_2.

Lastly, k^C, w_1^C and w_2^C can be determined by comparing firm profits in different cases. One can show that $\Pi_F^{1-1} \ge \Pi_F^3$ for any c_1,c_2,δ,η satisfying the assumption. Also, $\Pi_F^{1-1}>\Pi_F^{NR} \Leftrightarrow c_1<-\frac{\sqrt{(1-\delta)\eta(2\delta+\eta-2c_2)}-c_2+\eta}{\delta}$ or $c_1>\frac{\sqrt{(1-\delta)\eta(2\delta+\eta-2c_2)}+c_2-\eta}{\delta}$. Recall that (1-1) is valid only when $\frac{c_2}{\delta}-\eta \le c_1 \le \frac{1-\delta-2\eta}{2}+\frac{(1+\delta)c_2}{2\delta}$ and note that $-\frac{\sqrt{(1-\delta)\eta(2\delta+\eta-2c_2)}-c_2+\eta}{\delta} \le \frac{c_2}{\delta}-\eta$ and $\frac{c_2}{\delta}-\eta \le \frac{\sqrt{(1-\delta)\eta(2\delta+\eta-2c_2)}+c_2-\eta}{\delta}$ when $c_2 \le \delta$. Thus, $\Pi_F^{1-1} \ge \max\{\Pi_F^3,\Pi_F^{NR}\}$ when $\frac{\sqrt{(1-\delta)\eta(2\delta+\eta-2c_2)}+c_2-\eta}{\delta} \le c_1 \le \frac{1-\delta-2\eta}{2}+\frac{(1+\delta)c_2}{2\delta}$, which is the condition when R1 is optimal. Similarly, we can derive the conditions for R2 and NR to be optimal, respectively, which are illustrated in Table 3.1 and Proposition 3.3.1. In fact, (1-1) and (3) represent strategy R1 and R2, respectively. ⊠

Proof of Corollary 3.3.2. Recall that $c_1 \in [c_2+\eta, 1-\eta]$ under the assumption.

If $\eta>\frac{(\delta-c_2)\left(\sqrt{1+3\delta}-1-\delta\right)}{2\delta}$, then NR is not optimal when $\frac{2\delta+\eta+c_2-(\delta-c_2-\eta)\sqrt{1+3\delta}}{3\delta} \le c_2+\eta$, or equivalently $c_2+\eta \le \frac{1-\sqrt{1+3\delta}}{3} \le 0$. This is attainable only when $\delta=c_2=\eta=0$. This case is eliminated because $\delta>0$.

If $\eta \le \frac{(\delta-c_2)\left(\sqrt{1+3\delta}-1-\delta\right)}{2\delta}$, then NR is not optimal when $\frac{\sqrt{(1-\delta)\eta(2\delta+\eta-2c_2)}+c_2-\eta}{\delta} \le c_2+\eta$. Combining the two constraints, NR cannot be optimal when (i) $\frac{c_2(1-\delta)}{1+\delta} \le \eta \le \min\{\frac{(\delta-c_2)\left(\sqrt{1+3\delta}-1-\delta\right)}{2\delta},\frac{(1+c_2)\delta(1-\delta)-(1-\delta)\sqrt{\delta\left(-3c_2^2+2c_2\delta+\delta\right)}}{\delta(3+\delta)}\}$.

Table B.2: D2's Optimal Strategy in the Decentralized Scenario when $k = 1$

Case	Condition	d_1^*	d_2^*	w_2^*
A	$\frac{c_2}{\delta} \leq w_1 \leq \frac{2(1-\delta)}{3-\delta} + \frac{(1+\delta)c_2}{(3-\delta)\delta}$	$\frac{1}{2} - \frac{(2-\delta)w_1 - c_2}{4(1-\delta)}$	$\frac{w_1\delta - c_2}{4(1-\delta)\delta}$	$\frac{w_1\delta + c_2}{2}$
B	$\frac{1+4\delta-\delta^2+(1+\delta)c_2}{1+5\delta} \leq w_1 \leq 1$	$\frac{1+\delta-w_1-c_2}{4(1+3\delta)}$	d_1^*	$\frac{1+\delta-w_1}{2}$
C	$\frac{2(1-\delta)\delta+(1+\delta)c_2}{(3-\delta)\delta} \leq w_1 \leq \frac{1}{2} - \frac{(1+\delta)(\delta-c_2)}{1+5\delta}$	$\frac{1-w_1}{2(1+\delta)}$	d_1^*	$\frac{(2w_1-1+\delta)\delta}{1+\delta}$

$\frac{(1+c_2)\delta(1-\delta)-(1-\delta)\sqrt{\delta(\delta+2c_2\delta-3c_2^2)}}{\delta(3+\delta)} \geq \frac{c_2(1-\delta)}{1+\delta}$ requires that $\delta = c_2 = 1$ or $c_2 = 0$; or (ii) $\max\{\frac{c_2(1-\delta)}{1+\delta}, \frac{(1+c_2)\delta(1-\delta)+(1-\delta)\sqrt{\delta(\delta+2c_2\delta-3c_2^2)}}{\delta(3+\delta)}\} \leq \eta \leq \frac{(\delta-c_2)(\sqrt{1+3\delta}-1-\delta)}{2\delta}$. $\frac{(1+c_2)\delta(1-\delta)+(1-\delta)\sqrt{\delta(\delta+2c_2\delta-3c_2^2)}}{\delta(3+\delta)} \leq \frac{(\delta-c_2)(\sqrt{1+3\delta}-1-\delta)}{2\delta}$ requires that $\delta = c_2 = 0$ or $\delta = c_2 = 1$ since $\delta \geq c_2$.

In both case (i) and (ii), $\eta = 0$. Also, $\delta > 0$ and $c_2 < 1 \Rightarrow c_2 = \eta = 0$. ☒

Proof of Proposition 3.3.3 and the Optimal Solution. To prove part (i)-(ii), we first solve the sequential game with backward induction.

Firstly, we solve the retailer's problem. The retailer's problem is the same in the centralized and decentralized scenarios. Thus, the solution is illustrated in Table B.1.

Secondly, we solve D2's problem. If $k = 0$, then D2 makes no production and $\Pi_2^{NR} = 0$. Given w_1, if $k = 1$, we need to solve D2's problem $\Pi_2^* = \max_{w_2} d_2 (w_2 - c_2)$ and then D1's problem. Note that D2 will remanufacture only if $\Pi_2^* \geq 0$, which implies that $w_2 \geq c_2$ must hold. Similar to the centralized scenario, it is not optimal for D1 to choose $k = 1$ if $w_2 \geq \delta w_1$. Thus, we only need to consider two cases given in Table B.1: Case 1 ($\Pi_2 = \max_{w_2 \geq c_2} \frac{\delta w_1 - w_2}{2(1-\delta)\delta} (w_2 - c_2)$ $s.t.$ $\max\left\{\frac{(2w_1-1+\delta)\delta}{1+\delta}, 0\right\} \leq w_2 \leq \delta w_1$) and Case 3 ($\Pi_2 = \max_{w_2 \geq c_2} \frac{1+\delta-w_1-w_2}{2(1+3\delta)} (w_2 - c_2)$ $s.t.$ $0 \leq w_2 \leq \frac{(2w_1-1+\delta)\delta}{1+\delta}$). In a similar fashion to the proof of Proposition 3.3.1, we obtain D2's strategy, which is summarized in Table B.2:

Thirdly, we solve D1's problem. If $k = 0$, then D1 sets $w_1^{NR} = \frac{1+c_1}{2}$. Consequently, $d_1^{NR} = \frac{1-c_1}{4}$, $\Pi_1^{NR} = \frac{(1-c_1)^2}{8}$. Note that D1 can always choose $k = 0$ and earn at least Π_1^{NR}. If $k = 1$, then $\Pi_1^R = \max_{w_1 \geq C_1} d_1 (w_1 - C_1)$, where d_1 is given in Table B.2 and $C_1 = c_1 + \eta$. Note that D1 will not choose a remanufacturable product design if $\Pi_1 < 0$, which implies that $w_1 \geq C_1$ must hold. Thus, we consider the following three cases:

Case A ($\frac{c_2}{\delta} \leq w_1 \leq \frac{2(1-\delta)}{3-\delta} + \frac{(1+\delta)c_2}{(3-\delta)\delta}$): $\Pi_1 = \max_{w_1 \geq C_1} \frac{2(1-\delta)-(2-\delta)w_1+c_2}{4(1-\delta)} (w_1 - C_1)$

(A1) if $\frac{c_2(4-3\delta)-2(1-\delta)\delta}{(2-\delta)\delta} \le C_1 \le \frac{c_2\left(4-\delta-\delta^2\right)+2\delta(1-\delta)^2}{(3-\delta)(2-\delta)\delta}$, then $w_1^* = \frac{C_1(2-\delta)+2(1-\delta)+c_2}{2(2-\delta)}$, $\Pi_1^{A1} = \frac{[2(1-\delta)-C_1(2-\delta)+c_2]^2}{16(2-\delta)(1-\delta)}$.

(A2) if $\frac{c_2\left(4-\delta-\delta^2\right)+2\delta(1-\delta)^2}{(3-\delta)(2-\delta)\delta} \le C_1 \le \frac{2(1-\delta)\delta+c_2(1+\delta)}{(3-\delta)\delta}$, then $w_1^* = \frac{2(1-\delta)\delta+c_2(1+\delta)}{(3-\delta)\delta}$, $\Pi_1^{A2} = \frac{(\delta-c_2)[2-2\delta-C_1(3-\delta)]}{2(3-\delta)^2\delta} + \frac{(\delta-c_2)c_2(1+\delta)}{2(3-\delta)^2\delta^2}$.

(A3) if $C_1 \le \frac{c_2(4-3\delta)-2(1-\delta)\delta}{(2-\delta)\delta}$, then $w_1^* = \frac{c_2}{\delta}$, $\Pi_1^{A3} = \frac{(\delta-c_2)(c_2-C_1\delta)}{2\delta^2}$, $d_1 = \frac{\delta-c_2}{2\delta}$ and $d_2 = 0$. This case is dominated by strategy NR because $\Pi_1^{A3} < \Pi_1^{NR}$.

Case B ($\frac{1+4\delta-\delta^2+(1+\delta)c_2}{1+5\delta} \le w_1 \le 1$): $\Pi_1 = \max_{w_1 \ge C_1} \frac{1+\delta-w_1-c_2}{4(1+3\delta)}(w_1 - C_1)$

(B1) if $\frac{1+2\delta-7\delta^2+(3+7\delta)c_2}{1+5\delta} \le C_1 \le 1-\delta+c_2$, then $w_1^* = \frac{1+C_1+\delta-c_2}{2}$, $\Pi_1^{B1} = \frac{(1-C_1+\delta-c_2)^2}{16(1+3\delta)}$.

(B2) if $C_1 \le \frac{1+2\delta-7\delta^2+(3+7\delta)c_2}{1+5\delta}$, then $w_1^* = \frac{1+4\delta-\delta^2+c_2(1+\delta)}{1+5\delta}$, $\Pi_1^{B2} = \frac{(\delta-c_2)}{2(1+5\delta)^2}[1+4\delta-\delta^2-C_1(1+5\delta)+c_2(1+\delta)]$.

(B3) if $C_1 \ge 1-\delta+c_2$, then $w_1^* = 1$, $\Pi_1^{B3} = \frac{(\delta-c_2)(1-C_1)}{4(1+3\delta)}$.

Case C ($\frac{2(1-\delta)}{3-\delta}+\frac{(1+\delta)c_2}{(3-\delta)\delta} \le w_1 \le \frac{1+4\delta-\delta^2+(1+\delta)c_2}{1+5\delta}$): $\Pi_1 = \max_{w_1 \ge C_1} \frac{1-w_1}{2(1+\delta)}(w_1 - C_1)$

(C1) if $\frac{(1-3\delta)\delta+2c_2(1+\delta)}{(3-\delta)\delta} \le C_1 \le \frac{1+3\delta-2\delta^2+2c_2(1+\delta)}{1+5\delta}$, then $w_1^* = \frac{1+C_1}{2}$, $\Pi_1^{C1} = \frac{(1-C_1)^2}{8(1+\delta)}$.

(C2) if $\frac{1+3\delta-2\delta^2+2c_2(1+\delta)}{1+5\delta} \le C_1 \le \frac{1+4\delta-\delta^2+c_2(1+\delta)}{1+5\delta}$, then $w_1^* = \frac{1+4\delta-\delta^2+(1+\delta)c_2}{1+5\delta}$, $\Pi_1^{C2} = \Pi_1^{B2*}$.

(C3) if $C_1 \le \frac{(1-3\delta)\delta+2c_2(1+\delta)}{(3-\delta)\delta}$, then $w_1^* = \frac{2(1-\delta)\delta+(1+\delta)c_2}{(3-\delta)\delta}$, $\Pi_1^{C3} = \frac{(\delta-c_2)}{2(3-\delta)^2\delta^2}\{\delta[2-2\delta-C_1(3-\delta)]+c_2(1+\delta)\}$.

Lastly, we obtain D1's strategy by comparing profits across all cases, which is illustrated in Table 3.2. The two sets of solution associated with strategy R2 in Table 3.2 correspond to (B1) and (B3), respectively. Specifically, Ω_{Re}^D is the set of (c_1, c_2, δ, η) such that $\frac{1+5\delta+\eta+c_2-(\delta-\eta-c_2)\sqrt{2(1+3\delta)}}{1+6\delta} \le c_1 \le 1-\delta-\eta+c_2$ or $\max\{1-\delta-\eta+c_2, \frac{1+2\delta+c_2-\sqrt{(\delta-c_2)(\delta-2\eta-6\delta\eta-c_2)}}{1+3\delta}\} \le c_1 \le \frac{1+2\delta+c_2+\sqrt{(\delta-c_2)(\delta-2\eta-6\delta\eta-c_2)}}{1+3\delta}$ and $\eta \le \frac{\delta-c_2}{2(1+3\delta)}$.

To prove Part (i) and (ii), recall that for any given (c_1, c_2, δ, η), a centralized firm always has the option of choosing $k = 0$ so that its profit is at least $\Pi_F^{NR} = \frac{(1-c_1)^2}{8}$, and has the option of choosing $k = 1$ so that its profit is at least $\Pi_F^3 = \frac{(1-c_1-\eta+\delta-c_2)^2}{8(1+3\delta)}$ (see the proof of Proposition 3.3.1). Thus, $\Pi_F^C \ge \max\left\{\frac{(1-c_1)^2}{8}, \Pi_F^3\right\}$, where $\Pi_F^C = \Pi_F^{NR}$ holds if and only if $k^C = 0$, and $\Pi_F^C > \max\left\{\frac{(1-c_1)^2}{8}, \Pi_F^3\right\}$ if and only if strategy R1 is optimal. In a decentralized firm, D1 always has the option of choosing $k = 0$ (strategy NR) and therefore $\Pi_1^D = \frac{(1-c_1)^2}{8}$ and $\Pi_2^D = 0$. Thus, for the same (c_1, c_2, δ, η), $\frac{(1-c_1)^2}{8} \le \Pi_1^D +$

$\Pi_2^D \leq \max\left\{\frac{(1-c_1)^2}{8}, \frac{3(1-c_1-\eta+\delta-c_2)^2}{32(1+3\delta)}, \frac{(\delta-c_2)[2(1-c_1-\eta)+\delta-c_2]}{8(1+3\delta)}\right\}$ (see the above proof of Proposition 3.3.3), where $\Pi_1^D + \Pi_2^D = \frac{(1-c_1)^2}{8} \Leftrightarrow k^D = 0$. One can show that $\max\left\{\frac{3(1-c_1-\eta+\delta-c_2)^2}{32(1+3\delta)}, \frac{(\delta-c_2)[2(1-c_1-\eta)+\delta-c_2]}{8(1+3\delta)}\right\} < \frac{(1-c_1-\eta+\delta-c_2)^2}{8(1+3\delta)}$ because $1-c_1-\eta > 0$ and $\delta - c_2 \geq 0$. Thus, $\Pi_1^D + \Pi_2^D \leq \Pi_F^C$ for $\forall(c_1, c_2, \delta, \eta) \in \Omega$. Specifically, $\Pi_1^D + \Pi_2^D = \Pi_F^C \Leftrightarrow \Pi_1^D + \Pi_2^D = \frac{(1-c_1)^2}{8} = \Pi_F^C \Leftrightarrow k^C = k^D = 0$.

Next, we prove $\Omega_{Re}^D \subset \Omega_{Re}^C$ by showing that $(c_1, c_2, \delta, \eta) \in \Omega_{Re}^D \Rightarrow (c_1, c_2, \delta, \eta) \in \Omega_{Re}^C$. For $\forall(c_1, c_2, \delta, \eta) \in \Omega_{Re}^D$, either $\Pi_1^D + \Pi_2^D = \frac{3(1-c_1-\eta+\delta-c_2)^2}{32(1+3\delta)} > \frac{(1-c_1)^2}{8}$ or $\Pi_1^D + \Pi_2^D = \frac{(\delta-c_2)[2(1-c_1-\eta)+\delta-c_2]}{8(1+3\delta)} > \frac{(1-c_1)^2}{8}$ must hold. For the same choice of (c_1, c_2, δ, η), the centralized firm's profit satisfies $\Pi_F^C \geq \frac{(1-c_1-\eta+\delta-c_2)^2}{8(1+3\delta)}$ if $k = 1$ and $\Pi_F^C = \frac{(1-c_1)^2}{8}$ if $k = 0$. One can show that given the above $(c_1, c_2, \delta, \eta) \in \Omega_{Re}^C$, $\frac{(1-c_1-\eta+\delta-c_2)^2}{8(1+3\delta)} > \max\left\{\frac{3(1-c_1-\eta+\delta-c_2)^2}{32(1+3\delta)}, \frac{(\delta-c_2)[2(1-c_1-\eta)+\delta-c_2]}{8(1+3\delta)}\right\} > \frac{(1-c_1)^2}{8}$. Therefore, $k^C = 1$, or equivalently, $(c_1, c_2, \delta, \eta) \in \Omega_{Re}^C$.

Part (iii). $\Omega_{Re}^D \subset \Omega_{Re}^C \Rightarrow$ if (c_1, c_2, δ, η) is such that $k^D = 1$, then $k^C = 1$ for the same (c_1, c_2, δ, η). Also, according to Table 3.2, $d_1^D = d_2^D$ when $k^D = 1$. Therefore, to show $d_1^D = d_2^D < d_1^C$, we only need to compare $\left(d_{1-1}^D, d_{1-2}^D\right) = \left(\frac{1-c_1-\eta+\delta-c_2}{8(1+3\delta)}, \frac{\delta-c_2}{4(1+3\delta)}\right)$ with $\left(d_{1-1}^C, d_{1-2}^C\right) = \left(\frac{1-c_1-\eta-\delta+c_2}{4(1-\delta)}, \frac{1-c_1-\eta+\delta-c_2}{4(1+3\delta)}\right)$. One can show that $\max\left\{d_{1-1}^D, d_{1-2}^D\right\} < d_{1-2}^C$ because $1-c_1-\eta > 0$ and $\delta - c_2 \geq 0$. Also, $\max\left\{d_{1-1}^D, d_{1-2}^D\right\} < d_{1-1}^C$ when $c_1 < \frac{1-\delta-2\eta}{2} + \frac{(1+\delta)c_2}{2\delta}$ (a necessary condition for $d_1^C = d_{1-1}^C$). Hence, $d_1^D < d_1^C$.

Similarly, to show $d_1^D + d_2^D < d_1^C + d_2^C$, we only need to compare $d_{1-1}^D + d_{2-1}^D = \frac{1-c_1-\eta+\delta-c_2}{8(1+3\delta)} + \frac{1-c_1-\eta+\delta-c_2}{8(1+3\delta)} = \frac{1-c_1-\eta+\delta-c_2}{4(1+3\delta)}$ and $d_{1-2}^D + d_{2-2}^D = \frac{\delta-c_2}{4(1+3\delta)} + \frac{\delta-c_2}{4(1+3\delta)} = \frac{\delta-c_2}{2(1+3\delta)}$ with $d_{1-1}^C + d_{2-1}^C = \frac{1-c_1-\eta-\delta+c_2}{4(1-\delta)} + \frac{\delta(c_1+\eta)-c_2}{4(1-\delta)\delta} = \frac{\delta-c_2}{4\delta}$ and $d_{1-2}^C + d_{2-2}^C = \frac{1-c_1-\eta+\delta-c_2}{4(1+3\delta)} + \frac{1-c_1-\eta+\delta-c_2}{4(1+3\delta)} = \frac{1-c_1-\eta+\delta-c_2}{2(1+3\delta)}$. One can show that $\max\{d_{1-1}^D + d_{2-1}^D, d_{1-2}^D + d_{2-2}^D\} < d_{1-2}^C + d_{2-2}^C$ because $1-c_1-\eta > 0$ and $\delta - c_2 \geq 0$. Also, $\max\{d_{1-1}^D + d_{2-1}^D, d_{1-2}^D + d_{2-2}^D\} < d_{1-1}^C + d_{2-1}^C$ when $\frac{1+2\delta-7\delta^2+(3+7\delta)c_2}{1+5\delta} - \eta \leq c_1$ (a necessary condition for $d_1^D = d_{1-1}^D$ and $d_2^D = d_{2-1}^D$). Hence, $d_1^D + d_2^D < d_1^C + d_2^C$. The remaining results are directly obtained from Table 3.2. ⊠

Proof of Proposition 3.4.2: Firstly, we solve the retailer's problem. Table B.1 illustrated the optimal solution.

Secondly, we solve D2's problem. If $k = 0$, then D2 makes no production and $\Pi_2^{NR} = 0$. If $k = 1$ and D2 chooses $j = 0$, then the problem is essentially the same as in the decentralized scenario. Thus, in the following analysis, we only need to solve D2's problem $\Pi_2^* = \max_{w_2} d_2(w_2 - c_2) - d_1\tau - f$ when $k = 1$ and $j = 1$, where d_1 and d_2 are given in Table B.1. Note that f is fixed. Thus we first solve $\bar{\Pi}_2 = \max_{w_2} d_2\left(w_2 - c_2\right) - d_1\tau$ and assume that f is such that $\Pi_2^* \geq \Pi_2^D$.

Case 1 ($\max\left\{\frac{(2w_1-1+\delta)\delta}{1+\delta}, 0\right\} \leq w_2 \leq \delta w_1$): $\bar{\Pi}_2 = \max_{w_2} \frac{\delta w_1 - w_2}{2(1-\delta)\delta}\left(w_2 - c_2\right) - \frac{1-\delta-w_1+w_2}{2(1-\delta)}\tau$

(1-1) if $\max\left\{\frac{c_2}{\delta} - \tau, \tau - \frac{c_2}{\delta}\right\} \leq w_1 \leq \frac{2(1-\delta)-\tau(1+\delta)}{3-\delta} + \frac{(1+\delta)c_2}{(3-\delta)\delta}$, then $w_2^* = \frac{\delta(w_1-\tau)+c_2}{2}$, $\bar{\Pi}_2^{1-1} = \frac{\left[\delta w_1+\tau(2-\delta)-c_2\right]^2}{8(1-\delta)\delta} - \frac{(\tau+\delta-c_2)\tau}{2\delta}$ and $\bar{d}_1^{1-1} = \frac{2(1-\delta)-(2-\delta)w_1-\delta\tau+c_2}{4(1-\delta)}$ and $\bar{d}_2^{1-1} = \frac{(w_1+\tau)\delta-c_2}{4(1-\delta)\delta}$.

(1-2) if $\max\left\{\frac{2(1-\delta)-\tau(1+\delta)}{3-\delta} + \frac{c_2(1+\delta)}{(3-\delta)\delta}, \frac{1-\delta}{2}\right\} \leq w_1 \leq 1$, then $\bar{\Pi}_2^{1-2} = \frac{(1-w_1)\left[2\delta w_1-\delta(1-\delta)-\tau(1+\delta)-c_2(1+\delta)\right]}{2(1+\delta)^2}$, $w_2^* = \frac{(2w_1-1+\delta)\delta}{1+\delta}$ and $\bar{d}_1^{1-2} = \bar{d}_2^{1-2} = \frac{1-w_1}{2(1+\delta)}$.

(1-3) if $0 \leq w_1 \leq \min\left\{\frac{1-\delta}{2}, \tau - \frac{c_2}{\delta}\right\}$, then $w_2^* = 0$, $\bar{\Pi}_2^{1-3} = \frac{(w_1+\delta-1)\tau - c_2 w_1}{2(1-\delta)}$ and $\bar{d}_1^{1-3} = \frac{1-w_1-\delta}{2(1-\delta)}$ and $\bar{d}_2^{1-3} = \frac{w_1}{2(1-\delta)}$.

(1-4) if $0 \leq w_1 \leq \min\left\{\frac{c_2}{\delta} - \tau, 1\right\}$, then $w_2^* = \delta w_1$ and $\bar{d}_2 = 0$. This subcase is dominated by strategy NR because the participation constraints cannot be satisfied.

Case 3 ($0 \leq w_2 \leq \frac{(2w_1-1+\delta)\delta}{1+\delta}$): $\Pi_2 = \max_{w_2} \frac{1+\delta-w_1-w_2}{2(1+3\delta)}\left(w_2 - c_2 - \tau\right)$

(3-1) if $\max\left\{0, \frac{1+4\delta-\delta^2+(1+\delta)(\tau+c_2)}{1+5\delta}\right\} \leq w_1 \leq \min\left\{1, 1+\delta+\tau+c_2\right\}$, then $w_2 = \frac{1+\delta+\tau-w_1+c_2}{2}$, $\bar{\Pi}_2^{3-1} = \frac{(1+\delta-\tau-w_1-c_2)^2}{8(1+3\delta)}$ and $\bar{d}_1^{3-1} = \bar{d}_2^{3-1} = \frac{1+\delta-\tau-w_1-c_2}{4(1+3\delta)}$.

(3-2) if $\frac{1-\delta}{2} \leq w_1 \leq \min\left\{1, \frac{1+4\delta-\delta^2+(1+\delta)(\tau+c_2)}{1+5\delta}\right\}$, then $w_2 = \frac{(2w_1-1+\delta)\delta}{1+\delta}$, $\bar{\Pi}_2^{3-2} = \frac{(1-w_1)\left[2\delta w_1-\delta(1-\delta)-\tau(1+\delta)-c_2(1+\delta)\right]}{2(1+\delta)^2}$ and $\bar{d}_1^{3-2} = \bar{d}_2^{3-2} = \frac{1-w_1}{2(1+\delta)}$.

(3-3) if $\max\left\{\frac{1-\delta}{2}, 1+\delta+\tau+c_2\right\} \leq w_1 \leq 1$, then $w_2 = 0$, $\bar{\Pi}_2^{3-3} = \frac{w_1-\delta-1}{2(1+3\delta)}(\tau + c_2)$ and $\bar{d}_1^{3-3} = \bar{d}_2^{3-3} = \frac{1+\delta-w_1}{2(1+3\delta)}$.

Thirdly, we solve for w_1 and τ. Note that the optimal demand of new (remanufactured) products under the incentive scheme equals the optimal demand of new (remanufactured) products in the centralized scenario if the incentive scheme can result in the first-best solution. Based on this result, we solve w_1 and τ jointly by equating $\bar{d}_1^i = d_1^C$ and $\bar{d}_2^i = d_2^C$, where i =1-1, 1-2, 1-3, 3-1, 3-2 or 3-3 and $\left(d_1^C, d_2^C\right)$ is from Table 3.1. For example, we compare (3-2) with strategy R2 in the centralized scenario: By solving $\frac{1-w_1}{2(1+\delta)} = \frac{1-(c_1+\eta)+(\delta-c_2)}{4(1+3\delta)}$, we have $w_1^* = \frac{1+4\delta-\delta^2+(1+\delta)(c_1+\eta+c_2)}{2(1+3\delta)}$, $w_2^* = \frac{\delta(c_1+\eta+2\delta+c_2)}{1+3\delta}$ and $\Pi_1^* + \Pi_2^* = \frac{(1+\delta-c_1-c_2-\eta)^2}{8(1+3\delta)}$. To satisfy the condition of (3-2), that is, $\frac{1-\delta}{2} \leq w_1^* \leq \min\{1, \frac{1+4\delta-\delta^2+(1+\delta)(\tau+c_2)}{1+5\delta}\}$, we must have $-2\delta - c_2 \leq c_1 + \eta \leq \min\{1 + \delta - c_2, \frac{1+4\delta-\delta^2+2\tau(1+3\delta)+c_2(1+\delta)}{1+5\delta}\}$, which can be further simplified to $c_1 + \eta \leq \frac{1+4\delta-\delta^2+2\tau(1+3\delta)+c_2(1+\delta)}{1+5\delta}$ because $-2\delta - c_2 < 0$ and

$1+\delta-c_2>1$. In a similar fashion, we obtain the following cases:

(A1) If $k=1$ and $\frac{c_2}{\delta}\le c_1+\eta\le \frac{1-\delta}{2}+\frac{(1+\delta)c_2}{2\delta}$, then $w_1^{A1}=\frac{1+(c_1+\eta)}{2}$, $w_2^{A1}=\frac{\delta+c_2}{2}$, $\tau^{A1}=\frac{c_1+\eta-1}{2}$, $\Pi_1^{A1}=f$, $\Pi_2^{A1}=\frac{(1-c_1-\eta-\delta+c_2)^2}{8(1-\delta)}+\frac{(\delta-c_2)^2}{8\delta}-f$, $\Pi_1^{A1}+\Pi_2^{A1}=\frac{(1-c_1-\eta-\delta+c_2)^2}{8(1-\delta)}+\frac{(\delta-c_2)^2}{8\delta}$, $d_1^{A1}=\frac{1-(c_1+\eta)-(\delta-c_2)}{4(1-\delta)}$, and $d_2^{A1}=\frac{\delta(c_1+\eta)-c_2}{4(1-\delta)\delta}$.

(A2) If $k=1$ and $\frac{1-4\delta-\delta^2-2\tau(1+3\delta)}{3-\delta}+\frac{c_2(2+\delta)(1+\delta)}{(3-\delta)\delta}\le c_1+\eta$, then $w_1^{A2}=\frac{1+4\delta-\delta^2+(1+\delta)(c_1+\eta+c_2)}{2(1+3\delta)}$, $w_2^{A2}=\frac{1+4\delta-\delta^2+(1+\delta)(c_1+\eta+c_2)}{2(1+3\delta)}$,
$\Pi_1^{A2}=\frac{(1-c_1-\eta+\delta-c_2)\left[1+4\delta-\delta^2-(1+5\delta)(c_1+\eta)+2\tau(1+3\delta)+c_2(1+\delta)\right]}{8(1+3\delta)^2}+f$,
$\Pi_2^{A2}=\frac{(1-c_1-\eta+\delta-c_2)[\delta(c_1+\eta+2\delta)-c_2(1+2\delta)-\tau(1+3\delta)]}{4(1+3\delta)^2}-f$, $\Pi_1^{A2}+\Pi_2^{A2}=\frac{(1+\delta-c_1-c_2-\eta)^2}{8(1+3\delta)}$, and $d_1^{A2}=d_2^{A2}=\frac{1-(c_1+\eta)+(\delta-c_2)}{4(1+3\delta)}$.

(A3) If $k=1$ and $c_1+\eta\le\frac{1+4\delta-\delta^2+2\tau(1+3\delta)+c_2(1+\delta)}{1+5\delta}$, then $w_1^{A3}=w_1^{A2}$, $w_2^{A3}=w_2^{A2}$, $\Pi_1^{A3}=\Pi_1^{A2}$, $\Pi_2^{A3}=\Pi_2^{A2}$, $\Pi_1^{A3}+\Pi_2^{A3}=\frac{(1+\delta-c_1-c_2-\eta)^2}{8(1+3\delta)}$, and $d_1^{A3}=d_2^{A3}=\frac{1-(c_1+\eta)+(\delta-c_2)}{4(1+3\delta)}$.

(A4) If $k=1$ and $\max\{\tau,\frac{1+4\delta-\delta^2+2\tau(1+3\delta)+c_2(1+\delta)}{1+5\delta}\}\le c_1+\eta\le\min\{1+\tau,1+\delta+2\tau+c_2\}$, then $w_1^{A4}=c_1+\eta-\tau$, $w_2^{A4}=\frac{1-c_1-\eta+\delta+c_2}{2}+\tau$, $\Pi_1^{A4}=f$, $\Pi_2^{A4}=\frac{(1+\delta-c_1-c_2-\eta)^2}{8(1+3\delta)}-f$, $\Pi_1^{A4}+\Pi_2^{A4}=\frac{(1+\delta-c_1-c_2-\eta)^2}{8(1+3\delta)}$, and $d_1^{A4}=d_2^{A4}=\frac{1-(c_1+\eta)+(\delta-c_2)}{4(1+3\delta)}$.

(A5) If $k=1$ and $1+\delta+2\tau+c_2\le c_1+\eta\le 1-\delta-c_2$, then $w_1^{A5}=\frac{1+(c_1+\eta)+\delta+c_2}{2}$, $w_2^{A4}=0$, $\Pi_1^{A5}=\frac{(1-c_1-\eta+\delta-c_2)(1-c_1-\eta+\delta+2\tau+c_2)}{8(1+3\delta)}+f$, $\Pi_2^{A5}=\frac{-(1-c_1-\eta+\delta-c_2)(\tau+c_2)}{4(1+3\delta)}-f$, $\Pi_1^{A5}+\Pi_2^{A5}=\frac{(1+\delta-c_1-c_2-\eta)^2}{8(1+3\delta)}$, and $d_1^{A5}=d_2^{A5}=\frac{1-(c_1+\eta)+(\delta-c_2)}{4(1+3\delta)}$.

(A6) If $k=0$, then $w_1^{A6}=\frac{1+c_1}{2}$, $\Pi_1^{A6}=\frac{(1-c_1)^2}{8}$, and $d_1^{A6}=\frac{1-c_1}{4}$.

Note that the above cases are not exclusive. However, similar to the profit comparison procedure mentioned in the proof of Proposition 3.3.1, we can derive the optimal strategy and the corresponding conditions (illustrated in Table 3.1) except the value of w_1^* and w_2^* when strategy R2 is optimal. Thus, we have proven part (iii) of Proposition 3.4.2.

Proposition 3.4.2(i): if $(c_1,c_2,\delta,\eta)\in\Omega_{R1}^C$, then the optimal τ is directly derived from (A1) in the proof of Proposition 3.4.2. Recall that the participation constraint for D1 is $\Pi_1^T>\Pi_1^D$, where $\Pi_1^D\ge\frac{(1-c_1)^2}{8}$. Thus, $f^T>\frac{(1-c_1)^2}{8}>0$. Given that $c_1\ge\frac{\sqrt{(1-\delta)\eta(2\delta+\eta-2c_2)}+c_2-\eta}{\delta}$ and $\frac{\sqrt{(1-\delta)\eta(2\delta+\eta-2c_2)}+c_2-\eta}{\delta}\ge\frac{c_2}{\delta}-\eta$ when $\delta\ge c_2$, we have $c_1\ge\frac{c_2}{\delta}-\eta$, or equivalently, $c_2\le\delta(\eta+c_1)$. One can show that $d_1^T\cdot\tau^T+f^T\ge\frac{\eta[2(1-c_1-\eta)+\eta]}{8}\ge 0$. Thus, $f^T>0$ because $\tau^T<0$ and $d_1^T>0$.

Proposition 3.4.2(ii): if $(c_1,c_2,\delta,\eta)\in\Omega_{R2}^C$ and $\tau=0$, then (A2)-(A4)

Table B.3: The Retailer's Optimal Strategy ($w_1, w_2 \geq 0$)

Case	Cond.	d_1^*	d_2^*
1	$k = 1$ & $\max\left\{\frac{(2w_1-1+\delta)\delta}{1+\delta}, 0\right\} \leq w_2 \leq \delta w_1$	$\frac{1-\delta-w_1+w_2}{2(1-\delta)}$	$\frac{\delta w_1 - w_2}{2(1-\delta)\delta}$
2	$k = 1$ & $w_2 \geq \delta w_1$ & $w_1 \leq 1$ or $k = 0$ & $w_1 \leq 1$	$\frac{1-w_1}{2}$	0
3	$k = 1$ & $0 \leq w_2 \leq \min\left\{\frac{(2w_1-1+\delta)\delta}{1+\delta}, 1+\delta-w_1\right\}$	$\frac{1+\delta-w_1-w_2}{2(1+3\delta)}$	$\frac{1+\delta-w_1-w_2}{2(1+3\delta)}$

Case	Π_R^*
1	$\frac{w_2^2 - 2w_1w_2\delta + \left(1+w_1^2-2w_1(1-\delta)-\delta\right)\delta}{4(1-\delta)\delta}$
2	$\frac{(1-w_1)^2}{4}$
3	$\frac{(1-w_1-w_2+\delta)^2}{4(1+3\delta)}$

constitute the optimal solutions when R2 is optimal. That is, one of the three cases is associated with the optimal solution and the corresponding (τ, f) enables the firm to achieve the first-best profit. Letting $\tau = 0$ and given that $1 + \delta + c_2 \geq 1$ and $c_1 + \eta \in [0, 1]$, the condition for (A2)-(A4) can be simplified to $\frac{1-4\delta-\delta^2}{3-\delta} + \frac{c_2(2+\delta)(1+\delta)}{(3-\delta)\delta} \leq c_1 + \eta$, $c_1 + \eta \leq \frac{1+4\delta-\delta^2+c_2(1+\delta)}{1+5\delta}$ and $\frac{1+4\delta-\delta^2+c_2(1+\delta)}{1+5\delta} \leq c_1 + \eta$, respectively. Next, we show that $f^T > 0$ for all three cases. Note that the participation constraint for D1 is $\Pi_1^T > \Pi_1^D$, where $\Pi_1^D \geq \frac{(1-c_1)^2}{8}$. If (A4) is associated with the optimal solution, then $\Pi_1^T = f^T > \frac{(1-c_1)^2}{8} > 0$ holds when $\tau = 0$. Similarly, if (A2) or (A3) is associated with the optimal solution, then $\Pi_1^T > \frac{(1-c_1)^2}{8}$ should also hold. One can show that $f^T > \Pi_1^T - \frac{(1-c_1)^2}{8} = \frac{1}{8(1+3\delta)^2}\{(1+5\delta)(1-c_1)^2 - (1+5\delta)(1-c_1-\eta)^2 + (1-c_1)^2\delta(1+5\delta) + [2(1-c_1)\delta - \delta + c_2]^2 + 4\delta\eta(\delta - c_2) + \delta(\delta - c_2)^2\} > 0$ when $\tau = 0$. ⊠

Proof of Proposition 3.4.1: This can be directly derived from Proposition 3.4.2(i): In order to achieve the first-best firm profit Π_F^C, $\tau^V = \frac{c_1+\eta-1}{2}$ must hold. Otherwise, one of the following three cases would happen: 1) $k^V = 0$ and hence $\Pi_1^V = \frac{(1-c_1)^2}{8}, \Pi_2^V = 0$; 2) $k^V = 1$ but D2 opts out ($j = 0$) and hence $\Pi_i^V = \Pi_i^D$ ($i = 1, 2$); 3) $k^V = 1$ and $j = 1$ but $\Pi_1^V + \Pi_2^V < \Pi_F^C$ according to Proposition 3.4.2(i). In each case, $\Pi_1^V + \Pi_2^V < \Pi_F^C$ will always hold. However, if $\tau^V = \frac{c_1+\eta-1}{2}$, then $\Pi_1^V = 0$, which violates the participation constraint according to Proposition 3.4.2(i). ⊠

Model Extension 1: No upper limit on wholesale prices

1.1. The Centralized Scenario: Similar to the proof of Proposition 3.3.1, we obtain the retailer's optimal strategy (see Table B.3) and the firm's opti-

Table B.4: D2's Optimal Strategy in the Decentralized Scenario ($w_1, w_2 \geq 0$)

Case	Cond.	d_1^*	d_2^*	w_2^*
1	$\frac{c_2}{\delta} \leq w_1 \leq \frac{2(1-\delta)}{3-\delta} + \frac{(1+\delta)c_2}{(3-\delta)\delta}$	$\frac{1}{2} - \frac{(2-\delta)w_1 - c_2}{4(1-\delta)}$	$\frac{w_1\delta - c_2}{4(1-\delta)\delta}$	$\frac{w_1\delta + c_2}{2}$
2	$\frac{2(1-\delta)\delta+(1+\delta)c_2}{(3-\delta)\delta} \leq w_1 \leq 1 - \frac{(1+\delta)(\delta-c_2)}{1+5\delta}$	$\frac{1-w_1}{2(1+\delta)}$	d_1^*	$\frac{(2w_1-1+\delta)\delta}{1+\delta}$
3	$\frac{1+4\delta-\delta^2+(1+\delta)c_2}{1+5\delta} \leq w_1 \leq 1+\delta-c_2$	$\frac{1+\delta-w_1-c_2}{4(1+3\delta)}$	d_1^*	$\frac{1+\delta-w_1}{2}$

Table B.5: Optimal Strategy and Solutions in the Decentralized Scenario ($w_1, w_2 \geq 0$)

Strategy	Cond.	w_1^D	w_2^D	d_1^D	d_2^D
R2	(*)	$\frac{1+c_1+\eta+\delta-c_2}{2}$	$\frac{1-c_1-\eta+\delta+c_2}{4}$	$\frac{1-c_1-\eta+\delta-c_2}{8(1+3\delta)}$	d_1^D
NR	otherwise	$\frac{1+c_1}{2}$	–	$\frac{1-c_1}{4}$	–

Strategy	Π_1^D	Π_2^D	Π_R^D
R2	$\frac{(1-c_1-\eta+\delta-c_2)^2}{16(1+3\delta)}$	$\frac{\Pi_1^D}{2}$	$\frac{\Pi_1^D}{4}$
NR	$\frac{(1-c_1)^2}{8}$	–	$\frac{\Pi_1^D}{2}$

(*) $c_1 \geq \frac{1+5\delta+\eta+c_2-(\delta-\eta-c_2)\sqrt{2(1+3\delta)}}{1+6\delta}$

mal strategy. One can show that Proposition 3.3.1 and the optimal solution (see Table 3.1) still hold, except that when R2 is optimal, w_1 must satisfy $\frac{1+4\delta-\delta^2+(c_1+\eta+c_2)(1+\delta)}{2(1+3\delta)} \leq w_1 \leq \frac{1+\delta+c_1+\eta+c_2}{2}$, which is a relaxed condition, as compared to the constraint on w_1 in the benchmark model.

1.2. The Decentralized Scenario: Again, we obtain the equilibrium solutions by solving the problem backward. Similar to the proof of Proposition 3.3.3, one can derive the optimal strategy of the retailer (see Table B.3), of D2 (see Table B.4) and of D1 (see Table B.5).

Based on Table B.5, one can show the part (i)-(iii) of Proposition 3.3.3 still hold when there are no upper limits on w_1 and w_2.

1.3. The Two-part Coordination Scheme: Similar to the proof of Proposition 3.4.2, one can show that the optimal strategies and the corresponding conditions are the same with and without the upper limits on w_1 and w_2 except the value of w_1^* and w_2^* when strategy R2 is optimal.

Model Extension 2: No Retailer

2.1. The Centralized Scenario without the Retailer: If $k = 0$, then $p_1 = 1 - d_1$. The firm's problem is $\Pi_F^{NR} = \max_{d_1} d_1 \cdot (1 - d_1 - c_1)$ *s.t.* $0 \leq$

Table B.6: Optimal Solutions in the Centralized Scenario (No Retailer, $w_1, w_2 \in [0,1]$)

Strategy	Cond.	k^C	p_1^C	p_2^C
R1	(*)	1	$\frac{1+c_1+\eta}{2}$	$\frac{c_2+\delta}{2}$
R2	(**)	1	$\frac{1+4\delta-\delta^2+(c_1+\eta+c_2)(1+\delta)}{2(1+3\delta)}$	$\frac{\delta(c_1+c_2+2\delta+\eta)}{1+3\delta}$
NR	o.w.	0	$\frac{1+c_1}{2}$	—

Strategy	d_1^C	d_2^C	Π_F^C
R1	$\frac{1-c_1-\eta-\delta+c_2}{2(1-\delta)}$	$\frac{\delta(c_1+\eta)-c_2}{2(1-\delta)\delta}$	$\frac{(1-c_1-\eta-\delta+c_2)^2}{4(1-\delta)}+\frac{(\delta-c_2)^2}{4\delta}$
R2	$\frac{1+\delta-c_1-\eta-c_2}{2(1+3\delta)}$	d_1^C	$\frac{(1-c_1-\eta+\delta-c_2)^2}{4(1+3\delta)}$
NR	$\frac{1-c_1}{2}$	—	$\frac{(1-c_1)^2}{4}$

(*) and (**) correspond to the condition when R1 and R2 are optimal based on Proposition 3.3.1, respectively.

$d_1 \leq 1$. Thus, we have $d_1^{NR} = \frac{1-c_1}{2}$, $p_1^{NR} = \frac{1+c_1}{2}$ and $\Pi_F^{NR} = \frac{(1-c_1)^2}{4}$. If $k=1$, then $p_1 = 1-d_1-\delta d_2$ and $p_2 = \delta(1-d_1-d_2)$. The firm's problem is $\Pi_F = \max_{d_1,d_2} d_1(1-d_1-\delta d_2-c_1-\eta)+d_2[\delta(1-d_1-d_2)-c_2]$ $s.t.$ $d_1-d_2 \geq 0$, $1-d_1-d_2 \geq 0$ and $d_1, d_2 \geq 0$. Similar to the proof of Proposition 3.3.1, we derive the condition when each strategy is optimal and summarize the results in Table B.6.

2.2. The Decentralized Scenario without the Retailer: In this scenario, D1 decides k^D and $p_1 \in [0,1]$, and D2 decides $p_2 \in [0,1]$. Note that here we cannot formulate retail prices using (3.1)-(3.2) of the paper because neither division can exclusively determines the sales of new or remanufactured products when $k^D = 1$. By simultaneously solving $p_1 = 1-d_1-\delta d_2$ and $p_2 = \delta(1-d_1-d_2)$, we obtain $d_1 = \frac{1-\delta-p_1+p_2}{1-\delta}$ and $d_2 = \frac{\delta p_1-p_2}{(1-\delta)\delta}$. $d_1 \geq d_2 \Rightarrow p_2 \geq \frac{(2p_1-1+\delta)\delta}{1+\delta}$. Also note that if $p_2 < \frac{(2p_1-1+\delta)\delta}{1+\delta}$, then D2 can always increase p_2 to $\frac{(2p_1-1+\delta)\delta}{1+\delta}$ so that D2's profit and sales of remanufactured products both increase. Hence, it is not optimal for D2 to price remanufactured products at $p_2 < \frac{(2p_1-1+\delta)\delta}{1+\delta}$. Meanwhile, $d_2 \geq 0 \Rightarrow p_2 \leq \delta p_1$. Thus, in the decentralized scenario without vertical integration, D1's profit is $\Pi_1^{NR} = \max_{p_1}(1-p_1)\cdot(p_1-c_1)$ $s.t.$ $c_1 \leq p_1 \leq 1$ when $k=0$ and $\Pi_1^{RE} = \max_{p_1} \frac{1-\delta-p_1+p_2}{1-\delta}(p_1-c_1-\eta)$ $s.t.$ $c_1+\eta \leq p_1 \leq 1$ when $k=1$. Thus, D1 optimal profit is $\Pi_1^D = \max\{\Pi_1^{NR}, \Pi_1^{RE}\}$; the optimal design decision $k^D = 0 \Leftrightarrow \Pi_1^{NR} \geq \Pi_1^{RE}$. Given $k=1$ and p_1, D2's problem is $\Pi_2^D = \max_{p_2} \frac{\delta p_1-p_2}{(1-\delta)\delta}(p_2-c_2)$ $s.t.$ $\max\{c_2, \frac{(2p_1-1+\delta)\delta}{1+\delta}\} \leq p_2 \leq \delta p_1$. D2's optimal strategy is illustrated in Table B.7:

Table B.7: D2's Optimal Strategy in the Decentralized Scenario (No Retailer, w_1, $w_2 \in [0,1]$)

Case	Cond.	d_1^*	d_2^*	p_2^*
1	$k=1$ & $\frac{c_2}{\delta} \le p_1 \le \frac{2(1-\delta)}{3-\delta} + \frac{(1+\delta)c_2}{(3-\delta)\delta}$	$\frac{2(1-\delta)-(2-\delta)p_1+c_2}{2(1-\delta)}$	$\frac{p_1\delta-c_2}{2(1-\delta)\delta}$	$\frac{\delta p_1+c_2}{2}$
2	$k=1$ & $\frac{2(1-\delta)}{3-\delta} + \frac{(1+\delta)c_2}{(3-\delta)\delta} \le p_1 \le 1$	$\frac{1-p_1}{1+\delta}$	$\frac{1-p_1}{1+\delta}$	$\frac{(2p_1-1+\delta)\delta}{1+\delta}$
3	$k=1$ & $p_1 \le \frac{c_2}{\delta}$ or $k=0$	$\frac{1-c_1}{2}$	$-$	$-$

Next, we solve D1's problem. If $k=0$, then $d_1 = 1-p_1$ and D1's problem is $\Pi_1^{NR} = \max_{p_1}(1-p_1)\cdot(p_1-c_1)$ $s.t.$ $c_1 \le p_1 \le 1$. Thus, we have $d_1^{NR} = \frac{1-c_1}{2}$, $p_1^{NR} = \frac{1+c_1}{2}$ and $\Pi_1^{NR} = \frac{(1-c_1)^2}{4}$. If $k=1$, then D1's problem is $\Pi_1 = \max_{p_1} d_1(p_1-c_1-\eta)$ $s.t.$ $c_1+\eta \le p_1 \le 1$, where d_1 and the constraints are given in Table B.7. One can show that it is not optimal for D1 to set $p_1 \le \frac{c_2}{\delta}$ when $k=1$. Hence, we only need to consider case 1 and 2 in Table B.7.

Case 1 ($\frac{c_2}{\delta} \le p_1 \le \frac{2(1-\delta)}{3-\delta}+\frac{(1+\delta)c_2}{(3-\delta)\delta}$). D1's problem is $\Pi_1 = \max_{w_1} \frac{2(1-\delta)-(2-\delta)p_1+c_2}{2(1-\delta)}$ $(p_1-c_1-\eta)$ $s.t.$ $\max\{\frac{c_2}{\delta}, c_1+\eta\} \le p_1 \le \frac{2(1-\delta)}{3-\delta} + \frac{(1+\delta)c_2}{(3-\delta)\delta}$.

(1-1) if $\frac{c_2(4-3\delta)-2(1-\delta)\delta}{(2-\delta)\delta} \le c_1+\eta \le \frac{c_2\left(4-\delta-\delta^2\right)+2\delta(1-\delta)^2}{(3-\delta)(2-\delta)\delta}$, then $p_1^* = \frac{1}{2(2-\delta)}[(c_1+\eta)(2-\delta)+2(1-\delta)+c_2]$, $\Pi_1^{1-1} = \frac{[2(1-\delta)-(c_1+\eta)(2-\delta)+c_2]^2}{8(2-\delta)(1-\delta)}$, $d_1 = \frac{2(1-\delta)-(c_1+\eta)(2-\delta)+c_2}{4(1-\delta)}$, $d_2 = \frac{\delta[2(1-\delta)+(c_1+\eta)(2-\delta)]-c_2(4-3\delta)}{4(2-\delta)(1-\delta)\delta}$. However, $\Pi_1^{1-1} \le \Pi_1^{NR} = \frac{(1-c_1)^2}{4}$ when $\frac{c_2(4-3\delta)-2(1-\delta)\delta}{(2-\delta)\delta} \le c_1+\eta$. To see this, note that $\Pi_1^{1-1} \ge \Pi_1^{NR}$ is equivalent to $c_1 \le \frac{\sqrt{2(1-\delta)(2-\delta)}[\delta(1-\eta)+2\eta-c_2]+c_2(2-\delta)-(2-\delta)^2\eta}{(2-\delta)\delta}$. Also, Π_1^{1-1} is valid when $\frac{c_2(4-3\delta)-2(1-\delta)\delta}{(2-\delta)\delta} \le c_1+\eta$ or equivalently, $c_1 \ge \frac{c_2(4-3\delta)-2(1-\delta)\delta}{(2-\delta)\delta} - \eta$. However, $\frac{\partial}{\partial\eta}[\frac{c_2(4-3\delta)-2(1-\delta)\delta}{(2-\delta)\delta} - \eta - \frac{1}{(2-\delta)\delta}(\sqrt{2(1-\delta)(2-\delta)}[\delta(1-\eta)+2\eta-c_2] + c_2(2-\delta)-(2-\delta)^2\eta)] = \frac{\sqrt{2(1-\delta)(2-\delta)}+2(1-\delta)}{\delta} > 0$ while $\frac{c_2(4-3\delta)-2(1-\delta)\delta}{(2-\delta)\delta} - \eta - (\frac{\sqrt{2(1-\delta)(2-\delta)}[\delta(1-\eta)+2\eta-c_2]+c_2(2-\delta)-(2-\delta)^2\eta}{(2-\delta)\delta})|_{\eta=0} = \frac{[\sqrt{2(1-\delta)(2-\delta)}-2(1-\delta)](\delta-c_2)}{(2-\delta)\delta} \ge 0$. Therefore, $\Pi_1^{1-1} \le \Pi_1^{NR}$ is true when $\frac{c_2(4-3\delta)-2(1-\delta)\delta}{(2-\delta)\delta} \le c_1+\eta$, which means this subcase is dominated by strategy NR.

(1-2) if $\frac{c_2\left(4-\delta-\delta^2\right)+2\delta(1-\delta)^2}{(3-\delta)(2-\delta)\delta} \le c_1+\eta \le \frac{2(1-\delta)\delta+c_2(1+\delta)}{(3-\delta)\delta}$, then $p_1^* = \frac{2(1-\delta)\delta+c_2(1+\delta)}{(3-\delta)\delta}$, $\Pi_1^{1-2} = \frac{(\delta-c_2)[2-2\delta-(c_1+\eta)(3-\delta)]}{(3-\delta)^2\delta} + \frac{(\delta-c_2)c_2(1+\delta)}{(3-\delta)^2\delta^2}$ and $d_1 = d_2 = \frac{\delta-c_2}{(3-\delta)\delta}$. Note that (i) $\Pi_1^{1-2} \le \Pi_1^{1-1}$ when $\frac{c_2\left(4-\delta-\delta^2\right)+2\delta(1-\delta)^2}{(3-\delta)(2-\delta)\delta} \le c_1+\eta \le \frac{2(1-\delta)\delta+c_2(1+\delta)}{(3-\delta)\delta}$; (ii) $\Pi_1^{1-1} \le \Pi_1^{NR}$ when $\frac{c_2(4-3\delta)-2(1-\delta)\delta}{(2-\delta)\delta} \le c_1+\eta$ and (iii) $\frac{c_2(4-3\delta)-2(1-\delta)\delta}{(2-\delta)\delta} \le \frac{c_2\left(4-\delta-\delta^2\right)+2\delta(1-\delta)^2}{(3-\delta)(2-\delta)\delta}$ is always true since $c_2 \le \delta$. Therefore, this subcase is dominated by strategy NR.

(1-3) if $c_1+\eta \le \frac{c_2(4-3\delta)-2(1-\delta)\delta}{(2-\delta)\delta}$, then $p_1^* = \frac{c_2}{\delta}$, $\Pi_1^{1-3} = \frac{(\delta-c_2)[c_2-(c_1+\eta)\delta]}{\delta^2}$,

$d_1 = \frac{\delta - c_2}{\delta}$ and $d_2 = 0$. This case is dominated by strategy NR since $d_2 = 0$.

Case 2 ($\frac{2(1-\delta)}{3-\delta} + \frac{(1+\delta)c_2}{(3-\delta)\delta} \le p_1 \le 1$). D1's problem is $\Pi_1 = \max_{p_1} \frac{1-p_1}{1+\delta}(p_1 - C_1)$ *s.t.* $\max\{C_1, \frac{2(1-\delta)}{3-\delta} + \frac{(1+\delta)c_2}{(3-\delta)\delta}\} \le p_1 \le 1$, where $C_1 = c_1 + \eta$.

(2-1) $p_1^* = \frac{1+C_1}{2}$; $\Pi_1^{2-1} = \frac{(1-C_1)^2}{4(1+\delta)}$; $d_1 = d_2 = \frac{1-C_1}{2(1+\delta)}$ when $C_1 \ge \frac{(1-3\delta)\delta + 2c_2(1+\delta)}{(3-\delta)\delta}$. However, this subcase is dominated by NR because $\Pi_1^{2-1} = \frac{(1-C_1)^2}{4(1+\delta)} \le \frac{(1-c_1)^2}{4} = \Pi_1^{NR}$.

(2-2) $p_1^* = \frac{2(1-\delta)\delta + (1+\delta)c_2}{(3-\delta)\delta}$; $\mu_1^* = \frac{2c_2(1+\delta) - 3\delta^2 + \delta - C_1\delta(3-\delta)}{(3-\delta)\delta(\delta+1)}$; $\Pi_1^{2-2} = \frac{(\delta - c_2)}{(3-\delta)^2\delta^2}\{\delta[2 - 2\delta - C_1(3-\delta)] + c_2(1+\delta)\}$; $d_1 = d_2 = \frac{\delta - c_2}{(3-\delta)\delta}$ when $C_1 \le \frac{(1-3\delta)\delta + 2c_2(1+\delta)}{(3-\delta)\delta}$. However, this subcase is dominated by NR because $\frac{(1-c_1)^2}{4(1+\delta)} \ge \frac{(1-C_1)^2}{4(1+\delta)} \ge \frac{(\delta - c_2)\{\delta[2(1-\delta) - C_1(3-\delta)] + c_2(1+\delta)\}}{(3-\delta)^2\delta^2}$.

In all, it is not optimal for D1 to choose a remanufacturable design.

2.3. Two-Part Coordination Scheme without the Retailer: Again, we use backward induction, starting with D2's profit maximization problem. If $k = 0$, then D2's profit is $\Pi_2^{NR} = 0$. If $k = 1$, then D2's problem is $\Pi_2^* = \max_{p_2} \frac{\delta p_1 - p_2}{(1-\delta)\delta}(p_2 - c_2) - \frac{1-\delta-p_1+p_2}{1-\delta} \cdot \tau - f$ *s.t.* $\max\{0, \frac{(2p_1 - 1 + \delta)\delta}{1+\delta}\} \le p_2 \le \delta p_1$. Given that f is fixed, we can first solve the following problem: $\hat{\Pi}_2 = \max_{p_2} \frac{\delta p_1 - p_2}{(1-\delta)\delta}(p_2 - c_2) - \frac{1-\delta-p_1+p_2}{1-\delta} \cdot \tau$ *s.t.* $\max\{0, \frac{(2p_1-1+\delta)\delta}{1+\delta}\} \le p_2 \le \delta p_1$.

Case 1: $p_2^* = \frac{\delta(p_1 - \tau) + c_2}{2}$, $\Pi_2^1 = \frac{[\delta p_1 + \tau(2-\delta) - c_2]^2}{4(1-\delta)\delta} - \frac{(\tau + \delta - c_2)\tau}{\delta}$, $d_1 = 1 - \frac{(2-\delta)p_1 + \delta\tau - c_2}{2(1-\delta)}$, $d_2 = \frac{(p_1+\tau)\delta - c_2}{2(1-\delta)\delta}$ when $\max\left\{\frac{c_2}{\delta} - \tau, \tau - \frac{c_2}{\delta}\right\} \le p_1 \le \frac{2(1-\delta) - \tau(1+\delta)}{3-\delta} + \frac{(1+\delta)c_2}{(3-\delta)\delta}$.

Case 2: $p_2^* = \frac{(2p_1 - 1 + \delta)\delta}{1+\delta}$, $\mu_2^* = \frac{\delta[(2+\tau)\delta + (3-\delta)p_1 + \tau - 2] - c_2(1+\delta)}{\delta(1-\delta^2)}$, $\Pi_2^3 = \frac{(1-p_1)}{(1+\delta)^2}[2\delta p_1 - \delta(1-\delta) - \tau(1+\delta) - c_2(1+\delta)]$, $d_1 = d_2 = \frac{1-p_1}{1+\delta}$ when $\max\left\{\frac{2(1-\delta) - \tau(1+\delta)}{3-\delta} + \frac{c_2(1+\delta)}{(3-\delta)\delta}, \frac{1-\delta}{2}\right\} \le p_1 \le 1$.

Case 3: If $p_2^* = 0$ and $p_1 \le 1 - \delta$, then $\Pi_2^5 = \frac{(p_1 + \delta - 1)\tau - c_2 p_1}{1-\delta}$, $d_1 = \frac{1 - p_1 - \delta}{1-\delta}$ and $d_2 = \frac{p_1}{1-\delta}$. This case dominates when $0 \le p_1 \le \min\left\{\frac{1-\delta}{2}, \tau - \frac{c_2}{\delta}\right\}$.

To achieve the first-best solutions, we need to solve for p_1 and τ by comparing (d_1, d_2) in each of the above cases with those in Table B.6. Thus, we have

(A1) If $k = 1$ and $\frac{c_2}{\delta} \le c_1 + \eta \le \frac{1-\delta}{2} + \frac{(1+\delta)c_2}{2\delta}$, then $p_1^{A1} = \frac{1+(c_1+\eta)}{2}$, $p_2^{A1} = \frac{\delta + c_2}{2}$, $\tau^{A1} = \frac{c_1 + \eta - 1}{2}$, $\Pi_1^{A1} = f$, $\Pi_2^{A1} = \frac{(1 - c_1 - \eta - \delta + c_2)^2}{4(1-\delta)} + \frac{(\delta - c_2)^2}{4\delta} - f$, $\Pi_1^{A1} + \Pi_2^{A1} = \frac{(1 - c_1 - \eta - \delta + c_2)^2}{4(1-\delta)} + \frac{(\delta - c_2)^2}{4\delta}$, $d_1^{A1} = \frac{1 - (c_1+\eta) - (\delta - c_2)}{2(1-\delta)}$, and $d_2^{A1} = \frac{\delta(c_1+\eta) - c_2}{2(1-\delta)\delta}$.

(A2) If $k = 1$ and $\frac{1 - 4\delta - \delta^2 - 2\tau(1+3\delta)}{3-\delta} + \frac{c_2(2+\delta)(1+\delta)}{(3-\delta)\delta} \le c_1 + \eta$, then $p_1^{A2} = \frac{1 + 4\delta - \delta^2 + (1+\delta)(c_1 + \eta + c_2)}{2(1+3\delta)}$, $p_2^{A2} = \frac{\delta(c_1 + \eta + 2\delta + c_2)}{1+3\delta}$, $\Pi_1^{A2} = \frac{(1 - c_1 - \eta + \delta - c_2)}{4(1+3\delta)^2}[1 + 4\delta - \delta^2 - (1+5\delta)(c_1+\eta) + 2\tau(1+3\delta) + c_2(1+\delta)] + f$, $\Pi_2^{A2} = \frac{(1 - c_1 - \eta + \delta - c_2)}{4(1+3\delta)^2}[\delta(c_1 + \eta + 2\delta) - c_2(1+2\delta) - \tau(1+3\delta)] - f$, $\Pi_1^{A2} + \Pi_2^{A2} = \frac{(1 + \delta - c_1 - c_2 - \eta)^2}{4(1+3\delta)}$, and

$d_1^{A2} = d_2^{A2} = \frac{1-(c_1+\eta)+(\delta-c_2)}{2(1+3\delta)}$.

(A3) If $k = 0$, then $w_1^{A3} = \frac{1+c_1}{2}$, $\Pi_1^{A3} = \frac{(1-c_1)^2}{4}$, and $d_1^{A3} = \frac{1-c_1}{2}$.

Similar to the proof of Proposition 3.4.2, we can derive the optimal strategies and the corresponding conditions, which is represented by Table B.6 except different p_1^* and p_2^* for strategy R2 because the solution in that case is not unique.

APPENDIX C

APPENDIX FOR CHAPTER 4

Proof of Lemma 4.4.1. In the absence of the patent term extension and take-back regulation, neither company can benefit from the green pharmacy investment. Thus, the profit of the innovative company is $\Pi_1^N = \Pi_1^N(O,O) = \max_{p_1} \frac{1}{1-r} \cdot \frac{1-\delta-p_1+p_2}{1-\delta} \cdot p_1$, where $(\cdot,\cdot)$ represents the strategy pair. By taking the first derivative of RHS with respect to p_1 and setting it to 0, we obtain $p_1 = \frac{1-\delta+p_2}{2}$. Similarly, the profit of the generic company is $\Pi_2^N = \Pi_2^N(O,O) = \max_{p_2} \frac{1}{1-r} \cdot \frac{\delta p_1 - p_2}{(1-\delta)\delta} \cdot p_2$ and $p_2 = \frac{\delta p_1}{2}$. By solving $p_1 = \frac{1-\delta+p_2}{2}$ and $p_2 = \frac{\delta p_1}{2}$, one can show that $p_1^N = \frac{2(1-\delta)}{4-\delta}$, $p_2^N = \frac{(1-\delta)\delta}{4-\delta}$, $\Pi_1^N = \frac{4(1-\delta)}{(1-r)(4-\delta)^2}$, $\Pi_2^N = \frac{(1-\delta)\delta^2}{(1-r)(4-\delta)^2}$, $d_1^N = \frac{1-\delta-p_1+p_2}{1-\delta} = \frac{2}{4-\delta}$, and $d_2^N = \frac{\delta p_1 - p_2}{(1-\delta)\delta} = \frac{\delta}{4-\delta}$. Note our assumptions ensure that there is no boundary solution. ⊠

Proof of Lemma 4.4.2. In the absence of the patent term extension, the generic company cannot benefit from the green pharmacy investment because the patent extension does not apply to the firm. If the innovative company decides not to go green, then the solution is essentially the same as under policy N. Therefore, $\Pi_1^E(O,O) = \Pi_1^N(O,O)$. If the innovative company obtains green pharmacy and hence the patent term extension, then the profit of the innovative company is $\Pi_1^E(G_0,F) = \max_{p_m,p_1} \frac{1-r^n}{1-r} \cdot (1-p_m)\,p_m + \frac{r^n}{1-r} \cdot \frac{1-\delta-p_1+p_2}{1-\delta} p_1 - A$ while the profit of the generic company is $\Pi_2^E(G_0,F) = \max_{p_2} \frac{r^n}{1-r} \cdot \frac{\delta p_1 - p_2}{(1-\delta)\delta} \cdot p_2$. Similar to the proof of Lemma 4.4.1, we obtain $p_m^E = \frac{1}{2}$, $d_m^E = 1 - p_m^E = \frac{1}{2}$, p_i^E, d_i^E and Π_i^E $(i = 1,2)$ as stated in Lemma 4.4.2(i). In addition, one can show that $\Pi_1^E(G_0,F) \geq \Pi_1^E(O,O)$ if and only if $A \leq A^E$. The remaining statement follows. ⊠

Proof of Proposition 4.4.3. Based on Lemma 4.4.1 and Equation 4.1, the total impact under policy N is $TI^N = e\frac{1}{1-r}(1 - \frac{2}{4-\delta} - \frac{1}{4-\delta}) + \frac{1}{1-r}(\frac{2}{4-\delta} + \frac{1}{4-\delta})$ when $A \leq A^E$. Similarly, the total impact under policy E is $TI^E = e\frac{1-r^n}{1-r}(1 - \frac{1}{2}) + e\frac{r^n}{1-r}(1 - \frac{2}{4-\delta} - \frac{1}{4-\delta}) + \frac{1-r^n}{1-r}\alpha\frac{1}{2} + \frac{r^n}{1-r}\alpha(\frac{2}{4-\delta} + \frac{1}{4-\delta})$. It is optimal for the regulator to implement the patent term extension if and only if $TI^E < TI^N$, or equivalently, $e < e^E$. ⊠

Proof of Proposition 4.4.4. 1) According to Lemma 4.4.2, (G_0, F) is the equilibrium when $A \leq A^E$ or equivalently, $r^n \leq 1 - \frac{4A(1-r)(4-\delta)^2}{\delta(8+\delta)}$. It is not hard to see that (i) if $1 - \frac{4A(1-r)(4-\delta)^2}{\delta(8+\delta)} \leq 0$, or equivalently $A \geq \frac{\delta(8+\delta)}{4(1-r)(4-\delta)^2}$, then (O, O) is the equilibrium and therefore $n^E = 0$; and (ii) if $1 - \frac{4A(1-r)(4-\delta)^2}{\delta(8+\delta)} > 0$, or equivalently $A < \frac{\delta(8+\delta)}{4(1-r)(4-\delta)^2}$, then $r^n \leq 1 - \frac{4A(1-r)(4-\delta)^2}{\delta(8+\delta)}$ if and only if $n \geq log_r \left[1 - \frac{4A(1-r)(4-\delta)^2}{\delta(8+\delta)}\right]$.

2) Based on Proposition 4.4.3, given $A \leq A^E$, it is optimal to implement the patent term extension when $e < e^E$, or equivalently, $r^n \leq 1 - \frac{6(1-\alpha)}{(2+\delta)(e-\alpha)}$ when $e < \alpha$ and $r^n \geq 1 - \frac{6(1-\alpha)}{(2+\delta)(e-\alpha)}$ when $e > \alpha$. Note if $e < \alpha$, then $r^n \leq 1 - \frac{6(1-\alpha)}{(2+\delta)(e-\alpha)}$ holds for any n because $1 - \frac{6(1-\alpha)}{(2+\delta)(e-\alpha)} \geq 1$ and $r \in (0, 1)$; if $e > \alpha$, then $r^n \geq 1 - \frac{6(1-\alpha)}{(2+\delta)(e-\alpha)}$ holds if and only if $\frac{6(1-\alpha)}{(2+\delta)(e-\alpha)} > 1$ or $\frac{6(1-\alpha)}{(2+\delta)(e-\alpha)} < 1$ and $n < \log_r \left[1 - \frac{6(1-\alpha)}{(2+\delta)(e-\alpha)}\right]$, which holds if and only if $\alpha < e < \alpha + \frac{6(1-\alpha)}{2+\delta}$ or $e > \alpha + \frac{6(1-\alpha)}{2+\delta}$ and $n < \log_r \left[1 - \frac{6(1-\alpha)}{(2+\delta)(e-\alpha)}\right]$.

Combining 1) with 2), we have (G_0, F) is the equilibrium when (i) $n \geq log_r \left[1 - \frac{4A(1-r)(4-\delta)^2}{\delta(8+\delta)}\right]$, $A < \frac{\delta(8+\delta)}{4(1-r)(4-\delta)^2}$, and $e < \alpha + \frac{6(1-\alpha)}{2+\delta}$, or (ii) $\log_r \left[1 - \frac{4A(1-r)(4-\delta)^2}{\delta(8+\delta)}\right] \leq n < \log_r \left[1 - \frac{6(1-\alpha)}{(2+\delta)(e-\alpha)}\right]$, $A < \frac{\delta(8+\delta)}{4(1-r)(4-\delta)^2}$ and $e > \alpha + \frac{6(1-\alpha)}{2+\delta}$. One can show that if $A < \frac{\delta(8+\delta)}{4(1-r)(4-\delta)^2}$ and $e > \alpha + \frac{6(1-\alpha)}{2+\delta}$, then $0 < \log_r \left[1 - \frac{4A(1-r)(4-\delta)^2}{\delta(8+\delta)}\right] < \log_r \left[1 - \frac{6(1-\alpha)}{(2+\delta)(e-\alpha)}\right]$ when $e < \alpha + \frac{3(1-\alpha)\delta(\delta+8)}{2A(1-r)(2+\delta)(4-\delta)^2}$. Also, $\alpha + \frac{6(1-\alpha)}{2+\delta} \leq \alpha + \frac{3(1-\alpha)\delta(\delta+8)}{2A(1-r)(\delta+2)(4-\delta)^2}$ when $A < \frac{\delta(8+\delta)}{4(1-r)(4-\delta)^2}$.

Moreover, the total impact TI^E decreases in n when $e < \alpha$ and increases in n when $e > \alpha$. Thus, $n^E = \infty$ when $e < \alpha$ and $A < \frac{\delta(8+\delta)}{4(1-r)(4-\delta)^2}$; $n^E = \log_r \left[1 - \frac{4A(1-r)(4-\delta)^2}{\delta(8+\delta)}\right]$ when $\alpha < e < \alpha + \frac{3(1-\alpha)\delta(\delta+8)}{2A(1-r)(2+\delta)(4-\delta)^2}$; and $n^E = 0$ otherwise. ⊠

Proof of Lemma 4.5.1. If the innovative company does not go green and hence does not obtain patent term extension under policy ET, then the problem is essentially the same as under policy T. In particular, $\Pi_1^{ET}(O, O) = \frac{(1-\delta)(2-c_t)^2}{(1-r)(4-\delta)^2}$. If the innovative company chooses green pharmacy, then we simultaneously solve $\Pi_1^{ET}(G_0, F) = \max_{p_m, p_1} \frac{1-r^n}{1-r} \cdot (1 - p_m) \cdot (p_m - c_t) + \frac{r^n}{1-r} \cdot \frac{1-\delta-p_1+p_2}{1-\delta} \cdot (p_1 - c_t) - A$ and $\Pi_2^{ET}(G_0, F) = \max_{p_2} \frac{r^n}{1-r} \cdot \frac{\delta p_1 - p_2}{(1-\delta)\delta} \cdot (p_2 - c_t)$. Similar to the proof of Lemma 4.4.1, one can show that $\Pi_1^{ET}(G_0, F) = \frac{(2-c_t)^2(1-\delta)r^n}{(4-\delta)^2(1-r)} + \frac{(1-c_t)^2(1-r^n)}{4(1-r)} - A$. Due to the fact that $\Pi_1^{ET}(G_0, F) \geq \Pi_1^{ET}(O, O)$ if and only if $A \leq \frac{1-r^n}{1-r} \left[\frac{(1-c_t)^2}{4} - \frac{(2-c_t)^2(1-\delta)}{(4-\delta)^2}\right]$, the remaining part of the statements then follows. ⊠

Proof of Proposition 4.5.2. Similar to the proof of Proposition 4.4.4, one can show Proposition 4.5.2. ⊠

Proof of Corollary 4.5.3. According to according to Proposition 4.4.4(a), $n^E = log_r\left[1 - \frac{4A(4-\delta)^2(1-r)}{\delta(8+\delta)}\right]$ when $\alpha \le e < \alpha + \frac{3(1-\alpha)\delta(8+\delta)}{2A(1-r)(2+\delta)(4-\delta)^2}$ and $A < \frac{\delta(8+\delta)}{4(1-r)(4-\delta)^2}$. In addition, $n^{ET} = log_r[1 - \frac{4A(4-\delta)^2(1-r)}{\delta(8+\delta)-2c_t(8+\delta^2)+c_t^2(\delta^2-4\delta+12)}]$ when $\alpha\eta \le e < \max\left\{\alpha\eta + \frac{2(1-\alpha)(2+\delta)}{3\delta}, \alpha\eta + e^u_{ET}\right\}$ and $A < \frac{\delta(8+\delta)-2c_t\left(8+\delta^2\right)+c_t^2\left(12-4\delta+\delta^2\right)}{4(4-\delta)^2(1-r)}$, according to Proposition 4.5.2(a). Note $\frac{\delta(8+\delta)-2c_t\left(8+\delta^2\right)+c_t^2\left(12-4\delta+\delta^2\right)}{4(4-\delta)^2(1-r)} \le \frac{\delta(8+\delta)}{4(1-r)(4-\delta)^2}$ when $\delta > 2c_t$. One can show that $\frac{4A(4-\delta)^2(1-r)}{\delta(8+\delta)} \le \frac{4A(4-\delta)^2(1-r)}{\delta(8+\delta)-2c_t(8+\delta^2)+c_t^2(\delta^2-4\delta+12)}$ when $\delta > 2c_t$. Thus, the statement follows. ⊠

Proof of Lemma 4.6.1. In the presence of the modified take-back regulation (policy $\bar{T}$), the four possible strategy pairs are (G_1, G_1), (G_1, O), (O, O) and (O, G_1). Similar to the proof of the benchmark model and 4.4.2, we first obtain the solutions for each strategy pair. (1) Given strategy (G_1, G_1), $\Pi_1^{\bar{T}}(G_1, G_1) = \max_{p_1} \frac{1}{1-r} \cdot \frac{1-\delta-p_1+p_2}{1-\delta} \cdot (p_1 - \alpha \cdot c_t) - A$ and $\Pi_2^{\bar{T}}(G_1, G_1) = \max_{p_2} \frac{1}{1-r} \cdot \frac{1-\delta-p_1+p_2}{1-\delta} \cdot (p_2 - \alpha \cdot c_t) - A$, which give us the solution as stated in Proposition 4.6.1(a); (2) Given strategy (G_1, O), $\Pi_1^{\bar{T}}(G_1, O) = \frac{1}{1-r} \cdot \frac{1-\delta-p_1+p_2}{1-\delta} \cdot (p_1 - \alpha \cdot c_t) - A$; $\Pi_2^{\bar{T}}(G_1, O) = \max_{p_2} \frac{1}{1-r} \cdot \frac{\delta p_1 - p_2}{(1-\delta)\delta} \cdot (p_2 - c_t)$, which give us the solution as stated in Proposition 4.6.1(b); (3) Given strategy (O, O), $\Pi_1^{\bar{T}}(O, O) = \max_{p_1} \frac{1}{1-r} \cdot \frac{1-\delta-p_1+p_2}{1-\delta} \cdot (p_1 - c_t)$ and $\Pi_2^{\bar{T}}(O, O) = \max_{p_2} \frac{1}{1-r} \cdot \frac{\delta p_1 - p_2}{(1-\delta)\delta} \cdot (p_2 - c_t)$, which give us the solution as stated in Proposition 4.6.1(c); (4) Given strategy (O, G_1), $\Pi_1^{\bar{T}}(O, G_1) = \max_{p_1} \frac{1}{1-r} \cdot \frac{1-\delta-p_1+p_2}{1-\delta} \cdot (p_1 - c_t)$ and $\Pi_2^{\bar{T}}(O, G_1) = \frac{1}{1-r} \cdot \frac{1-\delta-p_1+p_2}{1-\delta} \cdot (p_2 - \alpha \cdot c_t) - A$. By solving the simultaneous game, we have $\Pi_1^{\bar{T}}(O, G_1) = \frac{[2(1-\delta)-c_t(2-\alpha-\delta)]^2}{(1-r)(1-\delta)(4-\delta)^2}$, $\bar{T}_2^T(O, G_1) = \frac{[\delta(1-\delta)-c_t(\alpha(2-\delta)-\delta)]^2}{(1-r)(1-\delta)(4-\delta)^2}$, $p_1^{\bar{T}}(O, G_1) = \frac{2(1-\delta)+(2-\alpha-\delta)}{4-\delta}$, $p_2^{\bar{T}}(O, G_1) = \frac{(1-\delta)\delta+c_t(2\alpha+\delta)}{4-\delta}$, $d_1^{\bar{T}}(O, G_1) = \frac{2(1-\delta)-c_t(2-\alpha-\delta)}{(1-\delta)(4-\delta)^2}$, and $d_2^{\bar{T}}(O, G_1) = \frac{\delta(1-\delta)-c_t(\alpha(2-\delta)+\delta)}{(1-\delta)(4-\delta)^2}$.

To obtain the equilibrium, we next derive the optimal strategy of one company given the strategy of the other. Given that the generic company chooses strategy O, the innovative company chooses strategy G_1 over strategy O iff $\Pi_1^T(G_1, O) \ge \Pi_1^T(O, O)$ iff $A \le B_1 \doteq \frac{(1-\alpha)c_t(2-\delta)[4(1-\delta)-c_t(\alpha(2-\delta)-\delta)]}{(1-r)(1-\delta)(4-\delta)^2}$. Given that the generic company chooses strategy G_1, the innovative company chooses strategy G_1 over strategy O iff $\Pi_1^T(G_1, G_1) \ge \Pi_1^T(O, G_1)$ iff $A \le B_2 \doteq \frac{(1-\alpha)c_t(2-\delta)[4(1-\delta)-c_t(2-\delta-\alpha\delta)]}{(1-r)(1-\delta)(4-\delta)^2}$. Note one can show that $B_1 \ge B_2$ when

$c_t \leq \frac{(1-\delta)\delta}{2-\alpha\delta-\delta}$. Thus, the innovative company always chooses strategy O if $A \geq B_1$ and always chooses strategy G_1 if $A \leq B_2$. Otherwise, its strategy depends on the strategy of the generic company.

Given that the innovative company chooses strategy O, the generic company chooses strategy G_1 over strategy O iff $\Pi_2^T(O, G_1) \geq \Pi_2^T(O, O)$ iff $A \leq B_3 \doteq \frac{(1-\alpha)c_t(2-\delta)[2(1-\delta)\delta - c_t(\alpha(2-\delta)-3\delta+2)]}{(1-r)(1-\delta)(4-\delta)^2}$. Given that the innovative company chooses strategy G_1, the generic company chooses strategy G_1 over strategy O if and only if $\Pi_2^T(G_1, G_1) \geq \Pi_2^T(G_1, O)$, if and only if $A \leq B_4 \doteq \frac{(1-\alpha)c_t(2-\delta)[2(1-\delta)\delta - c_t(\alpha(2-3\delta)-\delta+2)]}{(1-r)(1-\delta)(4-\delta)^2}$. Note one can show that $B_3 \geq B_4$ when $c_t \leq \frac{(1-\delta)\delta}{2-\alpha\delta-\delta}$. Thus, the generic company always chooses strategy O if $A \geq B_3$ and always chooses strategy U_1 if $A \leq B_4$. Otherwise, its strategy depends on the strategy of the innovative company.

Also note that $B_2 \geq B_3$, and therefore $B_1 \geq B_2 \geq B_3 \geq B_4$. By jointly considering the best response of both companies, it is not hard to show that the equilibrium is (G_1, G_1) if $A \leq B_4$, (G_1, O) if $B_4 \leq A \leq B_2$, and (O, O) if $A \geq B_1$. Letting $A_1^{\bar{T}} = B_4$ and $A_2^{\bar{T}} = B_1$, we proved the lemma. ⊠

Proof of Proposition 4.6.2. To prove the proposition, we only need to compare the total impacts under policy $\bar{T}$ with those under policy N. For example, according to Lemma 4.6.1, we have $d_1^{\bar{T}} = \frac{2-\alpha c_t}{4-\delta}$, and $d_2^{\bar{T}} = \frac{\delta-2\alpha c_t}{(4-\delta)\delta}$ when $A \leq A_1^{\bar{T}}$. Thus, the total impact under policy $\bar{T}$ is $TI^{\bar{T}} = e\frac{1}{1-r}[1 - \frac{2-\alpha c_t}{4-\delta} - \frac{\delta-2\alpha c_t}{(4-\delta)\delta}] + \eta\alpha\frac{1}{1-r}[\frac{2-\alpha c_t}{4-\delta} - \frac{\delta-2\alpha c_t}{(4-\delta)\delta}]$ when $A \leq A_1^{\bar{T}}$. Meanwhile, the total impact under policy N is $TI^N = e\frac{1}{1-r}(1 - \frac{2}{4-\delta} - \frac{1}{4-\delta}) + \frac{1}{1-r}(\frac{2}{4-\delta} + \frac{1}{4-\delta})$ for any system parameter set. Therefore, when $A \leq A_1^{\bar{T}}$, policy $\bar{T}$ is better than policy N if and only if $TI^{\bar{T}} < TI^N$, or equivalently, $e < \alpha\eta + \frac{3\delta(1-\alpha\eta)}{\alpha c_t(2+\delta)}$. Similarly, we can show that when $A_1^{\bar{T}} \leq A \leq A_2^{\bar{T}}$ and $e < \alpha\eta + \frac{\delta(1-\delta)(3-\eta-2\alpha\eta)+(1-\alpha)c_t\eta(2-\delta-\alpha\delta)}{c_t(1-\delta)(2+\alpha\delta)}$ or when $A > A_2^{\bar{T}}$ and $e < \eta + \frac{3\delta(1-\eta)}{c_t(\delta+2)}$, policy $\bar{T}$ is better than policy N. The remaining part of the statements follows. ⊠

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