ACHIEVING SUSTAINABLE DEVELOPMENT GOALS (SDGS): SUSTAINABLE SUPPLY CHAIN MANAGEMENT IN THE FASHION INDUSTRY

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CERTIFICATE OF ORIGINALITY

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Abstract

United Nations' new sustainable development agenda for 2030 has come into force since 2016, which initiates 17 sustainable development goals (SDGs). The SDGs well demonstrate the new objectives of economic, social, and environmental developments, such as ending poverty, economic growth, environmental protection and so on. SDGs call for everyone in the world to contribute to the goals, including the government, the companies, the civil organizations, and the public. From the private sector, it is reported that sustainable business can bring up to US$ 12 trillion in economic opportunities. Sustainable business can be observed in the real-world practice. For example, design for environment is considered in the initial stage of product development; quick response strategy is adopted in the production process to avoid overstock; and post-consuming (used) products are taken back for remanufacturing by retailers to reduce waste. This dissertation research is to solve the related issues: i) To study producer's choice of design-for-environment under environmental taxation; ii) To investigate the impacts of lead time reduction on fabric sourcing in apparel production with yield and environmental considerations; iii) To explore commercial used apparel collection operations in retail supply chains. These problems are new and have not been studied in the extant literature. To analyze the proposed problems, we build stylized analytical models and derived the following main results:

Firstly, we find that the "constant tax" does not encourage sustainable product design and the "zero tax" is even better than the "constant tax". On the contrary, the "linear tax" can promote sustainable product design and can be regarded as the best. We further discover that the "linear tax" can help balance the design for environment (DfE) level, the stakeholders' benefits and the social welfare performance. The leveraging effect of marginal DfE allowance in the "linear tax" is surprisingly important and useful.

Secondly, when the fabric supplier's profit is improved under lead time reduction, the environment must be hurt. We hence propose the use of an environment tax to help and prove that lead time reduction can even improve the environment if the environment tax is appropriately set. Finally, we show that the product's demand coefficients of variation would mediate how the fabric production yield affects the fabric supplier's expected benefit as well as the expected harm to the environment under lead time reduction.

Thirdly, we consider the case when a fashion retail brand promotes its used apparel collection (UAC) program and collects the used apparel from consumers in the basic model. Depending on the conditions of the collected apparel products, the fashion retail brand will classify and either donate them for charity or send to remanufacturing. For either case, the fashion retail brand gains a benefit. We analytically derive in closed-form the optimal promotion effort and study the mechanism for supply chain coordination. Our results indicate that many traditional supply contracts fail to achieve supply chain coordination. Thus, the effort cost sharing (ECS) contract is proposed and proven to be effective for "profit" coordination.

Finally, managerial insights are generated, and future research directions are discussed.

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Table of contents

Abstract i
List of Figures viii
List of Tables ix
Chapter 1 Introduction 1
  1.1 Background 1
  1.2 Research Objectives 2
  1.3 Thesis Outline 3
Chapter 2 Literature Review 5
  2.1 Design for Environment and Environmental Tax 6
    2.1.1 Design for Environment 6
    2.1.2 Environmental Tax 7
  2.2 Lead Time Reduction in Sourcing and Procurement 9
    2.2.1 Lead Time Reduction 9
    2.2.2 Sourcing and Procurement 10
  2.3 Reverse Supply Chain and Socially Responsible Operations 11
    2.3.1 Acquisition and Remanufacturing 11
    2.3.2 Socially Responsible Operations 13
Chapter 3 Producer's Choice of Design-for-Environment under Environmental Taxation 15
  3.1 Introduction 15
    3.1.1 Background 15
    3.1.2 Research Questions and Objectives 17
  3.2 Basic Model 19
  3.3 Optimal Decision of the Producer 22
    3.3.1 DfE Choice of the Producer 22
    3.3.2 Impacts of Taxation Choice on the Stakeholders and the Environment 24
  3.4 Social Welfare Performance 26
  3.5 Extended Models 29
    3.5.1 Investment on Technology Innovation 30
    3.5.2 DfE Level Dependent Consumer Returns 31
    3.5.3 Government Revenue Tax 33
    3.5.4 Quadratic Environmental Tax Scheme 34
  3.6 Concluding Remarks 36
Chapter 4 Impacts of Lead Time Reduction on Fabric Sourcing in Apparel Production with Yield and Environmental Considerations 38
  4.1 Introduction 38
  4.2 Lead Time and Fabric Sourcing Model 39
  4.3 Values of Lead Time Reduction 41
  4.4 Reducing Lead Time: Is It Wise? 45
    4.4.1 Expected Values of Lead-time Reduction 45

4.4.2 Deposit Payment Schemes 49
4.5 Pollution and Environment Tax 51
4.5.1 Expected Harm to the Environment...51
4.5.2 Environment Tax 54
4.6 Concluding Remarks..55
Chapter 5 Commercial Used Apparel Collection Operations in Retail Supply Chains 58
5.1 Introduction..58
5.1.1 Background...58
5.1.2 Research Questions and Objectives..60
5.2 Basic Model 61
5.3 Equilibrium Decisions and Performance 65
5.3.1 Decentralized Setting..65
5.3.2 Centralized Setting..66
5.4 Coordination 67
5.5 Extended Models and Analyses 69
5.5.1 Consumer Coupon Offering..69
5.5.2 "No RM" Model 71
5.5.3 Consumer Heterogeneity in Environmental Consciousness 72
5.5.4 Own-Brand Collection Versus Any-Brand Collection...............................73
5.5.5 Summary of Extended Models...74
5.6 Concluding Remarks...74
Chapter 6 Conclusions and Discussions for Future Research 78
6.1 Future research...80
References...82
Appendix I: Proofs for Lemmas and Propositions in Chapter 3 96
Appendix II: Proofs for Lemmas and Propositions in Chapter 4..............................105
Appendix III: Proofs for Lemmas and Propositions in Chapter 5 109

List of Figures

Figure 1.1 The structure of this thesis 4

Figure 3.1 The basic model structure of producer’s choice of DfE level 20

Figure 3.2 The social welfare performance with the change of DfE level 28

Figure 5.1 The basic model structure of UAC operations 62

List of Tables

Table 3.1 Three forms of environmental tax schemes 21
Table 3.2 Comparisons of social welfare values under different environmental taxation schemes 27
Table 3.3 The aims of the extended models...30
Table 4.1 Features of ordering at Time 1 versus ordering at Time 2 40
Table 4.2 The Bayesian demand and forecast updating model...................................41
Table 4.3 How $EVLR_M$ varies with the major parameters 47
Table 4.4 How $EVLR_S$ varies with the major parameters..48
Table 4.5 How $EVLR_{SC}$ varies with the major parameters..49
Table 4.6 How the expected harm to environment (with lead time reduction) varies with the major parameters 53
Table 5.1 UAC practices of the fashion retail brands 59
Table 5.2 Notation Table of UAC operations 64
Table 5.3 The summary table of the results from extended models 74

Chapter 1

Introduction[1]

1.1 Background

United Nation's new sustainable development agenda for 2030 has come into force in 2016, which initiates 17 sustainable development goals (SDGs), embracing a comprehensive "3BL" strategy. The SDGs well demonstrate the new objectives of economic, social and environmental perspectives, such as ending poverty, economic growth, environmental protection and so on. SDGs call for everyone in the world to contribute their responsibility, including the government, the companies, the civil organizations and the public people. From the private sector, sustainable business can bring up to US$ 12 trillion in economic opportunities. We have witnessed sustainable operations have been adopted by firms. For example, design for environment is considered in the initial stage of product development; quick response strategy is adopted in the production process to avoid overstock; and post-consuming (used) products are taken back for remanufacturing by retailers to reduce waste.

Sustainability related issues are very sensitive to the textile and apparel sector. From the environmental perspective, a huge number of resources (e.g., cotton, linen, wool, etc.), energies (e.g., electricity), and water are consumed and carbon emissions lead to the climate change. Especially in the dyeing process, the wastewater contains various kinds of chemicals. If not properly handled, the rivers and streams are seriously polluted. From the statistics of the World Bank, 17% to 20 % water pollution from industrial consumption is created by the dyeing and treatment process in the textile and apparel industry, and there are 72 toxic chemicals produced by the textile dyeing[2]. Moreover, fast fashion and fast changing fashion trends have caused a high frequency of consumers' purchasing, a shortened apparel lifespan, and a larger amount of post-consuming apparel waste (Dissanayake and Sinha 2015). From the social perspective, the textile and apparel industry is characterized by a labor-intensive sector. Global production takes advantage of low labor costs in some developing countries,

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[1] A part of this chapter has been published in Transportation Research Part E.

[2] http://chinawaterrisk.org/resources/analysis-reviews/the-environmental-cost-of-clothes/ [Accessed on 25 March 2019]

such as Cambodia, Vietnam, Bangladesh and so on. The factory accident Rana Plaza collapse in Bangladesh reflects the serious social problems hidden in the textile and apparel industry, which also arouse the public awareness on the labors' rights, their health and safety, their payment, etc. Thus, it is really a big challenge for the TA industry to achieve the new objectives of economic, social and environmental developments.

Sustainability is never such attractive and critical like nowadays. Especially in fashion and textile industry, more arguments are given to fast fashion in terms of sustainability, since fast fashion has created fast-speed disposal, a large amount of waste and high pressure on the environment. We also witness the measures have been taken by some fast fashion brands. On sustainable purchasing, "organic cotton" is widely used by many fashion brands. For example, sustainable sourcing of raw material cotton occupies 43% of H&M's total cotton consumption in 2018 and the goal is all the brands will employ sustainable raw materials and recycled materials by 2030[3]. To solve the water pollution in the jeans dyeing process, Levi's launched a "Waterless Dyeing Process" to reduce the water consumption and water pollution in 2016[4]. Levi's Eureka Lab has invented a new laser technology to make ripped and washed jeans more eco-efficient in 2018[5]. To protect the animal's rights, the luxury brand Gucci announced to stop using the genuine leather and fur. And sustainable brand Stella McCartney insists on using the artificial leather for handbag and shoes making. This type of artificial leather has a high-quality of functionality, which even can compete with the genuine leather. To protect the diversity of the ocean, the plastics pollution (e.g., PET bottles) have been collected and remanufactured for fashionable clothes and shoes by some sustainable fashion companies (e.g., ECOALF). To close the loop, H&M initiates the used apparel collection plan; Uniqlo collects the post-consumer products for donation; Nike recycles the old shoes for new ones; etc.

1.2. Research Objectives

Motivated by the real-world practices in the textile and apparel industry, this project is to solve the

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[3] http://about.hm.com/en/sustainability/sustainable-fashion/materials/cotton.html [Accessed on 25 March 2019]

[4] https://wellmadeclothes.com/articles/LevisMakesItsWaterlessDyeingProcessOpenSourceAndLaunchesSustainableFashionInnovationLab/ [Accessed on 25 March 2019]

[5] https://nyti.ms/1Orr3ja [Accessed on 25 March 2019]

related issues: i) To study producer’s choice of design-for-environment under environmental taxation; ii) To investigate the impacts of lead time reduction on fabric sourcing in apparel production with yield and environmental considerations; iii) To explore commercial used apparel collection operations in retail supply chains. These problems are new and have not been studies in the extant literature.

1.3. Thesis Outline

The thesis is organized as follows:

Chapter 2 conducts the literature review on the related topics, including design for environment, environmental tax, sourcing and procurement, lead time reduction, acquisition and remanufacturing, and socially responsible operations. And we identify the research gap in the areas of producer’s choice of design-for-environment under environmental taxation, impacts of lead time reduction on fabric sourcing in apparel production with yield and environmental considerations, and commercial used apparel collection operations in retail supply chains.

Chapter 3 studies producer’s choice of design-for-environment under environmental taxation. Observations from real-world practices and extant literature indicate that currently, companies do not have strong incentive to establish DfE. To this end, this paper proposes the use of an environmental tax to enhance DfE, which will contribute to reducing wastes from the origins, improving the environmental performance and maximizing the social welfare. In this paper, by building a stylized analytical model, we examine three forms of environmental taxes (linear tax, constant tax and zero tax) and evaluate how they affect the producer’s optimal DfE level.

Chapter 4 examines impacts of lead time reduction on fabric sourcing in apparel production with yield and environmental considerations. In apparel supply chains, manufacturers usually request a short lead time for fabric supplies. However, a short supply lead time would create environmental problems such as insufficient time for proper control of chemicals and material processing operations, and lead to a lower production yield of good quality supplies. Motivated by this observed industrial practice in fabric sourcing and apparel production, we build a stylized analytical model to investigate how lead time reduction in fabric sourcing affects performances of the fabric supplier and apparel manufacturer as well as the environment.

Chapter 5 explores commercial used apparel collection operations in retail supply chains. Motivated by the commonly observed commercial used apparel collection (UAC) programs in the fashion retail supply chain operations, this paper analytically explores the associated operational challenges that firms face. First, in the basic model, we consider the case when a fashion retail brand promotes its UAC program and collects the used apparel from consumers. Depending on the conditions of the collected apparel products, the fashion retail brand will classify and either donate them for charity or send to remanufacturing.

Chapter 6 summarizes the main findings of the thesis and discusses the limitation and future research for this thesis. Figure 1.1 depicts the structure of this thesis.

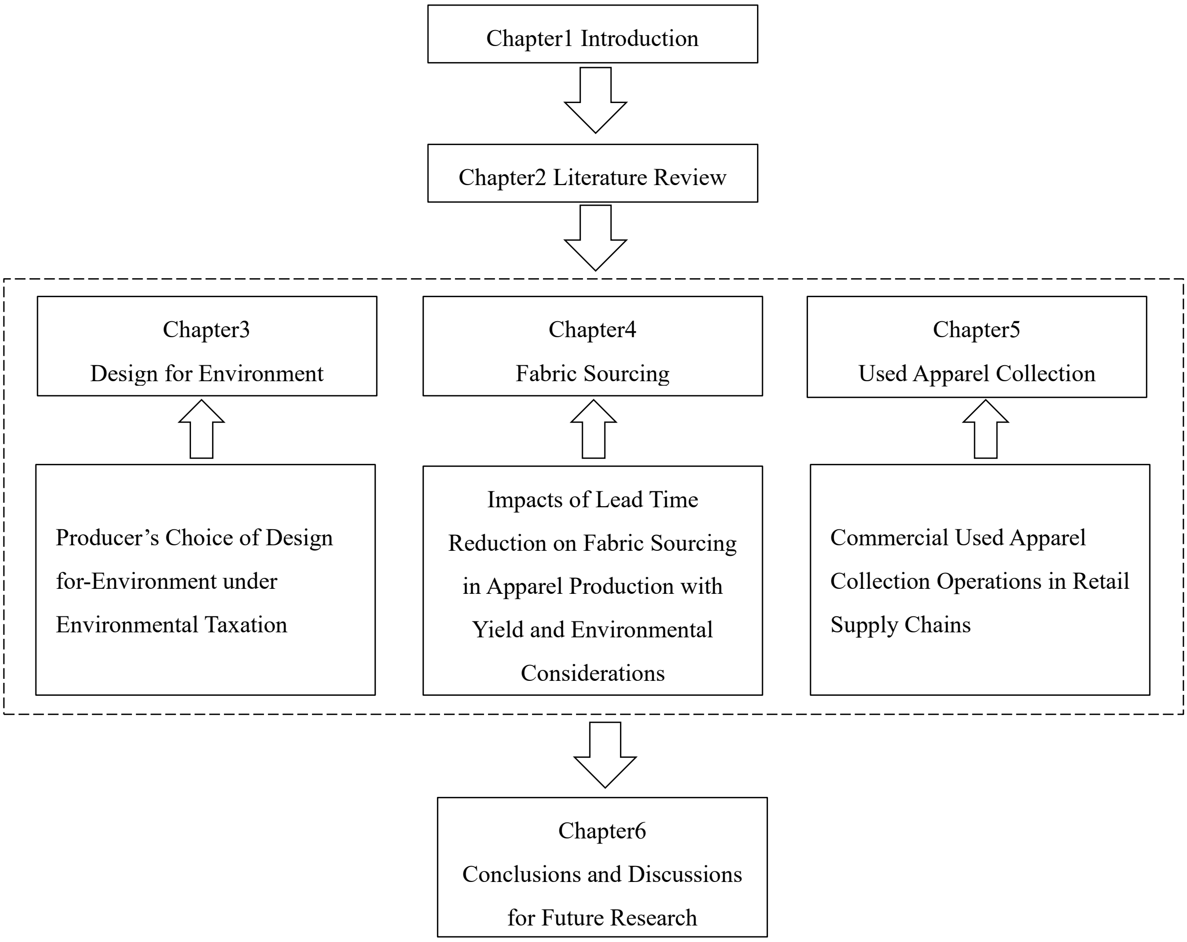

Figure 1.1 The structure of this thesis.

Chapter 2

Literature Review[6]

The "3BL" (i.e., Triple Bottom Line) based sustainability issues are critical in the TA sector. "3BL" is a well-established term for sustainability, which emphasizes the "three pillars" on economic, social and environmental sustainability (Elkington 1994&1998). Various issues may include information disclosure in sustainability reports, corporate social responsibility (CSR) initiatives, fairness, safety and wages for workers, carbon emissions, sustainable collaborations, sustainability awareness, intelligent forecasting and so on. The above-mentioned issues can appear in both forward and reverse supply chain in the TA sector.

Sustainable forward supply chain management contains upstream activities, including sustainable design, sustainable dyeing, sustainable sourcing, sustainable production, and downstream activities, including sustainable retailing and consumption. Sustainable design means to use more eco-friendly materials, patterns and techniques to design apparel, when comparing with the traditional apparel design (Kozlowski et al. 2018). The concept of design for disassembly, design for recycling, or design for environment is also a new approach for sustainable design (Liu et al. 2019). Dyeing process leads to serious pollution problems (e.g., water pollution) in the TA supply chain. For instance, toxic chemicals release, if not well treated, may affect the health of the workers as well as the surrounding community. The process involves activities like the choice of the dyes (e.g., natural or chemical), the dyeing method (e.g., spin-dyeing or conventional dyeing), the operations controlling, etc. Different choices and decisions will affect the sustainability in the dyeing section. Production in the TA supply chain creates issues like labours' rights, resources and energy consumption, waste generation and so on. For the OEM manufacturers, they need to prepare the raw materials, including the fabrics and accessories like zippers, buttons, and buckles, etc. For the fashion retailers, they need to select the suitable and reliable suppliers, to place the orders, and to control the lead time and quality assurance. To cooperate with green suppliers is a strategic approach for sustainable sourcing (Fang and Cho 2020).

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[6] A part of this chapter has been published in European Journal of Operations Research, Transportation Research Part E, and Annals of Operations Research.

Nowadays, reverse activities and closed loop supply chain are becoming increasingly popular in the TA sector. Increased consumption of fashion products creates a large amount of post-consuming waste to the planet, which is a worldwide concern. Reverse activities can provide opportunities to alleviate this situation (Pinheiro et al. 2019). Reverse activities may include reuse, remanufacturing, recycling and so on (Kannan et al. 2012; Bukhari et al. 2018). In closed-loop supply chain (CLSC), the recycled textile materials can act as raw materials for new products to minimize the solid waste and reducing the environmental burden. CLSC is an effective approach for circular textile and apparel, which creates both economic and environmental values.

After an overall review on sustainable supply chain management in the TA sector. We conduct a detailed literature review on design for environment, lead time reduction in sourcing and procurement, acquisition and remanufacturing, and socially responsible operations.

2.1 Design for Environment and Environmental Tax

2.1.1 Design for Environment

Design for environment has to consider design for product maintenance, disassembly or recycling (Hollander et al. 2017). Modular architecture design for many products (e.g., computers, motor vehicles, TVs, etc.) is a special feature for product design (Mukhopadhyay and Setoputro 2005; Talens Peiró et al. 2017). Huang and Kusiak (1998) present various kinds of modularity, like component-swapping, component-sharing, and bus modularity and find that the modules may be shared across different products. Krikke et al. (2004) show that reuse on a modular level has the greatest economic and ecological potential, and modularity helps further optimize the closed-loop supply chain. Tchertchian et al. (2013) state modular design can increase the proportion of remanufacturable and recyclable modules for a sustainable economy. Engel et al. (2017) find some architectural patterns such as modularity provide particular benefits for product adaptability. These findings prove that product design has both economic and environmental values, which provides important proofs for modelling the DfE in our paper. In other words, in our model, a higher product’s DfE level of an implies a higher product’s “resource efficiency” which yields a higher performance of sustainable product design.

Different from the research in the above paragraph, some analytical modelling studies also explore the product's DfE. For example, Chen (2001) studies DfE in green product development from a quality-based model perspective. Raz et al. (2013) examine how DfE affects the product's cost and demand and the environmental impact in a life-cycle approach. The authors find that many factors determine the overall environmental impact, such as the costs for recycling and consumers' purchasing behaviours. Agrawal and Ülkü (2012) study modular upgradability as a green design strategy for improving environmental performance and find that modular upgradability can reduce the environmental impacts. Shi et al. (2016) study effects of remanufacturable product design on market segmentation, and the environment and model the product. The authors conclude that the proposed measure for environmental efficiency, "emissions per revenue" is the best way for measuring overall environmental impacts. Aydinliyim and Murthy (2016) study sourcing problems in engineering design decision in a closed loop chain and model the engineering design into integral versus modular design. The authors find that recycling implications can affect the buyers' design decisions. Most recently, Agrawal et al. (2018) explore the economic and environmental performances brought by leasing and modularity. The authors find that integrating the two strategies is optimal for the firm under certain conditions, but it will do more harm to the environment than adopting the sole strategy. This stream of literature does have different focus on DfE. But, different from them, this paper examines the impact of environmental taxes on the sustainable product design and its implications on the real-world practices.

2.1.2 Environmental Tax

An environmental tax can act as an economic instrument to solve the environmental related problems (Xiao et al. 2020). Here, we review some literature with the interplay between the environmental tax and operational research. The early study on environmental tax is by Hartl (1994), who investigates how the introduction of an environmental tax influences the production rate and pricing. The author finds that a linear tax has no effect on the emissions, while a progressive tax can reduce the emission peaks. Kroes et al. (2012) study how Cap and Trade regulation affect the firm and the environment performance. The authors show that better environmental performance generally brings out better economic performance under stringent regulation. Zhao et al. (2012) address the water pollution problem by proposing a transfer tax analytical model. Choi (2013) studies the problem of supplier selection in the apparel supply chain under the regulation of carbon emission tax. The author reveals that the carbon emission tax schemes affect the fashion retailer's decision on supplier selection, and non-linear quadratic carbon taxation form can better promote the local suppliers. Krass et al. (2013) examine how environmental taxes affect the firm's choice of green technology by using a Stackelberg game model. The authors find that a tax-only policy maximizes social welfare and motivates the choice of clean technology. Yeung (2014) studies a dynamic game and derives the optimal dynamic solution to the collaborative managerial system for enhancing the environment by choosing the right production technique. Drake et al. (2016) also study the clean technology choice and the emissions regulation, and the authors reveal that dynamic charges under cap-and-trade regulation is better than a constant price under an emissions tax. Ma et al. (2018) investigate the pricing strategies under carbon tax scheme in a decentralized supply chain and find that the carbon tax and the unit procurement price are two predominant factors for the pricing issue of the manufacturer. Hammami et al. (2018) study the effects of customers' environmental awareness (CEA) and environmental regulations on the emission intensity and pricing issues. The authors find that CEA can be an efficient driver for better environmental performance. Regarding the external various environmental regulations. Xiao et al. (2020) examine firms' investment strategies in improving the environmental process to reduce the manufacturing impact on environment.

Wang et al. (2016) reveal how the government's inspection, supported by proper penalty and subsidy policies, on environmental problems can induce the companies to disclose voluntarily their environmental problems. Note that one argument behind the implementation of government taxation or subsidy schemes related to the environment is to entice manufacturers to improve their technologies so as to reduce the release of pollutants. In this area, Gong and Zhou (2013) explore the optimal production and technology choice model with emission trading. Alizamir et al. (2016) advocate the development of new green technologies by adopting the feed-in-tariff policy. Bi et al. (2017) analytically reveal how government rules can motivate companies to develop technologies to reduce pollutants. Other related studies include Song et al. (2016) and Basu et al. (2017). This paper also explores the use of an environmental tax and discusses how it can be designed to entice the fabric supplier to reduce the amount of pollutants by adopting technological solutions. However, this paper is different from the above reviewed papers in the scope and the detailed taxation scheme.

As a remark, the topic on “extended producer responsibility” or “take-back legislation” also relates to the environmental tax. While the respective topic is huge, it is not the focus of this study, we refer readers to Plambeck and Wang (2009), Atasu and Van Wassenhove (2012), Gui et al. (2018), Mazahir et al. (2019), Cai and Choi (2019) and Huang et al. (2019) for more discussions. Different from the above-mentioned literature on environmental tax, this study explores how different forms of environmental taxes influence the producer’s choice of DfE. To the best of our knowledge, this paper is the first analytical modelling paper that theoretically addresses the issue of DfE with the adoption of the environment tax.

2.2 Lead Time Reduction in Sourcing and Procurement

2.2.1 Lead Time Reduction

Lead time is a critical part of supply chain management as it affects the adoption of concepts like pull strategies as well as responsive supply chains (Kraiselburd et al. 2011; Shen et al. 2015). If manufacturers achieve reduced lead times in offering their products to the buyers, the respective measure is usually called “quick response practice” (Iyer and Bergen 1997; Choi et al. 2018b). Moreover, if the manufacturers can provide accurate response to the market changes, we call it the “accurate response program” (Fisher and Raman 1996; Reimann 2015). The major rationale behind lead time reduction is to get closer to the market and have better market information to improve decision making. In the related literature, Donohue (2000) is among the first to consider more than a single ordering opportunity in ordering: One with a longer lead time and one with a shorter lead time. The author establishes the optimal model and coordinates the supply chain. Krishman et al. (2010) investigate the lead time reduction problem with the focal point on retailer’s effort. Cachon and Swinney (2011) explore fast fashion business model and reveal how a responsive supply chain enjoys a competitive advantage in the fashion industry with strategic consumers. Lee et al. (2015) extend the problem examined by Cachon and Siwnney (2011) to include loss-averse and forward looking consumers. The authors derive the best procurement, product design, and inventory policy. Choi

(2016a) studies the situation when lead time reduction under a quick response program is associated with an inventory service target. The author reveals how a win-win situation can be achieved under quick response. Choi (2016b) explores the impacts of risk aversion on the retail quick response program. Chan et al. (2017) investigate the use of green technology in quick response supply chains. The authors develop contractual agreements to coordinate the channel. Other related studies include Lin and Parlakturk (2012), Liu and Nagurney (2013), Amornpetchkul et al. (2015), Zhang et al. (2017). Similar to the above reviewed papers on lead time reduction, this paper also pays attention to this important issue and employs the forecast updating Bayesian model. However, different from all of them, we focus on exploring issues related to production yield, environmental pollution, and forecast accuracy. This is very different from the above reviewed studies.

2.2.2 Sourcing and Procurement

Sourcing and procurement are two important tasks in supply chain operations, especially in fashion apparel (Sen 2008; Tokatli 2008; Fang et al. 2010; Perry et al. 2015). These two tasks are in general challenging owing to the stochastic nature of the problem (e.g., there are demand uncertainties, supply disruptions (Asian and Nie 2014) as well as problems with production yield). In the literature, a lot of recent analytical studies are devoted to exploring sourcing related to these issues. For instance, Chen et al. (2013) study the sourcing problem from multiple suppliers with random yield. The authors prove that a re-order point inventory system (for each individual supplier) may be optimal. Chen and Tan (2016) investigate the dynamic procurement problem when there are multiple suppliers. They consider the situation when the suppliers' capacities are stochastic. The authors identify that the presence of a more reliable supplier is highly desirable as it helps to stabilize the optimal dynamic procurement policy. Guo et al. (2016) examine the procurement problem in which a random yield as well as supply-side disruptions exist. The authors develop a dual-supplier system with a regular supplier, and a backup supplier". They reveal the situations under which it is optimal to source from the regular supplier and have little reservation with the backup supplier. Li (2016) studies the optimal procurement decisions in the presence of two unreliable suppliers. The author counterintuitively finds that ordering from a more expensive backup supplier is in fact an optimal decision in procurement. Ray and Jenamani (2016) explore risk averse decision-making behaviors in the multi-sourcing problem. The authors establish an algorithm to identify the optimal solution. Sheu (2016) explores the multi-sourcing problem by adopting a multi-methodological approach. The author uncovers one interesting insight which argues that buyers may choose suppliers with high relational quality, instead of just focusing on the price tag. Most recently, Nie et al. (2017) look into the material procurement problem and develop the optimal bidding strategies. Similar to the above reviewed studies, we also analytically explore the procurement problem under a stochastic problem setting. However, different from them, we focus mainly on the trade-off among forecast accuracy improvement via information updating, yield difference, and pollution problems in procurement, with respect to lead time reduction.

2.3 Reverse Supply Chain and Socially Responsible Operations

2.3.1 Acquisition and Remanufacturing

Reverse supply chain management receives a lot of attention from the academia (Kleindorfer et al. 2005; Ilgin and Gupta 2010; Agrawal et al. 2019; Atasu et al. 2020). The reverse supply chain includes activities such as product returns, used product take-back, reuse, and remanufacturing. (Brandenburg et al. 2014; Govindan et al. 2015; Feng et al. 2017). Used product acquisition and remanufacturing are widely explored in reverse supply chain management (Guide and Van Wassenhove 2001; Savaskan and Van Wassenhove 2006; Tsiliyannis 2018).

On used product acquisition, Guide and Van Wassenhove (2001) study the impact of product returns management and the profitability of remanufacturing. The authors find that product returns management is critical for firm’s profitability. Savaskan et al. (2004) examine the reverse channel design for collecting the used products from customers. The authors reveal that the scenario with the retailer undertaking the collection task is the most efficient one. Savaskan and Van Wassenhove (2006) study two product collection systems, namely the manufacturer-led and the retailers-led systems. The authors reveal that the supply chain profits are affected by the promotion effort under the manufacturer-led collection system; while under the retailers-led collection system, the supply chain profits are affected by the retail competition. Karakayali et al. (2007) study the end-of-life product collection in two decentralized supply chain settings: one is the remanufacturer-driven channel, and the other is the collector-driven channel. The authors find that the choice of collection channel is affected by the collection rate as well as the environmental regulation. Choi et al. (2018a) study the used intimate apparel collection programs and reveal that the collection approach and the retail competition level affect the used intimate apparel collection program significantly. Most, recently, Kleber et al. (2020) investigate the competition between two remanufacturers in the collection of used products and the sales of remanufactured products. The authors find that a remanufacturer with market advantage outperforms the one with acquisition advantage. In this paper, following the industrial practice, we consider the case when the fashion retailer is in charge of collecting the used apparel for the respective reverse supply chain. This is a commonly seen industrial practice but not yet examined in the existent OR literature.

On remanufacturing, Majumder and Groenevelt (2001) investigate the competition of remanufacturing between an original equipment manufacturer and a local remanufacturer. The authors suggest that the social planner should give incentives to the original equipment manufacturer or decrease the remanufacturing cost in order to encourage more remanufacturing activities. Atasu et al. (2008) study the remanufacturing problem and conclude that remanufacturing can be effective for marketing. The authors propose that price differentiation of remanufactured products is critical for the manufacturer to keep its market share. Teunter and Flapper (2011) consider the core quality related issues in remanufacturing. The authors focus on uncovering the impacts brought by the uncertainty of "core quality fractions". Wang et al. (2017) analytically study remanufacturing operations considering both profitability and environmental impacts. The authors find that although there is a conflict between profitability and environmental benefits, carefully meeting conditions on bargaining power and fixed cost of in-house remanufacturing may help align the two goals together. Kovach et al. (2018) investigate the impact of salesforce incentives on remanufacturing activities. The authors reveal that offering differentiated commissions for new and remanufactured products would help support remanufacturing and improve profit. Tsiliyannis (2018) adopts the Markov chain-based method in conducting real-time forecasting of product returns in remanufacturing. Li et al. (2019) study trade-in remanufacturing and find that customers' willingness to pay for the remanufactured product and production cost play an important role in the trade-in program. For more research on remanufacturing, please refer to Debo et al. (2005), Bakal and Akcali (2006), Galbreth and Blackburn (2010), Kim et al.

(2013), Bulmus et al. (2014), Cai et al. (2014), Flapper et al. (2014), Wu and Zhou (2016), Calmon and Graves (2017), Yan et al. (2017), and Ponte et al. (2019).

As a remark, remanufacturing is commonly seen in the "circular economy (CE)" (Prosman et al. 2017; Suzanne, Absi, and Borodin 2020). The concept of "CE" originates, when the concept of "industrial ecosystem" was proposed for optimizing the energy and resource consumption. Nowadays, CE is perceived as an eco-efficient production and consumption system with the ideal goal of "zero waste" by "3R" or beyond: reduce, reuse and recycling (Yuan et al. 2006; Haupt et al. 2017). CE is a big scope, which is not the focus of this paper. Therefore, this paper can be linked to CE, but demarcated from it.

2.3.2 Socially Responsible Operations

Profitability is not the only attribute of a successful firm nowadays. In OR, corporate social responsibility (CSR) is treated as much more important than ever before (Flammer 2015). This also gives rise to a lot of related studies in recent years. For instance, Servaes and Tamayo (2013) analytically study the impact of CSR on the corporate value. The authors explore the problem from the customer awareness perspective. They show that CSR activities can add value to the firm under some tricky conditions. Sodhi and Tang (2014) discuss socially responsible operations in supply chains. They focus on the case when the suppliers or distributors are from developing countries. The authors highlight that CSR remains an untapped OR research area. Besiou and Van Wassenhove (2015) address the challenge of modeling for decision-making in socially responsible operations. The authors present a novel umbrella approach which combines different methodologies to address CSR related operational issues. Plambeck and Taylor (2016) theoretically investigate how buyers can tactfully motivate suppliers to fulfill social and environmental responsibilities via setting contracts. The authors argue that the backfiring condition is likely to happen. Chen et al. (2017) analytically study the mutual dependence among supply chain agents for CSR. The authors explore a stylized two-party supply chain analytical model. They demonstrate that a win–win situation will be achieved if and only if the mutual commitments are "reciprocally similar".

Donation for charity is one form of CSR activities. In the literature, Arya and Mittendorf (2015) analytically study the role played by government subsidies for CSR in a supply chain. The authors argue that under government subsidies, firms will be incentivized to achieve certain pre-determined social goals like donation quantity, and this may result in an increase of the retail market price. Later on, Arya and Mittendorf (2016) indicate that the charity organization has to carry out an effective donation operation. The authors argue that the nonprofit accounting measures play an important role on the optimal use of resources. As a remark, similar to Arya and Mittendorf (2015&2016), this paper also explores the issue of an effective donation operation. However, this paper is different from Arya and Mittendorf (2015&2016) in the problem domain, scope, focal point as well as the core findings.

Based on the review of relevant literature, we identify the potential research gap in the domain of used product acquisition and remanufacturing, and socially responsible operations. Different from the reviewed literature in reverse supply chain management, this paper considers both remanufacturing activities and donation of collected used apparel, and examines how promotion effort for UAC affects the profitability of the fashion retail brand. In our model, remanufacturing can create economic values and donation can enhance the fashion retail brand's social responsibility and hence ethical image and reputation. To the best of our knowledge, this study is the first one which analytically explores the UAC problem with the consideration of charity donation and remanufacturing together. The analytical model is neat and novel. All results are theoretically derived in closed-form.

Chapter 3

Producer's Choice of Design-for-Environment under Environmental Taxation[7]

3.1 Introduction

3.1.1 Background

Today, it is a common consensus that environmental sustainability is critical to everybody, and it calls for specific actions, especially in product designs. For example, the recent OECD Global Forum on the environment presents a topic on plastics and advocates policy shaping to provide incentives for sustainable plastics designs[8]. Accenture's survey shows that 83% respondents believe it is extremely important for companies to design products that can be reused or recycled and 81% would like to buy more sustainable products in the future[9]. At the policy maker level, France has planned to levy producers' eco-taxes on non-recyclable products[10]. There is no doubt that design for environment (DfE) is getting more and more important and popular for sustainable operations (Gouda et al. 2016). In this context, a product needs to be properly designed for reuse, remanufacturing or recycling, not to be disposed directly after postconsumer stage, to circulate the materials and achieve a high level of eco-efficiency (Prosman et al. 2017). For example, SAMSUNG initiated its eco-design process in 2004 and took innovative measures to make its end-of-life products easy to recycle[11]. Recycled materials were used for its smartphone Galaxy S8, and "snap design" was employed for its QLED televisions. The recent literature has revealed that modularity design is an eco-efficient way for product reuse, upgrade and remanufacturing (Hollander et al. 2017; Talens Peiró et al. 2017; Atasu et al. 2020). Moreover, modular design of product is adopted in sustainable business practices and the concept of

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[7] A part of this chapter has been published in European Journal of Operations Research.

[8] http://www.oecd.org/env/waste/global-forum-on-environment-plastics-in-a-circular-economy.htm [Accessed on 20 May 2020]

[9] https://newsroom.accenture.com/news/more-than-half-of-consumers-would-pay-more-for-sustainable-products-designed-to-be-reused-or-recycled-accenture-survey-finds.htm [Accessed on 15 Jan 2021]

[10] https://www.euractiv.com/section/circular-economy/news/france-to-implement-a-new-environmental-tax/ [Accessed on 25 March 2020]

[11] http://www.samsung.com/ae/aboutsamsung/sustainability/environment/eco-conscious-products/ [Accessed on 20 May 2020]

being "green" and being profitable is realized by many firms (Ferguson et al. 2011; Teunter and Flapper 2011; Clottey et al. 2012; Govindan and Popiuc 2014; Xu et al. 2015; Feng et al. 2017).

Some pioneering firms (e.g., Mercedes-Benz, Xerox, ReCellullar, Philips, Volkswagen, and IBM, etc.) have realized that making returns profitable relies on good design of reverse chain business processes and that product design plays a crucial role (Krikke et al. 2004; Li et al. 2019). For example, based on the modularity design of product, IBM dismantled returned products to obtain separate parts, such as memory, video cards, and mother boards, which can be used for service repairs, or even for selling to customers (Ferguson et al. 2011). However, when many companies, especially for third-party service provider, conduct end-of-life product management, they often find the product is not well-designed for recycling or remanufacturing. (Tchertchian et al. 2013). In fact, remanufacturing has some technical constraints, of which, the most influential one is that the architecture of the product is not free to dismantle for separate parts (Giudice 2010). Thus, the rate of remanufacturable and recyclable modules results in a very limited level. In addition, electronic products are characterized by accelerated replacement cycle and poor design for product repairing or upgrading (Agrawal et al. 2016). For example, Microsoft, Apple and Samsung have not achieved a satisfactory result on their sustainable product design[12]. We believe that if the product is not well-prepared at the design stage, the end-of-life repurpose (e.g., remanufacturing) will be a big challenge. To this end, we study how the producer determines the optimal DfE level of its product in the presence of an environmental tax (i.e., DfE tax).

From the environmental legislation perspective, an environmental tax can act as an economic instrument to solve the environmental related problems. The policy can be designed to economically incentivize businesses and the public to take up eco-efficient activities[13]. Various prior studies have explored how the carbon emission regulations affect the firms' decisions in the operational research domain (Choi 2013; Krass et al. 2013; Hammami et al. 2018). However, this type of environmental tax does not directly promote "green" products, because it charges firms based on the carbon emission weights. Another environmental regulation originated from Europe is the extended producer responsibility (EPR). In fact, EPR is based on the "polluter pays" principle, in which the producer

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[12] https://www.greenpeace.org/usa/research/guide-to-greener-electronics-2017/ [Accessed on 8 June 2020]

[13] http://www.oecd.org/env/tools-evaluation/environmentaltaxation.htm [Accessed on 20 May 2020]

should not only pay for "end-of-pipe" pollution, but also be responsible for all stages of the product life cycle (Maxwell 2001). In EPR, the government pays close attention to the product end-of-life options (e.g., reuse, remanufacturing, recycling, etc.) and charges the producers with fees or targets (Atasu and Subramanian 2012). The incentive for producers to design for recyclability is far from sufficient (Plambeck and Wang 2009). In 2018, a novel environmental tax was initiated in France for *recyclable product design*, which will complement the extant environmental regulations from the perspective of DfE[14]. The concrete steps towards eco-design might come out in the future.

3.1.2 Research Questions and Objectives

Motivated by the immerging environmental tax initiative on DfE in places (e.g., France) and the calling for operational research on sustainable operations (Tang and Zhou 2012; Brandenburg et al. 2014; Bulmus et al. 2014; Govindan et al. 2015; Lee and Tang 2018; Atasu et al. 2020), we study a possible policy shaping measure (e.g., environmental tax) to enhance the DfE level of a product. To this end, we propose an environmental tax aiming at encouraging DfE, which will contribute to reducing wastes from the origins, improving the environmental performance and maximizing the social welfare. The objective of this study is to explore how environmental regulations and operations management will contribute to firms' sustainable operations. To be specific, we aim to identify how an environment tax affects the benefits of the stakeholders, the social welfare and the environment. We also attempt to provide the policy maker with possible guidelines for designing the environment tax. Thus, we come up with four research questions: *i) Which one is better for DfE, tax or no tax[15]; ii) How does the social planer make decisions on the environment tax design to balance the DfE level, the stakeholders' benefits and the social welfare; iii) How does the producer choose the DfE level in the robust cases, like investment on technology innovation, consumer returns depend on the DfE level, etc. iv) How does the environmental tax affects the environment?* On analytical modelling research, similar to Krass et al. (2013), we consider a Stackelberg game between a leader and a follower, of which the government acts as the leader aiming to encourage the DfE and maximize the social welfare, and the producer as a

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[14] https://www.euractiv.com/section/circular-economy/news/france-to-implement-a-new-environmental-tax/ [Accessed on 25 May 2020]

[15] "No tax" represents zero tax, which acts as a benchmark case in this paper.

follower to maximize its own profit. By building a stylized economic model, we study how different forms of environment taxes affect the performances of DfE and the social welfare.

To be specific, in the basic model, we consider the situation when a producer manufactures and sells a product to the market. The product is designed for remanufacturing with a certain level of DfE, where a higher DfE level implies a higher value of the returned item. The consumers evaluate the product with their own utilities, and they may return the product for a full refund if they are not satisfied, which is one scenario in Su (2009). For each product sold to the market which is not returned, the government imposes an environmental tax of DfE on the producer. We propose three forms of environmental taxes (linear tax, constant tax and zero tax) and evaluate how they affect the producer's choice of DfE level. In the linear environmental tax (LET) scheme, the tax value depends on the DfE level, while in the constant environmental tax (CET) scheme, the tax value is a constant, and the zero environmental tax (ZET) scheme means no tax charge. In the extended models, we consider another DfE tax form, i.e., the quadratic environment tax (QET) scheme, to check the performance of higher order taxation scheme, as well as other cases such as investment on technology innovation, etc.

3.2 Basic Model

We consider in this paper that a producer (he) manufactures a modular product and sells the product at the price p to the market. Its unit production cost is denoted by c. The product is designed to be dismantled at the end of life. For example, modular architecture design for many products (e.g., computers, motor vehicles, TVs, etc.) is a special feature for product design (Talens Peiró et al. 2017)[16]. For the sake of easy analysis, we consider that p is exogenous in this paper, since we focus on the interaction between the environmental tax and the DfE decisions of the producer. The market demand can be expressed as follows:

$$\overline{D} = \alpha + \sigma m - \beta p. \tag{3.1}$$

where $\alpha > 0$ is the base demand, $\beta > 0$ is the parameter which captures the price sensitivity, $0 \leq \mathrm{m} \leq 1$ is the producer's DfE level[17], and $\sigma > 0$ is the parameter which captures the sensitivity of DfE level on demand. The linear demand function is widely adopted in operational research literature (Camdereli and Swaminathan 2010; Chiang 2012; Ma et al. 2018). We adopt it so that our work is in line with the literature and analytically tractable results can be derived.

In the market, consumers evaluate the product with their own utility u. The cumulative distribution function and density function of u are respectively given by $G(u)$ and $g(u)$. To ensure that consumers have incentives to purchase the product, we assume that their utility from consuming one unit product u ranges from p to infinity, that is, $u > p$. However, consumers may return the product for a full refund if they are not satisfied due to some non-quality reasons (for example, the money back guarantee scheme is in place. Note that prior studies and industrial evidence shows that "false failure returns" are in fact very common nowadays). As a remark, consumer returns in this paper are regarded as the no question asked consumer returns (Ferguson et al. 2006) under the liberal return policy (Su 2009; Souza 2013). The return rate[18] is denoted as λ. For each returned product, its value is given by vm, which reflects the situation that a larger DfE level will yield a higher value for the returned product in refurbishment, remanufacturing, or recycling. We assume the transportation and

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[16] Huang and Kusiak (1998) present various kinds of modularity, like component-swapping, component-sharing, and bus modularity and find that the modules may be shared across different products.

[17] In this paper, "m=0" implies the product cannot be dismantled; "0<m<1" implies partial dismantling; "m=1" implies complete dismantling.

[18] We assume the return rate λ is exogenous in the basic model. We relax this assumption in an extension model in which consumer returns depend on the DfE level (see Subsection 6.2).

restocking costs of consumer returns are zero in the modelling. With the DfE level m, the system manufacturing cost is modeled as θm^2, which is a quadratic function, capturing the marginally increasing cost; θ is the cost coefficient of m. For each product sold to the market, which is not returned, the government imposes an environmental tax of DfE on the producer, denoted as t. Figure 3.1 depicts the basic model.

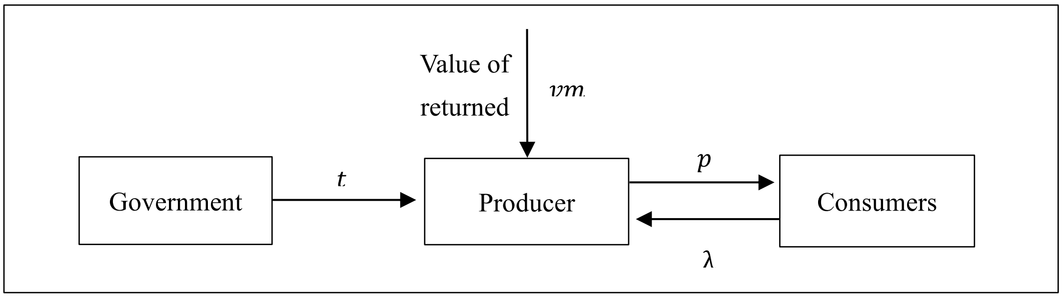

Figure 3.1. The basic model structure of producer's choice of DfE level.

In the real world, tax formats of progressive tax (e.g., income tax) and proportional tax (i.e., a lump-sum tax) are commonly seen (Sanchez and Sobel 1993; Mankiw et al. 2009; Diamond and Saez 2011). Regarding the "progressive tax", the tax rate increases in the taxable amount, while "regressive tax" is just opposite. For example, the income tax in many countries (USA, England, China, etc.) is featured by the "progressive tax". On proportional tax, for example, Finland is the pioneer introducing the carbon emission tax in 1990, at a fixed rate per ton[19]. Motivated by the tax forms, we consider three forms of environmental tax schemes in this paper, namely the linear environmental tax (LET) scheme, constant environmental tax (CET) scheme, and zero environmental tax (ZET) scheme. The LET scheme in this study is designed to be $t_L = k - \eta m$. The tax rate and the taxable amount can be expressed as t_L/p and $(1-\lambda)\bar{D}p$, respectively[20]. When m increases, the taxable amount increases, but the tax rate decreases. To this end, the LET scheme can be regarded as a "regressive tax". The CET scheme charges each sold product with a tax k, which can be seen as a "proportional tax". The ZET

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[19] https://taxfoundation.org/carbon-taxes-in-europe-2019/ [Accessed on 12 May 2020]

[20] The tax rate equals the tax charged to one-unit product (i.e., t_L), divided by the selling price p. For example, if a product is sold at the price of \$10 and is charged with the sales tax \$1, the tax rate is 10%. The taxable amount means the revenue generated by selling the product: i.e., $(1-\lambda)\bar{D}p$. Then, the tax rate times the taxable amount equals the total tax: i.e., $t_L/p*$ $(1-\lambda)\bar{D}p$= $(1-\lambda)Dt$, which is the term 3 shown in Equation (3.2).

scheme represents the scenario without levying an environmental tax. The details of the three forms of environmental tax schemes are summarized in Table 3.1.

Table 3.1. Three forms of environmental tax schemes.

Tax Format	Environmental Tax Schemes	Taxation Forms	Descriptions
Regressive tax	LET scheme	$t_L = k - \eta m$ $(k > 0)$	Environmental tax is linearly decreasing in m
Proportional tax	CET scheme	$t_C = k\ (k > 0)$	Fixed environmental tax
No tax	ZET scheme	$t_0 = 0$	No environmental tax

The profit of the producer can be expressed as follows:

$$\bar{\pi} = \underbrace{(p-c)\bar{D} - \lambda\bar{D}p}_{Term1} + \underbrace{\lambda\bar{D}vm}_{Term2} - \underbrace{(1-\lambda)\bar{D}t}_{Term3} - \underbrace{\theta m^2}_{Term4}, \tag{3.2}$$

where Term 1 represents the gross profit from sold and unreturned products; Term 2 represents the value of liberal returned products; Term 3 represents the tax paid to the government for sold and unreturned products; Term 4 represents the system cost associated with DfE and manufacturing.

The expected tax income (*TI*) of the government is:

$$\overline{TI} = (1-\lambda)\bar{D}t. \tag{3.3}$$

The expected consumer surplus is shown below:

$$\overline{CS} = \underbrace{(1-\lambda)\bar{D}}_{Term\ 5} \underbrace{\int_p^{\infty}(u-p)g(u)d(u)}_{Term\ 6}. \tag{3.4}$$

where Term 5 represents the quantity of goods sold to the market and Term 6 represents the expected individual consumer surplus.

Current studies believe that the environmental damage is marginally increasing in the production quantity (De Zeeuw 2008; Zhou et al. 2019). The modeling of environmental damage in this paper is also marginally increasing in the production quantity but decreasing in the DfE level. That is, when the DfE level is higher, the environmental damage is lower. The expected environmental impact is modeled as follows:

$$\overline{EI} = (1-m)\varepsilon, \tag{3.5}$$

where ε is regarded as the unit environmental impact and $\varepsilon > 0$. When $m = 0$, the DfE level of the product is normalized to be zero and the environmental impact is $\varepsilon\bar{D}$. However, when $m = 1$, the used product can be totally reused or recycled, and the environmental impact is hence set to be zero.

The higher value of EI under the i scheme, the worse environmental performance under the i scheme, where $i = LET, CET$ and ZET.

Finally, the game sequence is shown as follows. First, the policy maker determines the format of environmental tax. Second, the producer determines the optimal DfE level to maximize her profit, with the given format of environmental tax. All technical proofs and numerical analyses are placed in Appendix I.

3.3 Optimal Decision of the Producer

3.3.1 DfE Choice of the Producer

In the basic model, we first consider a linear environmental tax (LET) scheme: $t_L = k - \eta m$, where t_L can be positive or negative. When η is small enough, t_L can be positive, which means that the producer needs to pay the environmental tax. However, when η is large enough, t_L can be negative, which implies that the government provides a pure environmental sponsorship. As we will see later on, η is a critical parameter and we call it the *marginal DfE allowance*, as it captures how the environmental tax is reduced (i.e., "allowance") when the product's DfE level increases. For the sake that the producer can make a non-zero profit, we argue that: $c < (1-\lambda)(p-k)$; otherwise, the production cost is too high, and it does not make sense for the producer to participate in the game.

By exploring the expected profit of the producer under the three environmental tax schemes, we have Lemma 3.1.

Lemma 3.1. *(a) Under the LET scheme: (i)* $\bar{\pi}_L$ *is a concave function if and only if* $\theta > \lambda\upsilon\sigma + (1-\lambda)\eta\sigma$. *(ii) When* $\theta > \lambda\upsilon\sigma + (1-\lambda)\eta\sigma$, *the optimal DfE level is* $m_L^* = \frac{\left((1-\lambda)(p-k)-c\right)\sigma+\lambda\upsilon(\alpha-\beta p)+(1-\lambda)(\alpha-\beta p)\eta}{2(\theta-\lambda\upsilon\sigma)-2(1-\lambda)\eta\sigma}$. *(b) Under the CET scheme, the optimal DfE level is* $m_C^* = \frac{\left((1-\lambda)(p-k)-c\right)\sigma+\lambda\upsilon(\alpha-\beta p)}{2(\theta-\lambda\upsilon\sigma)}$. *(c) Under the ZET scheme, the optimal DfE level is* $m_0^* = \frac{\left((1-\lambda)p-c\right)\sigma+\lambda\upsilon(\alpha-\beta p)}{2(\theta-\lambda\upsilon\sigma)}$.

From Lemma 3.1, we can see that under the LET scheme, $\theta > \lambda\upsilon\sigma + (1-\lambda)\eta\sigma$ actually implies that the marginal cost for establishing the DfE level is sufficiently large. In this case, the expected profit function is concave (with tradeoff between the cost and benefit) and the optimal DfE levels under the three tax schemes can be derived. As a remark, if $\theta \leq \lambda\upsilon\sigma + (1-\lambda)\eta\sigma$, we know that $\bar{\pi}_L$ becomes a convex function and the optimal DfE level will go to the boundary. In this paper, we focus on the case when $\theta > \lambda v\sigma + (1-\lambda)\eta\sigma$ and try to derive more analytically tractable results. Note that when η becomes zero, the environmental tax becomes a constant k, i.e., the CET, and we have the optimal DfE level m_C^*. When $\eta = 0$ and $k = 0$, the environmental tax is zero and we have the optimal DfE level m_0^* under the ZET scheme.

By comparing the optimal DfE levels under the three environmental tax schemes, we conclude the results in Proposition 3.1.

Proposition 3.1. *(a) The optimal DfE level under the LET scheme is always higher than that under the CET scheme, that is* $m_L^* > m_C^*$. *(b) The optimal DfE level under the ZET scheme is always higher than that under the CET scheme, that is* $m_0^* > m_C^*$. *(c) The relationship of the optimal DfE levels under the LET and ZET schemes depends on* η, *that is* $m_L^* \left(\substack{>\\=\\<}\right) m_0^*$, *if and only if* $\eta \left(\substack{>\\=\\<}\right) \eta_L$. *And* $\eta_L = \frac{(\theta-\lambda v\sigma)k\sigma}{\theta(\alpha-\beta p)+((1-\lambda)p-c)\sigma^2}$.

Proposition 3.1 (a) indicates that the LET scheme offers an incentive for a high DfE level, while the CET scheme does not encourage high-level DfE. Proposition 3.1 (b) implies that the CET scheme is even worse than no tax charge. Under the CET scheme, the producer has to pay extra tax, which reduces the total profit. If the producer under the CET scheme chooses a high DfE level, the market demand will increase. Accordingly, the tax payment amount will also increase with the increased sales quantity, which creates a financial burden to the producer under the CET scheme. Therefore, after tradeoff between the DfE level and the tax payment amount, the producer has to choose a comparatively lower DfE level "m_C^*". That is why we have $m_C^* < m_0^*$, which means the CET scheme is not a good choice for encouraging DfE. Proposition 3.1 (c) shows under the LET and the ZET schemes, we cannot claim that m_L^* must be larger than m_0^*. Their relationship is subject to the marginal DfE allowance η. Here, η is a decision variable of the policy maker, which affects the value of linear tax and the producer's choice of DfE level.

To conclude, the LET and the ZET schemes can provide a higher DfE level than the CET scheme does. The DfE level under the LET scheme is not always larger than that in the ZET scheme. The marginal DfE allowance acts as an important role in the LET scheme, which can affect the producer's decision on the choice of DfE level. For the policy maker, to encourage the producer to enhance DfE, it is better to choose the LET scheme and offer *a high marginal DfE allowance*.

3.3.2 Impacts of Taxation Choice on the Stakeholders and the Environment

Based on the findings above, we learn the producer's choice of DfE level under different tax schemes. In this subsection, we explore the performances of the stakeholders' benefits under the three environmental tax schemes. The expected profits of the producer under the three schemes of environmental taxes are denoted as $\bar{\pi}_L$, $\bar{\pi}_C$, and $\bar{\pi}_0$. The analytical findings are summarized in Proposition 3.2.

Define η_p is a threshold, which allows the equal expected profits of the producer in the LET and ZET schemes. And $\eta_p = arg_\eta\{\bar{\pi}_L(m_L^*) = \bar{\pi}_0(m_0^*)\}$. Define η_G is a thredhold, which allows the equal tax revenues of the government in the LET and ZET schemes. And $\eta_G = arg_\eta\{\overline{TI}(m_L^*) = \overline{TI}(m_0^*)\}$.

Proposition 3.2. *Under the three environmental tax schemes: (a) From the producer's perspective, we have* $\bar{\pi}_0(m_0^*) > \bar{\pi}_L(m_L^*) > \bar{\pi}_C(m_C^*)$, *when* $\eta < \eta_p$, *while* $\bar{\pi}_L(m_L^*) \geq \bar{\pi}_0(m_0^*) > \bar{\pi}_C(m_C^*)$, *when* $\eta \geq \eta_p$. *(b) For the government, we have* $\overline{TI}(m_C^*) > \overline{TI}(m_L^*) > \overline{TI}(m_0^*)$, *when* $\eta < \eta_G$, *while* $\overline{TI}(m_C^*) > \overline{TI}(m_0^*) \geq \overline{TI}(m_L^*)$, *when* $\eta \geq \eta_G$. *(c) For the consumer surplus, we have* $\overline{CS}(m_0^*) > \overline{CS}(m_L^*) > \overline{CS}(m_C^*)$, *when* $\eta < \eta_L$; *while* $\overline{CS}(m_L^*) \geq \overline{CS}(m_0^*) > \overline{CS}(m_C^*)$, *when* $\eta \geq \eta_L$. *(d) For the environmental impact, we have* $\overline{EI}(m_C^*) > \overline{EI}(m_L^*) > \overline{EI}(m_0^*)$, *when* $\eta < \eta_L$; *while* $\overline{EI}(m_C^*) > \overline{EI}(m_0^*) \geq \overline{EI}(m_L^*)$, *when* $\eta \geq \eta_L$.

From Proposition 3.2 (a), we learn that the producer's expected profit in the ZET scheme dominates the other two tax schemes when the *marginal DfE allowance* is small. The producer's expected profit in the LET scheme exceeds the one in the ZET scheme, only when the *marginal DfE allowance* is large enough. The expected profit in the CET scheme is the lowest one. Usually, the producer's expected profit in the LET scheme is less than that in the ZET scheme, because the LET scheme charges the producer with an extra amount of penalty. However, there is the marginal DfE allowance in the LET scheme, which can be decided by the policy maker and will affect the producer's expected profit. That's why the producer's expected profit in the LET scheme exceeds the one in the ZET scheme, only when the marginal DfE allowance is large enough. Then, why does the producer's expected profit in the LET scheme exceed that in the ZET scheme? We learn from Proposition 1 that the CET scheme does not encourage a high DfE level and implementing the CET scheme is even worse than the case with no tax charge. Under the CET scheme, the producer has to pay an extra tax, which reduces the total profit. If the producer chooses a high DfE level under the CET scheme, the market demand will increase, but the unit tax payment does not change with the increased DfE level. Accordingly, the tax payment amount will also increase with the increased sales quantity, which creates a financial burden to the producer and hence reduces the profit under the CET scheme.

Proposition 3.2 (b) reveals that the revenue of the government, generated from DfE tax charges, is largest in the CET scheme. The government does not collect any tax in the ZET scheme. Most importantly, the threshold η_G is the critical point, where the government shifts from collecting the environmental tax to providing *a pure environmental sponsorship* if the marginal DfE allowance is larger than η_G. This transition allows the producer to enhance the DfE level and to earn more profits in the LET scheme. Proposition 3.2 (c) shows that the consumer surplus becomes large, when the DfE level increases. The LET and ZET schemes can provide a larger consumer surplus than the CET scheme does. The consumer surplus under the LET scheme is not always larger than that in the ZET scheme. Their relationship is subject to the *marginal DfE allowance*. However, the CET scheme results in the lowest consumer surplus.

Proposition 3.2 (d) reveals that the CET scheme brings more harm to the environment than both the LET and ZET schemes. When the *marginal DfE allowance* is small, no tax charge creates the least environmental impacts. However, the LET scheme is optimal for the environment, when the *marginal DfE allowance* is high. Usually, less production will bring lower environmental impacts in the presence of carbon taxes. Thus, the producer may bring less harm to the environment under the CET scheme than under ZET. Different from “carbon taxes”, the environmental tax proposed in this paper focuses on the “design for environment”. The “design for environment” level is higher under the ZET scheme than that under the CET scheme. Therefore, environmental damage is lower under the ZET scheme that under the CET counterpart, due to the enhanced “design for environment” level. That is why the result shown in this paper is different.

3.4 Social Welfare Performance

In this section, we explore the social welfare performances under three environmental tax schemes. Following Atasu et al. (2009), we model the producer's profit, government's tax income, consumer surplus, and environmental impacts into the social welfare performance and examine how the policy maker will make decisions on the environmental tax design.

Combine Equations (3.2), (3.3), (3.4), and (3.5), we can solve the problem of the social welfare:

$$SW(m) = \left((1-\lambda)\left(p + \int_p^{\infty}(u-p)g(u)d(u)\right) - c + \lambda v m - (1-m)\varepsilon\right)\bar{D} - \theta m^2. \tag{3.6}$$

Equation (3.6) shows that the total social welfare performance is affected by the DfE level. To obtain the maximum social welfare, we show the findings in Lemma 3.2.

Lemma 3.2. *The optimal DfE level which maximizes the total social welfare is* $m_{SW}^* = \frac{\left((1-\lambda)\left(p+\int_p^{\infty}(u-p)g(u)d(u)\right)-c-\varepsilon\right)\sigma+(\lambda v+\varepsilon)(\alpha-\beta p)}{2\theta-2(\lambda v+\varepsilon)\sigma}$.

From Lemma 3.2, we learn that the optimal DfE level for maximizing the social welfare is affected by several important parameters, like the product return rate λ, the value of the returned product v, as well as the cost coefficient of system design and manufacturing θ. We also see that m_{SW}^* increases in the value of the returned product. Moreover, the returned product is valued as vm. When v is high, the producer is encouraged to design the product with a high DfE level. Thus, a high value of the returned product can increase the producer's profit. For example, the producer can easily dismantle the returned product with a high DfE level and repair it for resale. However, m_{SW}^* decreases in θ. If θ is too large, the cost of system design and manufacturing will be large and the producer cannot afford it, which leads to a low DfE level. So, how to address this issue? For example, the system design and manufacturing cost can be reduced by investment on the technology innovation. The government can fund the project and incentivize the R&D engineers to concentrate on this technological progress.

Combining Lemmas 3.1 and 3.2, we have Lemma 3.3.

Lemma 3.3. *(a)* $m_{SW}^* > m_0^* > m_C^*$. *(b)* $m_L^* \left(\begin{smallmatrix}\geq\\=\\<\end{smallmatrix}\right) m_{SW}^*$, *if and only if* $\eta \left(\begin{smallmatrix}\geq\\=\\<\end{smallmatrix}\right) \eta_S$, *where* $\eta_S = \frac{(\theta-\lambda v\sigma)\left(k-\frac{\varepsilon}{1-\lambda}+\int_p^{\infty}(u-p)g(u)d(u)\right)\sigma+\frac{\varepsilon\theta}{1-\lambda}(\alpha-\beta p)+\left(p-k+\frac{c}{1-\lambda}\right)\varepsilon\sigma^2}{\theta(\alpha-\beta p)+\left((1-\lambda)\left(p+\int_p^{\infty}(u-p)g(u)d(u)\right)-c-\varepsilon\right)\sigma^2}$. *(c)* $\eta_S > \eta_L$.

After identifying the optimal DfE levels under different scenarios, we proceed to examine how these DfE levels influence the social welfare performance. Lemma 3.3 reveals that both m_0^* and m_C^* can not help maximize the social welfare performance, because both m_0^* and m_C^* are lower than m_{SW}^*. However, m_L^* can reach the level m_{SW}^* when the social planer sets $\eta = \eta_S$.

We denote the social welfare performance under the LET scheme as $SW(m_L^*)$. We learn from Lemma 1 that the larger η leads to the higher m_L^*. However, the highest m_L^* does not mean the largest $SW(m_L^*)$. If η is sufficiently large, m_L^* is far larger than m_{SW}^*, and the $SW(m_L^*)$ could be very small. Here, for the ease of comparison, we arrange various values of η: $\eta_L < \eta_S < \eta_1 < \eta_2$, where $\eta_1 = arg_{\eta_1}(m_L^*(\eta_1) = 2m_{SW}^* - m_0^*)$, and $\eta_2 = arg_{\eta_2}(m_L^*(\eta_2) = 2m_{SW}^* - m_C^*)$. We denote the social welfare performances under the CET and ZET schemes as $SW(m_C^*)$ and $SW(m_0^*)$, respectively. Finally, we have Proposition 3.3.

Proposition 3.3. *From the social welfare perspective: (a) The social welfare under the ZET scheme is larger than that under the CET scheme. (b) Both the ZET and the CET schemes cannot achieve the best social welfare performance. (c) The LET scheme can maximize the social welfare, only when* $\eta = \eta_S$.

From Proposition 3.3, we can derive the comparisons of social welfare values under different environmental taxation schemes in Table 3.2.

Table 3.2. Comparisons of social welfare values under different environmental taxation schemes.

Areas	The Range of η	Comparisons of Social Welfare Performances under Different Taxation Schemes
I	$\eta < \eta_L$	$SW(m_0^*) > SW(m_L^*) > SW(m_C^*)$
II+ III	$\eta_L \leq \eta < \eta_1$	$SW(m_L^*) \geq SW(m_0^*) > SW(m_C^*)$
IV	$\eta_1 \leq \eta < \eta_2$	$SW(m_0^*) \geq SW(m_L^*) > SW(m_C^*)$
V	$\eta \geq \eta_2$	$SW(m_0^*) > SW(m_C^*) \geq SW(m_L^*)$

To better illustrate the social welfare performance under the environmental taxation schemes, we plot the social welfare performance function (a parabola) with the change of m (see Figure 3.2). It is obvious that when η is sufficiently small (Area I), the social welfare performance in the LET scheme is larger than the one in the CET, but smaller than the ZET scheme. Meanwhile, the DfE level in the

ZET scheme is highest among the three taxation schemes. When η is medium (Areas II and III), the LET scheme outperforms the CET and ZET schemes, on both the social welfare performance and the DfE level. Most importantly, when $\eta = \eta_S$, we have $m_L^* = m_{SW}^* > m_0^* > m_C^*$, which implies the LET scheme can achieve the *maximum social welfare performance*, while both the CET and ZET schemes cannot. When η is large (Area IV), the social welfare performance in the LET scheme is worse than that in the ZET scheme, but better than that in the CET scheme. However, the DfE level in the LET scheme is higher than the ones in the ZET and CET schemes. When η is sufficiently large (Area V), the LET scheme will provide the lowest social welfare performance, but the highest DfE level.

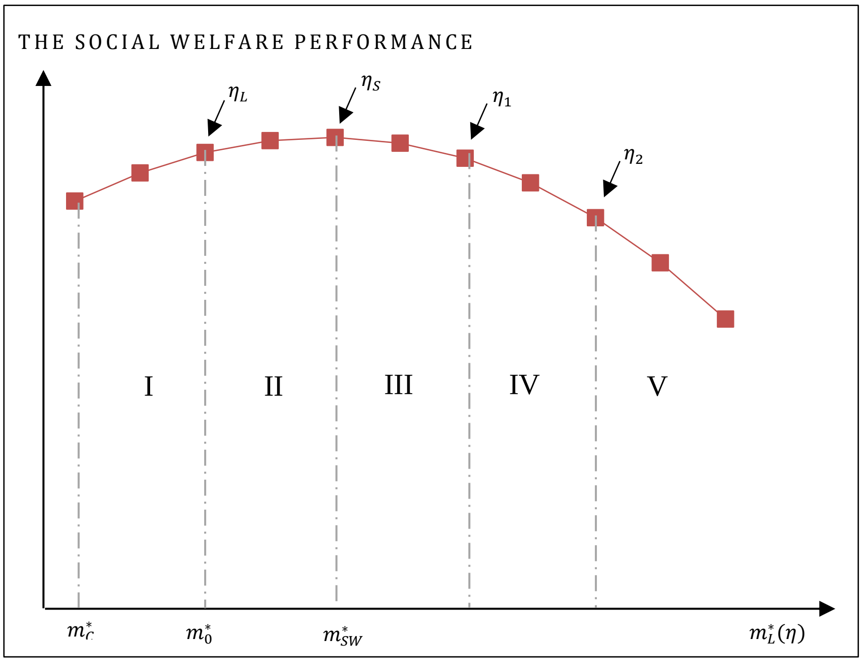

Figure 3.2. The social welfare performance with the change of m (depicted with $\alpha = 1$, $\beta = 0.1$, $\lambda = 0.1$, $p = 6$, $\sigma = 0.2$, $c = 1.5$, $v = 4.5$, $u = 6.5$, $k = 0.5$, $\theta = 1.5$, $\varepsilon = 0.5$).

The analytical findings suggest that if the government aims to maximize the social welfare performance, the optimal plan is to choose the LET scheme and set $\eta = \eta_S$. If the government aims to obtain a high social welfare performance and a high government's tax income, she can choose the LET scheme and set $\eta_L < \eta < \eta_S$. That is the area II. If the government aims to obtain a high social welfare performance and a high producer's profit, she can choose the LET scheme and set $\eta_S < \eta < \eta_1$. That is the area III. If the government aims to allow the producer to choose a high DfE level, the best choice is to set a sufficiently high η, which means the optimal DfE level of the producer could reach 1. However, a *super high marginal DfE allowance* implies the government will provide *a pure environmental sponsorship* to the producer. Thus, the government's benefits will drop sharply.

From the above analyses, we conclude some important managerial insights in the following. The policy maker has to balance the DfE level, the stakeholders' benefits and the social welfare performance, when initiating the environmental tax for DfE. Levying an environmental tax is not always good to the DfE level and the social welfare performance. For example, imposing the CET scheme does not encourage improvement of the DfE level, but do more harm to the environment. Moreover, the LET scheme with a low marginal DfE allowance is even worse than the scenario without charging the environmental tax. All in all, the LET scheme is more flexible for the government to control the DfE level and the social welfare performance. The LET scheme also plays an important role in allocating benefits between the government and the producer. Last but not the least, providing a pure environmental sponsorship is better to the environment than charging an environmental tax.

3.5 Extended Models

To check robustness of the derived results, we extend the basic model in Sections 3, 4 and 5 by considering several extended scenarios, namely investment on technology innovation, DfE level dependent (DLD) consumer returns, and government revenue tax collection. We describe the aims of these extended models in Table 3.3. As a remark, to simplify the analytical results in the extended analyses, we focus on the social welfare maximization and the design strategy of the environmental tax. The government first determines the environmental tax format, and then the producer decides the optimal DfE level to maximize her own profits. The result in the basic model is regarded as a benchmark case to facilitate the comparisons. In addition, the CET and ZET schemes in the extended scenarios (from Subsection 6.1 to 6.3) fail to maximize the social welfare, similar to the basic model. Therefore, we do not analyze the CET and ZET schemes to avoid duplication. Finally, we examine another form of environmental tax, i.e., quadratic environmental tax (QET) scheme, to check how the QET scheme affects the decision making of both the producer and the policy maker.

Table 3.3. The aims of the extended models.

	Extended models	Aims
Subsection 3.5.1	Investment on technology innovation	To examine how investment on technology innovation affects producer's choice of DfE level and the social welfare performance.
Subsection 3.5.2	DfE level dependent consumer returns	To explore how DfE level dependent consumer returns affect producer's choice of DfE level and the social welfare performance. This serves as a robustness check of the findings in the basic model.
Subsection 3.5.3	Government revenue tax	To examine how multiple taxes, affect producer's choice of DfE level and the social welfare performance.
Subsection 3.5.4	Quadratic environmental tax (QET) scheme	To check the higher order taxation scheme's performance.

3.5.1 Investment on Technology Innovation

Another impact factor for the optimal DfE level of the producer is the system design and manufacturing cost coefficient θ. If θ is substantially reduced, the optimal DfE level of the producer will increase distinctively. In this section, we assume the government funds the investment on technology innovation and the fund is denoted as *F*. The declined θ is denoted as $\hat{\theta}$ ($\hat{\theta} < \theta$). For notational purpose, we use $(.^{\hat{\theta}})$ to denote the investment on technology innovation scenario.

Define $\tilde{F}$ as the threshold, which achieves the equal social welfare performance between with and without investment on technology innovation (i.e., $SW^{\hat{\theta}}(m_L^{\hat{\theta}*}(\eta_{\hat{\theta}})) = SW(m_L^*(\eta_S))$). And $\tilde{F} = arg_F\left\{SW^{\hat{\theta}}\left(m_L^{\hat{\theta}*}(\eta_{\hat{\theta}})\right) - SW\left(m_L^*(\eta_S)\right) = 0\right\}$. Define $\eta_{\hat{\theta}}$ as the threshold, which allows the DfE level under the LET scheme is equal to the optimal DfE level for maximizing the social welfare with the investment on technology innovation. And $\eta_{\hat{\theta}} = \frac{(\hat{\theta}-\lambda\upsilon\sigma)\left(k+\int_p^{\infty}(u-p)g(u)d(u)\right)\sigma+\frac{\varepsilon\hat{\theta}}{1-\lambda}(\alpha-\beta p)+\left(p-k+\frac{c+\varepsilon}{1-\lambda}\right)\varepsilon\sigma^2}{\hat{\theta}(\alpha-\beta p)+\left((1-\lambda)\left(p+\int_p^{\infty}(u-p)g(u)d(u)\right)-c-\varepsilon\right)\sigma^2}$.

Comparing the optimal DfE levels and the social welfare performances between the two cases, we conclude the results in Proposition 3.4.

Proposition 3.4. *(a) With the investment from the government on technology innovation, we have* $m_{SW}^{\hat{\theta}*} > m_{SW}^*$. *(b) Under the LET scheme, to attain the maximum social welfare value, the government should set* $\eta = \eta_{\hat{\theta}}$ *to achieve* $m_L^{\hat{\theta}*}(\eta_{\hat{\theta}}) = m_{SW}^{\hat{\theta}*}$. *And* $\eta_{\hat{\theta}} < \eta_S$. *(c) Comparing the social welfare values under the LET scheme with and without the investment on technology innovation, we have*

$SW^{\widehat{\theta}}(m_L^{\widehat{\theta}*}(\eta_{\widehat{\theta}})) \geq SW(m_L^*(\eta_S))$, *if and only if* $F \leq \tilde{F}$. *(d) For the environmental impacts, we have* $\overline{EI}^{\widehat{\theta}}(m_L^{\widehat{\theta}*}(\eta_{\widehat{\theta}})) < \overline{EI}(m_L^*(\eta_S))$.

From Proposition 3.4, we can see that with the investment from the government on technology innovation, the DfE level for maximizing the social welfare is improved. But the LET scheme can achieve the best social welfare, only when the social planer sets $\eta = \eta_{\widehat{\theta}}$. Moreover, it is interesting to find that the $\eta_{\widehat{\theta}}$ gets smaller when θ is reduced, which implies the government needs to provide a *lower marginal DfE allowance*. The social welfare performance under the LET scheme is better off than before, when the investment fund is considerably small. Otherwise, the social welfare will become worse off. However, the investment on technology innovation can reduce the environmental impacts. The findings reveal that the government's funding on technology innovation allows the producer to choose a higher DfE level and may facilitate the enhancement of the social welfare. Our findings hence suggest that it is critical for the government to reduce the systems design and manufacturing cost by effectively using the environmental fund. For example, the government can fund an environmental project and hire environmental and technological experts to contribute to the research on DfE system cost reduction.

3.5.2 DfE Level Dependent (DLD) Consumer Returns

Consumers have a special valuation of DfE products, due to the characteristics of modular upgradeability and environmental harm reduction (Ülkü et al. 2012). In this extended model, we consider the case when consumer returns depend on the DfE level and try to examine (a) how the producer should choose the optimal DfE level to maximize his profit under environmental taxation schemes, (b) how the social welfare performance changes, comparing with the corresponding value in the basic model, and (c) what actions can be taken by the government to maximize the social welfare. For notational purpose, we use $(.^{\lambda_m})$ to denote the DLD consumer returns scenario.

In the basic model, we learn that the consumer return rate λ is assumed to be fixed. However, in this extended model, the consumer return rate is assumed to be dependent on the DfE level, denoted as λ_m. We assume consumer preference for the DfE level is a $(0 < a \leq 1)$ and $f(a)$ follows a uniform distribution. If the DfE level m provided by the producer is larger than a, the consumers will keep the product; otherwise, the consumers will return the product. Thus, we have $\lambda_m = \int_m^1 f(a)da = 1 - F(m)$, where $f(x)$ is the uniform density distribution function and $F(x)$ is the uniform cumulative distribution function. Therefore, we yield $\lambda_m = 1 - m$.

Define η_{λ_m} as the threshold, which allows the optimal DfE level of the producer under the LET scheme is equal to the optimal DfE level for maximizing the social welfare with the DLD consumer returns. And $\eta_{\lambda_m} = \frac{(k+\int_p^{\infty}(u-p)g(u)d(u))v\sigma+v\sqrt{\Delta_{SW}}-v\sqrt{\Delta_L}}{(p+v+\varepsilon+\int_p^{\infty}(u-p)g(u)d(u))\sigma-\theta+\sqrt{\Delta_{SW}}}$.

Define λ_F is the fixed consumer return rate and $\tilde{\lambda}_F$ is the threshold, which allows the equal social welfare performances in the DLD consumer returns case and the benchmark case. And $\tilde{\lambda}_F = arg_{\lambda}\left\{SW^{\lambda_m}(m_L^{\lambda_m *}(\eta_{\lambda_m})) - SW(m_L^{\lambda_F *}(\eta_S)) = 0\right\}$. We conclude the findings in Proposition 3.5.

Proposition 3.5. *(a) Under the DLD consumer returns, we have* $m_{SW}^{\lambda_m *} > m_{SW}^*$ *when* λ_F *is small;* $m_{SW}^{\lambda_m *} < m_{SW}^*$ *when* λ_F *is sufficiently large. (b) Under the LET scheme, to yield the maximum social welfare value, the government should set* $\eta = \eta_{\lambda m}$ *to achieve* $m_L^{\lambda_m *}(\eta_{\lambda_m}) = m_{SW}^{\lambda_m *}$*, and* $\eta_{\lambda_m} > \eta_S$*. (c) Comparing the social welfare values in the DLD consumer returns case and the benchmark case, we have* $SW^{\lambda_m}(m_L^{\lambda_m *}(\eta_{\lambda_m})) \geq SW(m_L^{\lambda_F *}(\eta_S))$*, if and only if* $\lambda_F \geq \tilde{\lambda}_F$*. (d) For the environmental impacts, we have* $\overline{EI}^{\lambda_m}(m_L^{\lambda_m *}(\eta_{\lambda_m})) < \overline{EI}(m_L^{\lambda_F *}(\eta_S))$*, when* $\lambda_F = \tilde{\lambda}_F$*.*

From Proposition 3.5, we learn that when the consumer returns depend on the DfE level, the DfE level is usually much higher than that in the case with fixed consumer returns rate. However, when λ_F is sufficiently large, the DfE level under the DLD consumer returns case is lower than that in the fixed consumer returns case. Only when the policy maker sets $\eta = \eta_{\lambda_m}$, the LET scheme can achieve the optimal DfE level for maximizing the social welfare. Moreover, $\eta_{\lambda_m} > \eta_S$ implies a higher *marginal DfE allowance* should be offered to the producer. Numerical examples show that η_{λ_m} is much larger than η_S and the LET scheme may become *a pure sponsorship* for encouraging DfE. Generally, the social welfare performance under the DLD consumer returns case becomes lower than that in the fixed consumer returns case, except when the fixed consumer returns rate is sufficiently high. The reason is that DLD consumer returns link the DfE level with the consumer returns rate, which makes the situation more complicated. Specifically, a high DfE level will lead to a low consumer returns rate but increase the system design and manufacturing cost (θm^2) and thereby reduce the social welfare performance. A low DfE level will lead to a high consumer returns rate under the DLD consumer returns case, which damages the producer's profit and the social welfare performance. Last but not the least, the environmental impacts under the DLD consumer returns case are lower than that in the fixed consumer returns case, when both social welfare performances under the two cases are equal (i.e., when $\lambda_F = \tilde{\lambda}_F$). The above findings suggest that when consumers become more environmental conscious and tend to return the products depending on the product's DfE level, the optimal DfE level will be improved, and the environmental impacts are reduced. For the government, the optimal choice is to select the LET scheme by offering *a pure environmental sponsorship*. At the same time, exert efforts in investment on technology innovation, to reduce the system design and manufacturing cost in the process of improving the product's DfE level. Thus, the social welfare performance could be improved to a large extent.

3.5.3 Government Revenue Tax

In practice, it is common for the government to charge the producer a revenue tax. Here, we consider the government charges the producer with the revenue tax on the sold products as an extended model. The tax rate is ξ and $0 < \xi < 1$. The total revenue tax is expressed as $t^{\xi} = (1-\lambda)\xi\bar{D}p$. Thus, this section examines the effects of two taxes on the producer's choice and the policy maker's decision making. For notational purpose, we use $(.^{\xi})$ to denote the government revenue tax scenario.

Define η_{ξ} as the threshold, which allows the DfE level under the LET scheme is equal to the optimal DfE level for maximizing the social welfare with the government revenue tax. And $\eta_{\xi} = \frac{(\theta-\lambda\upsilon\sigma)\left(\xi p+k-\frac{\varepsilon}{1-\lambda}+\int_p^{\infty}(u-p)g(u)d(u)\right)\sigma+\frac{\varepsilon\theta}{1-\lambda}(\alpha-\beta p)+\left((1-\xi)p-k+\frac{c}{1-\lambda}\right)\varepsilon\sigma^2}{\theta(\alpha-\beta p)+\left((1-\lambda)\left(p+\int_p^{\infty}(u-p)g(u)d(u)\right)-c-\varepsilon\right)\sigma^2}$. Comparing the optimal DfE levels and the social welfare performances with the benchmark case, we conclude the results in Proposition 3.6.

Proposition 3.6. *(a) When the government revenue tax and the DfE tax coexist, we have* $m_{SW}^{\xi*} = m_{SW}^{*}$. *(b) Under the LET scheme, to attain the maximum social welfare value, the government should set* $\eta = \eta_{\xi}$ *to achieve* $m_L^{\xi*}(\eta_{\xi}) = m_{SW}^{\xi*}$, *and* $\eta_{\xi} > \eta_S$. *(c) Comparing the social welfare values under the*

LET scheme in this subsection with that under the benchmark case, we have $SW^{\xi}(m_L^{\xi*}(\eta_{\xi})) = SW(m_L^{*}(\eta_S))$. *(d) For the environmental impacts, we have* $\overline{EI}^{\xi}(m_L^{\xi*}(\eta_{\xi})) = \overline{EI}(m_L^{*}(\eta_S))$.

From Proposition 3.6, we learn that with an extra revenue tax on the sold products, the optimal DfE level for maximizing the social welfare is equal to the one in the benchmark case. The CET and ZET schemes fail to maximize the social welfare. Only in the LET scheme, when the government sets $\eta = \eta_{\xi}$, $m_L^{\xi*}(\eta_{\xi})$ becomes equal to $m_{SW}^{\xi*}$ and the social welfare performance can achieve the best. Moreover, η_{ξ} is larger than η_S, which implies that the government needs to provide a *larger marginal DfE allowance* to the producer. Since the optimal DfE level is not changed, the consumer surplus, the environmental impacts and the social welfare also keep unchanged. However, the producer's profit is worse off, while the tax income of the government increases with the extra revenue tax. The findings imply that the revenue tax does not affect the optimal DfE level of the producer and the social welfare performance but influences the benefit allocation among the stakeholders. This scenario suggests that the government should arrange the revenue tax rate ξ and choose the LET scheme by setting $\eta = \eta_{\xi}$. If the government's objective is to incentivize the producer to enhance DfE level and reduce the producer's burden, she can choose to give up the revenue tax and only charge the producer with the environmental tax by setting $\eta = \eta_S$.

3.5.4 Quadratic Environmental Tax (QET) Scheme

In the basic model, we have investigated the linear environmental tax form (i.e., $t_L = k - \eta m$). We explore the quadratic environmental tax form in this subsection to check the higher order taxation scheme's performance. The QET scheme is denoted as $t_Q = k - \eta m^2$. The game sequences keep unchanged. We aim to reveal how the QET scheme affects the decision making of both the producer and the policy maker, respectively. We find that the QET scheme, similar to the LET scheme, can achieve the maximum social welfare performance by properly designing the tax form, but it is different from the LET scheme on some aspect. For notational purpose, we use $(.^{Q})$ to denote the QET scheme scenario.

Define η_Q as the threshold, which allows the producer's optimal DfE level under the QET scheme to be equal to the optimal DfE level for maximizing the social welfare under the QET scheme, i.e., $m_Q^*(\eta_Q) = m_{SW}^{Q*}$, and $\eta_Q = arg_\eta\{m_Q^*(\eta) - m_{SW}^{Q*} = 0\}$. Comparing the optimal DfE levels and the social welfare performances in the QET and LET schemes, we conclude the results in Proposition 3.7.

Proposition 7. (*a) When the environmental tax form is quadratic, we have* $m_{SW}^{Q*} = m_{SW}^*$. *(b) Under the QET scheme, to attain the maximum social welfare value, the government should set* $\eta = \eta_Q$ *to achieve* $m_Q^*(\eta_Q) = m_{SW}^{Q*}$, *and* $\eta_Q > \eta_S$. *(c) Comparing the social welfare values under the QET and LET schemes, we have* $SW^Q(m_Q^*(\eta_Q)) = SW(m_L^*(\eta_S))$. *(d) The environmental impacts under both the QET and LET schemes are the same, i.e.,* $\overline{EI}^Q(m_Q^*(\eta_Q) = \overline{EI}(m_L^*(\eta_S))$.

Proposition 3.7 shows that the QET scheme plays the same role on the social welfare performance as the LET scheme. In the QET scheme, the marginal DfE allowance is an effective tool for the policy maker to achieve the maximal social welfare value. But, to achieve the maximum social welfare under the QET scheme, the government needs to provide *a higher marginal DfE allowance* to the producer, i.e., $\eta_Q > \eta_S$, which is the big difference between the two tax schemes. In addition, when the optimal DfE levels for maximizing the social welfare are equal under the QET and LET schemes (i.e., $m_Q^*(\eta_Q) = m_L^*(\eta_S)$), the unit environmental tax charge under the QET scheme is larger than that in the LET scheme, which means the producer needs to pay more taxes for the sold products. Thus, the producer's profit is reduced, but the government can collect more taxes in the QET scheme. For the social welfare performance, the policy maker can achieve the equal social welfare values under both the QET and LET schemes by properly designing the environmental tax form. On the environmental impacts, both the QET and LET schemes make no difference. The above findings reveal that the QET scheme provides an alternative choice for the policy maker to enhance the DfE level. The QET scheme can also help achieve the maximum social welfare performance, but it requires the producer to afford more tax payment which hurts the producer's profit.

3.6 Concluding Remarks

In this paper, to encourage the sustainable product design, we propose three forms of environmental taxations aiming at enhancing the DfE level. We study how different forms of environmental taxations affect producer's choice of DfE level and the social welfare performance by building a stylized economic model. Based on the findings above, we discuss how DfE level under the environmental taxation contributes to the sustainable operations, how the stakeholders should respond to the environmental taxation, and how the environment will be affected. A series of important managerial insights for achieving sustainability are concluded.

Implications to the policy maker: Our research provides valuable guidelines for the policy makers in the DfE taxation design and implementation. First, in the design stage, it is suggested to consider how different tax schemes affect the DfE level, the benefits of the stakeholders and the environment. Afterwards, the tax parameter setting is also important for balancing the performances. Second, in the implementation stage, some measures can be taken to promote the DfE level and the social welfare, e.g., investment on technology innovation, counting the environment impact, etc. Our findings also indicate that the "revenue-neutral" tax strategy (Oates 1994) can be adopted in which the government can choose to give up the revenue tax by collecting the DfE tax to promote the DfE. Thus, this tax exemption will reduce the burden of the producer on total tax payment and encourage the producer to focus on enhancing DfE level.

Implications to the producer**:** The concept of being "green" and profitable at the same time is realized by many firms (Ferguson et al., 2011; Clottey et al., 2012). Therefore, to respond to the regulations and legislations of sustainable operations, the producer is suggested to rethink about the business model innovation (Girotra and Netessine, 2013). Business & Sustainable Development Commission (2017) reports that from the private sector, sustainable business can bring up to US$ 12 trillion in economic opportunities[21]. Therefore, it is a huge potential market for the producer to run sustainable business. For example, under the DfE tax, the producer can improve its DfE level and promote it by eco-labeling to increase the market demand and reduce the return rate. To get the "EU Ecolabel" and "ETV (EU Environmental Technology Verification)" is also a strategy for enhancing

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[21] http://report.businesscommission.org/uploads/BetterBiz-BetterWorld_170215_012417.pdf [Accessed on 12 June 2020]

the brand reputation and the green brand image.

***Implications to the environment*:** Under sustainable product design, it is expected that zero waste is generated, and the product is designed to be easy for repair, reuse and recycling. Thus, resource-efficiency and low carbon emission will be achieved. The findings in this paper show that different environmental tax policies have different impacts on the environment. For example, the CET scheme brings more harm to the environment than both the LET and ZET schemes. When the *marginal DfE allowance* is small, no tax charge creates the least environmental impacts. However, the LET scheme is optimal for the environment, when the *marginal DfE allowance* is high. Anyway, a high product's DfE level will do good to the environment.

Chapter 4

Impacts of Lead Time Reduction on Fabric Sourcing in Apparel Production with Yield and Environmental Considerations[22]

4.1 Introduction

Lead time reduction is a common industrial requirement in the fashion industry. This fact is supported by the great success of fast fashion brands such as Zara, H&M, Uniqlo, Mango, etc. However, the fast fashion concept is usually accused for being associated with many environmental problems, which include both the consumer side (e.g., “disposal fashion” consumer behaviors) and the supply side (e.g., releasing a lot of pollutants). For the supply side, we actually refer to the textile and apparel manufacturing part of the fashion supply chain, and it includes many sectors. For example, the upstream sectors include fiber and yarn manufacturing, and fabric production. The downstream sectors include apparel manufacturer and distributor. In this study, we focus on the supply chain link between the apparel manufacturer and the fabric supplier, where the fabric sourcing operation takes place.

Fabric sourcing has been a globalization operation for decades (Nathan 1996). Countries like China, India (Tokatli 2008), Vietnam (Nadvi et al. 2004), Mexico (Gereffi 2001), and Turkey (Tokatli 2008), are all “major players in the league” as well-established textile companies and they are suppliers for major apparel manufacturers and fashion brands all around the world. Even though there are debates on the optimal choice of production and sourcing options (Hines 2002; Su et al. 2005; Fang et al. 2010), it is commonly believed that the globalization operational mode will continue. As a result, in general, fabric sourcing also includes many far away fabric suppliers from the manufacturer’s perspective if, e.g., the cost is low and product quality is reasonably good. However, if the apparel manufacturer requests the fabric supplier for a lead time reduction (because it can potentially improve forecast accuracy by making market observation), since the fabric supplier is in general located rather far away, having a shorter lead time is a challenge to its operations. In particular, the fabric supplier

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[22] A part of this chapter has been published in Annals of Operations Research.

has little time to properly control the production process and hence more pollutants (per unit production) will be released. Even worse, with a shorter lead time, the amount of good quality fabric may drop owing to the yield problem. This phenomenon has been validated by industrial practitioners.

Based on the commonly observed industrial practices in the fashion industry and motivated by the above-mentioned industrial problem, we explore in this chapter the impacts brought by lead time reduction on fabric sourcing in apparel production. We focus our analysis on how the production yield, the pollution level (measured by the "per unit pollutant") and demand uncertainty affect the whole manufacturing supply chain and its members. We further investigate how an environment tax can be imposed on the fabric supplier so as to entice it to invest in green technologies (Ozturk et al. 2015; Chen et al. 2017) to reduce the amount of per unit pollutant when lead time is reduced. To the best of our knowledge, this is the first analytical study focusing on the lead time reduction problem with the considerations of production yield, environmental tax and demand uncertainty in fabric sourcing. Many novel insights, as discussed in the conclusion section, are generated.

4.2 Lead Time and Fabric Sourcing Model

In this study, we study a fabric sourcing problem in which the decision maker is the apparel manufacturer. The apparel manufacturer has to prepare fabric before the start of an upcoming season in which it will receive orders from the retailers. It needs to decide the time point to order from the fabric supplier and the respective quantity. Owing to the lead time requirements, the apparel manufacturer can order at Time 1 (with a longer delivery lead time) or order at Time 2 (with a shorter delivery lead time). We consider the situation when the fabric supplier operates in a make-to-order mode in which it will start production after receiving the apparel manufacturer's order. However, the fabric production at Time 1 and Time 2 will have different features.

First, in terms of the amount of pollutants released, at Time 1, since the fabric supplier has more time to produce and process the chemicals, the amount of "per unit pollutant" is smaller than when the production is conducted at Time 2. Second, in terms of the production yield, which refers to the proportion of fabric, which is well-prepared and produced with the needed product specifications. It is known that perfect yield rarely occurs while if more time is given (e.g., production at Time 1), the fabric supplier can provide a higher proportion of good fabric whereas a smaller proportion of good fabric is expected if production has to be completed in a rush (e.g., production at Time 2). Third, for the apparel manufacturer, with a shorter lead time (i.e., ordering at Time 2), despite facing a potential lower proportion of good fabric products from the fabric supplier, it can order with a better forecast for demand and hence the ordering is more precise (Zhang et al. 2016). This reduced uncertainty in demand forecast potentially can bring benefit to the apparel manufacturer. Table 4.1 shows the key features of the fabric sourcing problem considered in this study.

Table 4.1. Features of ordering at Time 1 versus ordering at Time 2

	Scenario (notation)	*Per unit pollutant (notation)*	*Supply side production yield (notation)*	*Forecast error (notation)*
Time 1	Long lead time (LLT)	Lower (Q_1)	Higher (λ_1)	Higher ($\sigma_1 = \sqrt{d_1 + \delta}$)
Time 2	Short lead time (SLT)	Higher (Q_2)	Lower (λ_2)	Lower ($\sigma_2 = \sqrt{d_2 + \delta}$)
Relationship	LLT > SLT	$Q_2 > Q_1$	$1 \geq \lambda_1 > \lambda_2 > 0$	$\sigma_2 < \sigma_1$

For the fabric product, we consider the situation when it is a seasonal type of fabric in which the apparel manufacturer will use it just for the upcoming season and leftover will be salvaged at a unit price *v* (e.g., selling it to other manufacturers or fabric retailers) and also incur a unit holding cost *h*. The unit wholesale price is *w*, production cost at the fabric supplier is *m*, and the unit revenue of using the fabric for production is *r*. The above parameters are consistent with the standard newsvendor problem. In order to capture the long lead time and short lead time trade-off as shown in Table 3.1, we employ the classic Bayesian normal conjugate theory to develop the inventory model (Iyer and Bergen 1997). As this model is well-established in the literature, we simply present the standard results in Table 4.2 and refer readers to Iyer and Bergen (1997) and Choi et al. (2018) for more details.

Table 4.2. The Bayesian demand and forecast updating model

	Demand	*Demand distribution*	*Remarks*
Time 1	x_1	The prior distribution $x_1 \sim f_{Normal}(\mu_1, \sigma_1^{\ 2})$, $\sigma_1 = \sqrt{d_1 + \delta}$	δ is called the demand uncertainty which cannot be reduced by market observation and forecast updating. d_1 is the demand uncertainty which can be reduced by forecast updating.
Time 2	x_2	The posterior distribution $x_2 \sim f_{Normal}(\mu_2, \sigma_2^{\ 2})$, $\sigma_2 = \sqrt{d_2 + \delta}$, $d_2 = \dfrac{\delta\, d_1}{d_1 + \delta}$, $\mu_2 = \left(\dfrac{d_1}{d_1 + \delta}\right)\mathrm{A} + \left(\dfrac{\delta}{d_1 + \delta}\right)\mu_1$	A is the market observation, collected between Time 1 and Time 2, and it is used to update the demand forecast at Time 2. As A is unknown before Time 2, the distribution of the posterior mean $\mu_2 \sim f_{Normal}(\mu_1, \dfrac{d_1^{\ 2}}{d_1 + \delta})$. We denote the standard normal density and cdf respectively by $\phi(\cdot)$ and $\Phi(\cdot)$, and define: $\Psi(x) = \int_x^\infty (y - x)\phi(y)dy$.

4.3. Values of Lead Time Reduction

We first derive the profit functions under LLT and SLT scenarios, which refer to Time 1 and Time 2 in terms of the ordering time point. In this study, we use the subscript 1 to denote the ordering case under LLT (i.e., at Time 1), and subscript 2 to represent the ordering case under SLT, i.e., lead time reduction (Time 2).

At Time $i \in (1, 2)$, with the order quantity q_i, the profit function of the manufacturer is given as follows:

$$\pi_{M,i}(q_i) \ = \ -q_i w + r\min(\lambda_i q_i, x_i) + a(1-\lambda_i)q_i - (h-v)\max(\lambda_i q_i - x_i, 0), \tag{4.1}$$

where $\lambda_i q_i$ represents the quantity of quality fabric that can be used for production and make a revenue of *r* if it is demanded; $(1-\lambda_i)q_i$ denotes the quantity of sub-quality fabric that carries a value of *a* per unit for the manufacturer. To avoid trivial cases (such as producing infinite amount of fabrics because of having an arbitrage opportunity), we have: $r > w > a$.

By simple algebra, we can express (4.1) as (4.2):

$$\pi_{M,i}(q_i) \; = \; -q_i w + r\lambda_i q_i + a(1-\lambda_i)q_i - (r+h-v)\max(\lambda_i q_i - x_i, 0)\,. \tag{4.2}$$

Define: $\hat{q}_i = \lambda_i q_i$. (4.3)

Changing the decision variable by substituting (4.3) into (4.2), and taking expectation with the further standardization of the normal distribution, we have the expected profit function at Time $i, i \in (1,2)$, for a given mean of demand μ_i:

$$E[\pi_{M,i}(\hat{q}_i)\,|_{\mu_i}] \; = \; (r+h-v)\left[\mu_i - \sigma_i \Psi\left(\frac{\hat{q}_i - \mu_i}{\sigma_i}\right)\right] - \left(\frac{w - a(1-\lambda_i)}{\lambda_i} + h - v\right)\hat{q}_i\,. \tag{4.4}$$

Note that (4.4) is similar to the expected profit function of the newsvendor problem with a normal demand distribution but there are also many differences such as $\hat{q}_i$ is the adjusted quantity (as it is only a fraction of the ordering quantity), λ_i is the yield and *a* is the unit value of sub-quality fabric, and these are not common in the standard newsvendor problem.

Define: $\hat{w}_i = \left(\frac{w - a(1-\lambda_i)}{\lambda_i}\right), \;\; \forall i \in (1,2)$. (4.5)

It is easy to check that $E[\pi_{M,i}(\hat{q}_i)\,|_{\mu_i}]$ is a concave function of $\hat{q}_i$ because $\frac{d^2 E[\pi_{M,i}(\hat{q}_i)\,|_{\mu_i}]}{d\hat{q}_i^{\,2}} < 0$. Thus, the optimal $\hat{q}_i$ (denoted by $\hat{q}_i^*$) at Time $i, i \in (1,2)$ is given by solving the first order condition ($\frac{dE[\pi_{M,i}(\hat{q}_i)\,|_{\mu_i}]}{d\hat{q}_i} = 0$):

$$\hat{q}_i^* = \; \mu_i + \sigma_i \Phi^{-1}[s_i], \tag{4.6}$$

where $s_i = \frac{r - \hat{w}_i}{r+h-v}, \;\; \forall i \in (1, 2)$. (4.7)

Lemma 4.1. *For* $i \in (1, 2)$ *: (a)* $\hat{w}_i$ *is the effective wholesale price of quality fabric and it is a decreasing function of the fabric production yield rate* λ_i. *(b)* s_i *represents the achieved inventory service level at Time* i *and it is an increasing function of the fabric production yield rate* λ_i.

Proof of Lemma 4.1. All proofs are placed in Appendix II.

Lemma 4.1(a) shows how the fabric production yield rate affects the effective wholesale price for fabrics with a good enough quality to generate a unit revenue *r* for the apparel manufacturer if there is demand for them. It is intuitive to note that the effective wholesale price will drop if the fabric production yield rate increases because the percentage of good quality fabric is higher. For Lemma 4.1(b), we know that for the apparel manufacturer, the inventory service level at its optimal ordering quantity is increasing in the fabric production yield rate, which is a highly desirable situation. The reason explaining this occurrence is that, with a higher fabric production yield rate, the fabric becomes more "profitable" to order and then use to generate revenue, this entices the apparel manufacturer to increase the inventory service level as stockout becomes more costly and its chance of occurrence should be reduced. In this study, unless otherwise specified, we consider $s_i > 50\%$, which means the apparel manufacturer will not tolerate a high out of stock probability. This is realistic and in line with the industrial practice. In addition, focusing on this situation avoids having a negative $\Phi^{-1}[s_i]$ in our analysis. With (4.7), Lemma 4.2 gives the apparel manufacturer's optimal fabric ordering quantity at Time $i, i \in (1, 2)$.

Lemma 4.2. *At Time* $i, i \in (1, 2)$*, the apparel manufacturer's optimal fabric ordering quantity is given as follows:*

$$q_i^* = \frac{1}{\lambda_i}\hat{q}_i^* = \frac{\mu_i + \sigma_i \Phi^{-1}[s_i]}{\lambda_i}. \tag{4.8}$$

Lemma 4.2 shows the optimal fabric ordering quantity and there are two points to note. First, its major part is in fact similar to the standard newsvendor fractile solution (i.e., "$\mu_i + \sigma_i \Phi^{-1}[s_i]$"). Second, it is a "scaled" quantity with the factor $\frac{1}{\lambda_i} > 1$ to ensure a sufficient amount of good quality fabrics will be received owing to the production yield problem from the fabric supplier.

Using the above optimal ordering quantity results, we can derive the optimal expected profit of the apparel manufacturer and the fabric supplier at Time 1 as follows:

$$E[\pi_{M,1}(\hat{q}_1^*)\,|_{\mu_1}] = (r+h-v)\left[\mu_1 - \sigma_1 \Psi\left(\frac{\hat{q}_1^* - \mu_1}{\sigma_1}\right)\right] - \left(\frac{w - a(1-\lambda_1)}{\lambda_1} + h - v\right)\hat{q}_1^*$$

$$= (r - \hat{w}_1)\mu_1 - (r+h-v)\sigma_1 \phi[\Phi^{-1}(s_1)], \tag{4.9}$$

$$E[\pi_{S,1}(\hat{q}_1^*)\,|_{\mu_1}] \;=\; q_1^*(w-m) \;=\frac{(w-m)(\mu_1+\sigma_1\Phi^{-1}[s_1])}{\lambda_1} \;. \tag{4.10}$$

As μ_1 is a known parameter given at Time 1, to simplify notation, we can take the "given μ_1" away from (4.9) and (4.10), and have the following notation:

$$E[\pi_{M,1}]^* \;=\; E[\pi_{M,1}(\hat{q}_1^*)\,|_{\mu_1}], \tag{4.11}$$

$$E[\pi_{S,1}]^* \;=\; E[\pi_{S,1}(\hat{q}_1^*)\,|_{\mu_1}]. \tag{4.12}$$

Similarly, at Time 2, the optimal expected profit of the apparel manufacturer and the fabric supplier (when the posterior demand mean is given) can be found to be the following:

$$E[\pi_{M,2}(\hat{q}_2^*)\,|_{\mu_2}] \;=\; (r-\hat{w}_2)\mu_2-(r+h-v)\sigma_2\phi[\Phi^{-1}(s_2)], \tag{4.13}$$

$$E[\pi_{S,2}(\hat{q}_2^*)\,|_{\mu_2}] \;=\frac{(w-m)(\mu_2+\sigma_2\Phi^{-1}[s_2])}{\lambda_2} \;. \tag{4.14}$$

Since (4.13) and (4.14) are the expected profit functions derived with the information available at Time 2 (i.e., the posterior distribution), the unconditional values of them "back to Time 1" can be done by taking expectation with respect to μ_2 and we have:

$$E[\pi_{M,2}]^* = \underset{\mu_2}{E}[\pi_{M,2}(\hat{q}_2^*)\,|_{\mu_2}] \;=\; (r-\hat{w}_2)\mu_1-(r+h-v)\sigma_2\phi[\Phi^{-1}(s_2)], \tag{4.15}$$

$$E[\pi_{S,2}]^* = \underset{\mu_2}{E}[\pi_{S,2}(\hat{q}_2^*)\,|_{\mu_2}] = \frac{(w-m)(\mu_1+\sigma_2\Phi^{-1}[s_2])}{\lambda_2} \;. \tag{4.16}$$

With (4.11), (4.12), (4.15) and (4.16), the unconditional expected profit functions of the whole manufacturing supply chain, when the apparel manufacturer orders q_i^* at Time $i, i\in(1,2)$, can be obtained by the following simple relationship:

$$E[\pi_{SC,1}]^* = \; E[\pi_{M,1}]^* + \; E[\pi_{S,1}]^*, \tag{4.17}$$

$$E[\pi_{SC,2}]^* = \; E[\pi_{M,2}]^* + \; E[\pi_{S,2}]^*. \tag{4.18}$$

4.4. Reducing Lead Time: Is It Wise?

In this section, we explore the conditions under which it is wise to reduce lead time for the apparel manufacturer, the fabric supplier and the whole manufacturing supply chain.

4.4.1. Expected Values of Lead-time Reduction

Define the expected value of lead time reduction (EVLR) for the apparel manufacturer (M), the fabric supplier (S) and the whole manufacturing supply chain (SC) as follows:

$$EVLR_M = E[\pi_{M,2}]^* - E[\pi_{M,1}]^*, EVLR_S = E[\pi_{S,2}]^* - E[\pi_{S,1}]^*, EVLR_{SC} = E[\pi_{SC,2}]^* - E[\pi_{SC,1}]^*.$$

Define:

$$T = (r+h-v)(\sigma_1\phi[\Phi^{-1}(s_1)] - \sigma_2\phi[\Phi^{-1}(s_2)]),\ Y = \left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right),\ L = \left(\frac{\sigma_1\Phi^{-1}[s_1]}{\lambda_1} - \frac{\sigma_2\Phi^{-1}[s_2]}{\lambda_2}\right).$$

Lemma 4.3 shows the analytical expressions of the EVLRs which are very critical to let us know when it is beneficial to reduce lead time from the perspective of each respective party, e.g., the manufacturer.

Lemma 4.3. *The expected values of lead time reduction are: (a)* $EVLR_M = T - (\hat{w}_2 - \hat{w}_1)\mu_1$*; (b)* $EVLR_S = (w-m)(Y\mu_1 - L)$. *(c)* $EVLR_{SC} = ((w-m)Y - \hat{w}_2 + \hat{w}_1)\mu_1 + (T - (w-m)L)$.

From Lemma 4.3, we can derive Proposition 4.1 to show the conditions in which lead time reduction is beneficial to the apparel manufacturer, and the fabric supplier, respectively.

Proposition 4.1. *Comparing between placing orders at Time 2 and Time 1: (a) Ordering at Time 2 is beneficial for the apparel manufacturer if and only if* $EVLR_M > 0 \Leftrightarrow \mu_1 < \bar{\mu}_1 \equiv \frac{T}{\hat{w}_2 - \hat{w}_1}$*; (b) ordering at Time 2 is beneficial for the fabric supplier if and only if* $EVLR_S > 0 \Leftrightarrow \mu_1 > \underline{\mu}_1 \equiv \frac{L}{Y}$.

Proposition 4.1(a) shows some very important results. To be specific, from the perspective of the apparel manufacturer, lead time reduction is beneficial (i.e., $EVLR_M > 0$) if and only if the prior mean of demand is not too big (bounded above by a threshold). This actually means two things: (i) If the prior mean of demand is not too big, then we know that the relative prior demand uncertainty (i.e., from the perspective of coefficient of variation) is relatively high. This directly means that lead time reduction is more significant because the apparel manufacturer can make use of the market information (from Time 1 to Time 2) to improve its forecast and postpone the ordering decision to the future (i.e., Time 2). (ii) If the market mean of demand is huge, then the prior market demand uncertainty will be relatively small (as the demand uncertainty is given and fixed). As a result, lead time reduction is less significant. However, just on the contrary, the situation is totally different for the fabric supplier. In fact, from Proposition 4.1(b), we can see that the fabric supplier will be benefited by lead time reduction (i.e., $EVLR_S > 0$) if the prior mean of demand is sufficiently big. This can be explained as follows. In this supply chain, the operational mode is MTO (i.e., make-to-order) and the ordering quantity is decided by the apparel manufacturer. If the apparel manufacturer can order with a better forecast (at Time 2, with lead time reduction) and the forecasting's accuracy is significantly improved, its ordering quantity will tend to be smaller because of the reduced demand uncertainty (keeping other factors unchanged). This is undesirable for the fabric supplier as its profit is reduced. Thus, if the prior mean of demand is sufficiently big, then relatively speaking, the significance of lead time reduction in dampening demand uncertainty is smaller (as the demand variance will relatively be less significant when the mean is larger). This is beneficial to the fabric supplier.

From Lemma 4.3 and Proposition 4.1, we can derive Proposition 4.2 regarding the conditions for the whole manufacturing supply chain to benefit from lead time reduction.

Proposition 4.2. *Comparing between placing orders at Time 2 and Time 1: Ordering at Time 2 is beneficial for the whole manufacturing supply chain: (a) if* $\underline{\mu}_1 < \mu_1 < \bar{\mu}_1$ *(the sufficient condition); (b) if and only if* $EVLR_{SC} > 0 \Leftrightarrow ((w-m)Y - \hat{w}_2 + \hat{w}_1)\mu_1 + (T-(w-m)L) > 0$.

Proposition 4.2 shows the conditions for the whole manufacturing supply chain system to be benefited by lead time reduction. For Proposition 4.2(a), having a well-bounded prior mean of demand (i.e., $\underline{\mu}_1 < \mu_1 < \bar{\mu}_1$) is a sufficient condition, which is basically implied by the respective conditions from Proposition 5.1 under which both the apparel manufacturer and the fabric supplier are benefited by lead time reduction. Proposition 4.2(b) gives the necessary and sufficient condition for the situation when the whole supply chain system is benefited by lead time reduction. Define: $\Omega_i = \frac{\partial \Phi^{-1}[s_i]}{\partial \lambda_i}$, and $D_i = \frac{\partial \sigma_i}{\partial d_1}$ for $i \in (1, 2)$. Note that $\Omega_i > 0$ and $D_1 > D_2$. We now analytically conduct a sensitivity analysis to examine how the change of major model parameters (including the demand uncertainty and the production yield) affect the EVLPs. Tables 4.3, 4.4 and 4.5 show the results[23].

Table 4.3. How $EVLR_M$ varies with the major parameters (increase ↑; no change $-$; decrease ↓)

Parameter	$EVLR_M$
d_1↑	↑ if and only if $\frac{\phi(\Phi^{-1}[s_1])D_1}{\phi(\Phi^{-1}[s_2])D_2}>1$ $-$ if and only if $\frac{\phi(\Phi^{-1}[s_1])D_1}{\phi(\Phi^{-1}[s_2])D_2}=1$ ↓ if and only if $\frac{\phi(\Phi^{-1}[s_1])D_1}{\phi(\Phi^{-1}[s_2])D_2}<1$
λ_1 ↑	↓
λ_2 ↑	↑

From Table 4.3, we observe that for the apparel manufacturer, its benefit derived from lead time reduction is actually higher if: (i) the fabric production yield rate at Time 2 is higher, (ii) the fabric production yield rate at Time 1 is lower. This result is intuitive as a higher fabric production yield rate at Time 2 means the apparel manufacturer will receive a higher proportion of good quality fabric when it orders at Time 2 (i.e., with lead time reduction), and a lower fabric production yield rate at Time 1 (the long lead time case) implies that ordering at Time 2 (with lead time reduction) is relatively beneficial. Regarding the effect brought by the prior demand uncertainty which can be reduced by forecast updating (d_1), the situation is tricky and rather complex as it depends on other parameters such as the inherent demand uncertainty which cannot be reduced (δ) and the fabric production yields at Time 1 and 2 (which affect the respective inventory service levels). As a remark, in the classic literature (e.g., Iyer and Bergen 1997), a change of demand uncertainty (d_1) will always benefit the ordering party (i.e., the apparel manufacturer in our case). However, in the presence of fabric production yield rates change the whole scenario and hence one can no longer take for granted that lead time reduction is always beneficial to the ordering party. From Table 4.4, we note that this

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[23] The results are derived based on checking the first order condition of the EVLPs with respect to each major parameter.

situation also applies to the supplier, because the classic literature indicates that the supplier will suffer a loss under lead time reduction (when the inventory service level is normal, i.e., above 50% (Iyer and Bergen 1997)) but Table 4.4 shows another picture. For the effects brought by a change of the fabric production yield to the fabric supplier's benefit under lead time reduction, we observe the presence of $\frac{\sigma_1}{\mu_1}$ and $\frac{\sigma_2}{\mu_1}$ in the conditions (for the cases with λ_1 and λ_2, respectively). In fact, $\frac{\sigma_1}{\mu_1}$ represents the prior market demand's coefficient of variation, and $\frac{\sigma_2}{\mu_1}$ denotes the expected posterior market demand's coefficient of variation. Their values are influential as they reflect the market demand uncertainties which would directly affect the fabric supplier's benefit under lead time reduction. Finally, from Table 4.5, we can see how different parameters affect the supply chain system under lead time reduction. The results are all sufficient conditions, implied by checking the respective conditions for the fabric supplier and the apparel manufacturer.

Table 4.4. How $EVLR_S$ varies with the major parameters (increase ↑; no change −; decrease ↓)

Parameter	$EVLR_S$
d_1 ↑	↑ if and only if $\frac{\lambda_1}{\lambda_2} > \frac{\Phi^{-1}[s_1]D_1}{\Phi^{-1}[s_2]D_2}$ − if and only if $\frac{\lambda_1}{\lambda_2} = \frac{\Phi^{-1}[s_1]D_1}{\Phi^{-1}[s_2]D_2}$ ↓ if and only if $\frac{\lambda_1}{\lambda_2} < \frac{\Phi^{-1}[s_1]D_1}{\Phi^{-1}[s_2]D_2}$
λ_1 ↑	↑ if and only if $\frac{\sigma_1}{\mu_1} < \frac{1}{\lambda_1\Omega_1 - \Phi^{-1}[s_1]}$ − if and only if $\frac{\sigma_1}{\mu_1} = \frac{1}{\lambda_1\Omega_1 - \Phi^{-1}[s_1]}$ ↓ if and only if $\frac{\sigma_1}{\mu_1} > \frac{1}{\lambda_1\Omega_1 - \Phi^{-1}[s_1]}$
λ_2 ↑	↑ if and only if $\frac{\sigma_2}{\mu_1} > \frac{1}{\lambda_2\Omega_2 - \Phi^{-1}[s_2]}$ − if and only if $\frac{\sigma_2}{\mu_1} = \frac{1}{\lambda_2\Omega_2 - \Phi^{-1}[s_2]}$ ↓ if and only if $\frac{\sigma_2}{\mu_1} < \frac{1}{\lambda_2\Omega_2 - \Phi^{-1}[s_2]}$

Table 4.5. How $EVLR_{SC}$ varies with the major parameters (increase ↑; no change $-$; decrease ↓)

Parameter	$EVLR_{SC}$
$d_1 \uparrow$	$\uparrow$ if $\frac{\phi(\Phi^{-1}[s_1])D_1}{\phi(\Phi^{-1}[s_2])D_2} > 1$ and $\frac{\lambda_1}{\lambda_2} > \frac{\Phi^{-1}[s_1]D_1}{\Phi^{-1}[s_2]D_2}$ $\downarrow$ if $\frac{\phi(\Phi^{-1}[s_1])D_1}{\phi(\Phi^{-1}[s_2])D_2} < 1$ and $\frac{\lambda_1}{\lambda_2} < \frac{\Phi^{-1}[s_1]D_1}{\Phi^{-1}[s_2]D_2}$
$\lambda_1 \uparrow$	$\downarrow$ if $\frac{\sigma_1}{\mu_1} \geq \frac{1}{\lambda_1\Omega_1 - \Phi^{-1}[s_1]}$
$\lambda_2 \uparrow$	$\uparrow$ if $\frac{\sigma_2}{\mu_1} \geq \frac{1}{\lambda_2\Omega_2 - \Phi^{-1}[s_2]}$

4.4.2. Deposit Payment (DP) Schemes

From the last section, we note that lead time reduction (ordering at Time 2) does not always benefit the apparel supply chain and its members. If we have $EVLR_{SC} > 0$, we know that the supply chain is benefited by lead time reduction (i.e., it is a good measure for the supply chain). However, it does not imply that the apparel manufacturer and the fabric supplier will both necessarily be benefited. On the contrary, it is possible that only one member is benefited. Lemma 4.4 shows such a situation.

Lemma 4.4. *If* $((w-m)Y - \hat{w}_2 + \hat{w}_1)\mu_1 + (T-(w-m)L) > 0$ *holds, but* $\underline{\mu}_1 < \mu_1 < \overline{\mu}_1$ *does not hold, we have (i)* $EVLR_{SC} > 0$*; (ii) A win-win situation does not appear in the supply chain which means either the apparel manufacturer or the fabric supplier will suffer a loss.*

When the situation in Lemma 4.4 appears, under a decentralized setting, the supply chain agent (either the apparel manufacturer and the fabric supplier) that will suffer a loss with the reduction of lead time will not be happy to support the lead time reduction. Thus, in order to achieve a win-win situation, we need to implement a certain contractual measure.

Upon our discussion with the industrialists, we note that in the textiles industry, paying deposit is quite common for the supply business. The deposit payment is usually given to the fabric supplier by the apparel manufacturer, as an early partial payment. However, if it is needed, it can be reversed, and the fabric supplier pays the “deposit” to the apparel manufacturer as a guarantee for providing supply.

We consider the situation in which if a supply chain agent gives a deposit to another supply chain agent, the recipient will earn an interest rate in the market which is denoted by ξ. When the situation of Lemma 4.4 arises, either the apparel manufacturer or the fabric supplier suffers a loss even though the whole manufacturing supply chain is benefited by lead time reduction. In the following, we denote the positive supply chain's expected benefit from lead time reduction (i.e., $EVLR_{SC}$) by Δ_{SC}, and divide the analysis into two cases.

DP Case 1: The apparel manufacturer benefits with a gain of $B_M > 0$, but the fabric supplier suffers a loss $l_S > 0$. The deposit, denoted by $DP_{M\to S}$, is granted by the apparel manufacturer to the fabric supplier.

DP Case 2: The apparel manufacturer suffers a loss $l_M > 0$, but the fabric supplier benefits with a gain of $B_S > 0$. The deposit, denoted by $DP_{S\to M}$, is granted by the fabric supplier to the apparel manufacturer.

Proposition 4.3 shows the conditions to achieve win-win by using the deposit schemes when the situation of Lemma 4.4 appears.

Proposition 4.3. *To achieve the win-win situation in the supply chain by lead time reduction (when Lemma 4.4 holds): (a) The apparel manufacturer can grant a deposit payment to the fabric supplier in which* $\frac{l_S}{\xi} < DP_{M\to S} < \frac{\Delta_{SC} - l_S}{\xi}$ *in DP Case 1. (b) The apparel manufacturer can grant a deposit payment to the fabric supplier in which* $\frac{l_M}{\xi} < DP_{S\to M} < \frac{\Delta_{SC} - l_M}{\xi}$ *DP Case 2.*

From Proposition 4.3, we can see how the deposit payment scheme can be utilized to achieve the win-win situation in the whole manufacturing supply chain when lead time reduction is proven to be beneficial to the supply chain system. As a remark, this scheme is easy to implement and should be offered by the supply chain party which earns a lion share of the supply chain benefit to the supply chain party which suffers a loss. It is also robust as it can flexibly divide the supply chain surplus under lead time reduction (i.e., Δ_{SC}) in any arbitrarily proportion between the fabric supplier and the apparel manufacturer.

4.5. Pollution and Environment Tax

4.5.1. Expected Harm to the Environment

In the above sections, we focus on the monetary gains or losses associated with lead time reduction (i.e., the respective business value). However, as we know, fabric production is a “dirty” process, which creates a lot of pollutants. The situation may be even worse under fast fashion when lead time is short because there is little time to deal with the pollutants. As the general public and society all have serious concerns on environmental harms, addressing the pollution issue is critical. In our model, we already include such a factor (see Table 4.1). In this section, we analyse the pollution problem and propose how the environment tax can be imposed to overcome the pollution problem associated with lead time reduction.

To be specific, in the manufacturing supply chain that we considered, if ordering is placed at Time 1 with the apparel manufacturer’s optimal ordering quantity, the amount of pollutant released (TP_1) is equal to the order quantity times the per unit pollutant threshold:

$$TP_1 = Q_1\, q_1^* = \left(\frac{\mu_1 + \sigma_1 \Phi^{-1}[s_1]}{\lambda_1} \right) Q_1 .$$

Similarly, at Time 2, for given μ_2, the amount of pollutant released (TP_2) with the apparel manufacturer’s optimal ordering quantity is:

$$TP_{2|\mu_2} = Q_2\, q_2^* = \left(\frac{\mu_2 + \sigma_2 \Phi^{-1}[s_2]}{\lambda_2} \right) Q_2 .$$

Un-conditioning $\left(\frac{\mu_2 + \sigma_2 \Phi^{-1}[s_2]}{\lambda_2} \right) Q_2$ yields:

$$TP_2 = \left(\frac{\mu_1 + \sigma_2 \Phi^{-1}[s_2]}{\lambda_2} \right) Q_2 .$$

We denote the expected harm to environment by lead time reduction by $EHTE^{(LTR)}$ (P.S.: “LTR” stands for lead time reduction), and define it as follows:

$$EHTE^{(LTR)} = TP_2 - TP_1 .$$

Proposition 6.1 summarizes some key features of $EHTE^{(LTR)}$.

Proposition 4.4. *(a)* $EHTE^{(LTR)} = \left(\frac{Q_2}{\lambda_2}\right)(\mu_1 + \sigma_2\Phi^{-1}[s_2]) - \left(\frac{Q_1}{\lambda_1}\right)(\mu_1 + \sigma_1\Phi^{-1}[s_1])$. *(b) If* $\mu_1 > \underline{\mu}_1$, $EHTE^{(LTR)} > 0$. *If* $\mu_1 \le \underline{\mu}_1$, *then (i)* $EHTE^{(LTR)} > 0$ *if and only if* $\frac{Q_2}{Q_1} > \left(\frac{\lambda_2(\mu_1 + \sigma_1\Phi^{-1}[s_1])}{\lambda_1(\mu_1 + \sigma_2\Phi^{-1}[s_2])}\right)$, *(ii)* $EHTE^{(LTR)} \le 0$ *if and only if* $\frac{Q_2}{Q_1} \le \left(\frac{\lambda_2(\mu_1 + \sigma_1\Phi^{-1}[s_1])}{\lambda_1(\mu_1 + \sigma_2\Phi^{-1}[s_2])}\right)$.

Proposition 4.4(a) shows us the analytical closed-form expression of $EHTE^{(LTR)}$, which is (i) positively and directly proportional to Q_2 and μ_1, and (ii) negatively and directly proportional to Q_1 . These findings are intuitive as $EHTE^{(LTR)}$ represents the expected harm to the environment as brought by lead time reduction. If we take a look at the physical meanings behind the parameters, we will find that a larger Q_2 , a larger μ_1 and a smaller Q_1 will all naturally lead to a larger $EHTE^{(LTR)}$. Proposition 4.4(b) shows the conditions for $EHTE^{(LTR)}$ to be positive or negative. In particular, note that when $\mu_1 > \underline{\mu}_1$, from Proposition 4.1(b), we know that the fabric supplier is benefited by lead time reduction. However, in this situation, Proposition 4.4(b) also shows that $EHTE^{(LTR)} > 0$, which means that even though the fabric supplier is financially benefited by lead time reduction, the environment suffers. For the environment to be benefited, we need to fulfil two conditions: $\mu_1 \le \underline{\mu}_1$ and $\frac{Q_2}{Q_1} \le \left(\frac{\lambda_2(\mu_1 + \sigma_1\Phi^{-1}[s_1])}{\lambda_1(\mu_1 + \sigma_2\Phi^{-1}[s_2])}\right)$. When $\mu_1 \le \underline{\mu}_1$ holds, it means the fabric supplier suffers a loss under lead time reduction. When $\frac{Q_2}{Q_1} \le \left(\frac{\lambda_2(\mu_1 + \sigma_1\Phi^{-1}[s_1])}{\lambda_1(\mu_1 + \sigma_2\Phi^{-1}[s_2])}\right)$, it means the per unit pollutant released under lead time reduction (i.e., Q_2) has to be relatively small compared to the per unit pollutant released under the long lead time case (i.e., Q_1).

To have a better understanding regarding $EHTE^{(LTR)}$, we conduct a sensitivity analysis and results are shown in Table 4.6[24].

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[24] The results are derived based on checking the first order derivative of $EHTE^{(LTR)}$ with respect to each major parameter.

Table 4.6. How the expected harm to environment (with lead time reduction) varies with the major parameters (increase ↑; no change −; decrease ↓)

Parameter	$EHTE^{(LTR)}$
d_1 ↑	↑ If and only if $\frac{Q_2}{Q_1} > \left(\frac{\lambda_2\sigma_1\Phi^{-1}[s_1]D_1}{\lambda_1\sigma_2\Phi^{-1}[s_2]D_2}\right)$ − if and only if $\frac{Q_2}{Q_1} = \left(\frac{\lambda_2\sigma_1\Phi^{-1}[s_1]D_1}{\lambda_1\sigma_2\Phi^{-1}[s_2]D_2}\right)$ ↓ if and only if $\frac{Q_2}{Q_1} < \left(\frac{\lambda_2\sigma_1\Phi^{-1}[s_1]D_1}{\lambda_1\sigma_2\Phi^{-1}[s_2]D_2}\right)$
λ_1 ↑	↑ if and only if $\frac{\sigma_1}{\mu_1} < \frac{1}{\lambda_1\Omega_1 - \Phi^{-1}[s_1]}$ − if and only if $\frac{\sigma_1}{\mu_1} = \frac{1}{\lambda_1\Omega_1 - \Phi^{-1}[s_1]}$ ↓ if and only if $\frac{\sigma_1}{\mu_1} > \frac{1}{\lambda_1\Omega_1 - \Phi^{-1}[s_1]}$
λ_2 ↑	↑ if and only if $\frac{\sigma_2}{\mu_1} > \frac{1}{\lambda_2\Omega_2 - \Phi^{-1}[s_2]}$ − if and only if $\frac{\sigma_2}{\mu_1} = \frac{1}{\lambda_2\Omega_2 - \Phi^{-1}[s_2]}$ ↓ if and only if $\frac{\sigma_2}{\mu_1} < \frac{1}{\lambda_2\Omega_2 - \Phi^{-1}[s_2]}$
Q_1 ↑	↓
Q_2 ↑	↑

It is interesting to note from Table 4.6 that an increase of prior demand uncertainty may increase or decrease $EHTE^{(LTR)}$, depending on the relative size of Q_2 with respect to Q_1. To be specific, if Q_2 is sufficiently big with respect to Q_1, then a higher prior demand uncertainty yields a higher $EHTE^{(LTR)}$; this effect will be reversed if Q_2 is not sufficiently big with respect to Q_1. For the effects brought by the yield, the explanations are quite similar to those on $EVLR_S$ and we note the importance of the prior and expected posterior demand coefficients of variation (i.e., $\frac{\sigma_1}{\mu_1}$ and $\frac{\sigma_2}{\mu_1}$). Finally, for the effects brought by Q_1 and Q_2, they are simply the same as what we have explained above for Proposition 6.1(a).

4.5.2. Environment Tax

Suppose that the fabric supplier can install a new technological device to reduce Q_2 (to a new lower level $\hat{Q}_2$), which is the amount of per unit pollutant under the lead time reduction ordering scenario (Time 2's ordering). To be specific, the cost of reduce the per unit of pollutant from Q_2 to $\hat{Q}_2$, denoted by $C(\hat{Q}_2)$, is given by (6.5):

$$C(\hat{Q}_2) = \frac{\varepsilon(Q_2 - \hat{Q}_2)^2}{2},$$

where Q_2 represents the current "per unit pollutant" level for the ordering at Time 2.

Note that the quadratic cost function has been rather well-employed in modelling environment-related cost (see Song et al. 2015), and we follow the literature for it. Define:

$$\beta = \frac{\lambda_2^2(\mu_1 + \sigma_1\Phi^{-1}[s_1])}{\lambda_1(\mu_1 + \sigma_2\Phi^{-1}[s_2])^2},$$

$$\hat{t} = \varepsilon(Q_2 - \beta Q_1).$$

The environmental impacts are created by the dyeing and finishing process of the fabric production, which may lead to the severe water pollution problem. The scenario of the environmental tax in our study refers to charges for the water pollution during the process of the fabric production. We consider the situation when the government imposes an environment tax in which for each unit of pollutant released by the fabric production process, the fabric supplier will be penalized by *t* dollars. Proposition 4.5 shows the impacts brought by imposing the environment tax on fabric pollution.

Proposition 4.5. *Under the lead time reduction ordering scenario (i.e., ordering at Time 2), in the presence of the environment taxation scheme: (a) The optimal per unit pollutant after the use of a new technological device* $\hat{Q}_2^* = Q_2 - \frac{t}{\varepsilon}\left(\frac{\mu_1 + \sigma_2\Phi^{-1}[s_2]}{\lambda_2}\right)$. *(b)* $EHTE^{(LTR)}(\hat{Q}_2^*)\begin{cases} > 0, if\ t < \hat{t} \\ = 0\ if\ t = \hat{t} \\ < 0, if\ t > \hat{t} \end{cases}$ ·

Proposition 4.5(a) shows the optimal per unit pollutant level at Time 2 (i.e., under lead time reduction) $\hat{Q}_2^*$ when the fabric supplier can implement new technological devices to help. It is easy to see that if the environment tax (*t*) is higher, $\hat{Q}_2^*$ will be smaller and the two are directly proportional. It shows that the environmental taxation scheme is an effective measure to drive the fabric supplier to lower its release of pollutants under lead time reduction. Proposition 4.5(b) further derives the environment tax threshold with which the environment will not get hurt when the supply chain operates with lead time reduction (i.e., $EHTE^{(LTR)} = 0 \text{ } if \text{ } t = \hat{t}$). It is also interesting to note that lead time reduction can even improve the environment if the environment tax is further lifted to be higher than $\hat{t}$.

4.6. Conclusion Remarks

Under the current fast fashion industrial trend, apparel manufacturers tend to request a short lead time for their fabric supplies. However, lead time reduction means the fabric supplier has reduced time to properly monitor the production process and hence leads to environmental problems with a higher per unit pollutant and an expectedly lower fabric production yield. Motivated by this observed industrial practice, we have conducted an analytical study with the focus on how lead time reduction affects the performance of the supply chain agents as well as the environment. Some major managerial insights are concisely summarized as follows.

First, we have shown in Lemma 4.1 that for the ordering at Time *i*, the effective wholesale price will drop and the inventory service level (achieved at the apparel manufacturer's optimal ordering quantity) will increase if the respective fabric production yield rate increases. Then, we have also proven in Lemma 4.2 that the optimal fabric ordering quantity can be expressed in a neat close-form and it is a scaled quantity with respect to the standard newsvendor fractile solution.

Second, by exploring the expected values of lead time reduction (see Proposition 5.1), we have derived the analytical conditions under which lead time reduction is beneficial to the apparel manufacturer, fabric supplier and the whole supply chain. From the conditions, we have revealed some very important results. For instance, we have found that lead time reduction is beneficial to the apparel manufacturer (i.e., $EVLR_M > 0$) if and only if the prior mean of demand is not too big (bounded above by a threshold). We have explained this finding with respect to the relative significance of forecast information updating under lead time reduction. However, the situation for the fabric supplier is just the opposite. This highlights the inherent difference in incentive between the fabric supplier and the apparel manufacturer in which a situation favouring one of them usually does not favour the other one.

Third, regarding the impacts of fabric production yield, we have found from the sensitivity analysis that the apparel manufacturer's benefit from lead time reduction is higher if: (i) the fabric production yield rate at Time 2 is higher, (ii) the fabric production yield rate at Time 1 is lower. This is an intuitive and important result. For the effects brought by a change of the fabric production yield to the fabric supplier's benefit under lead time reduction, we have found that the prior market demand's coefficient of variation and the expected posterior market demand's coefficient of variation play a crucial role in determining whether the fabric supplier will be benefited or hurt with a change of fabric production yield.

Fourth, for the case when the whole supply chain is benefited under lead time reduction, but a win-win situation has not yet appeared, we have proposed the use of a deposit payment scheme to help. To be specific, we have demonstrated analytically how the win-win situation in the whole manufacturing supply chain can be achieved.

Fifth, in exploring the environment, we have defined a measure, called the expected harm to the environment under lead time reduction, i.e., $EHTE^{(LTR)}$, and derived its analytical closed-form expression. We have found from Proposition 6.1(a) that $EHTE^{(LTR)}$ is directly proportional to Q_2, μ_1, and Q_1. We have found that if the fabric supplier is benefited by lead time reduction, the environment will suffer (i.e., $EHTE^{(LTR)} > 0$). For the environment to be benefited, we need to fulfil two conditions, in which the fabric supplier suffers a loss under lead time reduction, and the per unit pollutant released under lead time reduction (i.e., Q_2) must be relatively small compared to the per unit pollutant released under the long lead time case (i.e. Q_1). In our sensitivity analysis, we have found that an increase of prior demand uncertainty may lift or reduce $EHTE^{(LTR)}$, depending on the relative size of Q_2 with respect to Q_1. For the effects brought by the fabric production yield, the explanations are quite similar to those on $EVLR_S$ and the prior and expected posterior demand coefficients of variation play a critical role.

Finally, with the consideration of environment tax and the probable reduction on the amount of per unit pollutant under lead time reduction by the fabric supplier's use of technological devices, we have analytically derived the optimal per unit pollutant level at under lead time reduction ($\hat{Q}_2^*$). We have shown that $\hat{Q}_2^*$ is directly proportional to the environment tax. We have further found the environment tax threshold with which the environment will not get hurt when the supply chain operates with lead time reduction. We have proven that lead time reduction can even improve the environment if the environment tax is properly adjusted up.

Chapter 5

Commercial Used Apparel Collection Operations in Retail Supply Chains[25]

5.1 Introduction

5.1.1 Industrial Background

In fashion retail supply chains, the commercial used apparel collection (UAC) program has been widely implemented over the past few years. H&M, a renowned fast fashion brand and retailer, has implemented its UAC program since 2013[26]. In fact, H&M was one of the first large scale fast fashion brands which launched a commercial UAC. Under H&M's UAC program, consumers can bring properly cleaned used apparel to H&M's retail stores. H&M collects the used apparel for commercial recycling as well as charity donation. H&M issues coupons (e.g., 10% off) to each small bag of collected used apparel. In 2019, H&M collected 29,005 tons of used garments through its UAC program[27]. Another fashion brand, Uniqlo, focuses on collecting its own "Uniqlo-branded" products which are in good shape. Uniqlo 100% donates its collected clothes to support children, refugees and others. In particular, through a special organization named UNHCR (Uniqlo and the United Nations High Commissioner for Refugees), Uniqlo provides emergent assistance to refugees, like those in Myanmar, South Sudan, Rwanda, Uganda, etc. Marks and Spencer (M&S)[28], a Britain's biggest fashion retailer, launched a "shwopping" scheme in 2012 to take back the old or unwanted apparel from customers. M&S cooperates with its charity partner Oxfam to arrange the donation, reuse, and recycling of the collected clothes. The "shwopping" scheme is one of M&S' "Plan A" sustainability program. Over the past five years, "Plan A" achieves a very profitable outcome with £185 million in net benefits. In 2017, another fast fashion giant ZARA[29] initiated its "Join Life" program which aims at collecting used clothes and donating the collected apparel directly to charity organizations like

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[25] A part of this chapter has been published in European Journal of Operations Research.

[26] https://www2.hm.com/en_gb/ladies/shop-by-feature/16r-garment-collecting.html [Accessed 30 September 2019]

[27] https://sustainabilityreport.hmgroup.com/wp-content/uploads/2020/04/HM-Group-SR19-Highlights.pdf [Accessed 21 July 2020]

[28] http://www.marksandspencer.com/s/plan-a-shwopping [Accessed 30 September 2019]

[29] https://www.zara.com/hk/en/sustainability-collection-program-l1452.html?v1=967749 [Accessed 30 September 2019]

Caritas, the Red Cross, Salvation Army, CEPF, Redress, and Oxfam. More industrial practices on UAC in fashion brands are shown in Table 5.1.

Table 5.1. UAC Practices of the Fashion Retail Brands (Yes: √; No: /).

		H&M	**M&S**	**Uniqlo**	**Zara**
Collection	Own brands' products	√	√	√	√
	Any brands	√	√	/	√
Usage	Remanufacturing or other commercial activities	√	√	/	√
	Donation (DO)	√	√	√	√
Incentive	Coupon for consumers	√	√	/	/
Facility	Collection box	√	√	√	√

As we can see from Table 5.1, despite having some slight differences (own brands' products, or any brands; with coupon or without; solely for charity or with remanufacturing and commercial elements, etc.), there is no doubt that UAC programs are very popular in the fashion industry. To a certain extent, fashion brands establish these programs, especially those in fast fashion (Caro and Martínez-de-Albéniz, 2015), as a way to change their traditionally unsustainable image (such as disposable fashion clothing, "dirty" to the environment, etc.) and gain a kind of intangible benefit in brand image improvement.

From the literature, there is a considerable amount of research on the problem of electronic wastes and vehicles, involving collection, take-back, and remanufacturing (Bakal and Akcali, 2006; Bulmus et al., 2014; Govindan and Popiuc, 2014; Atasu et al., 2008; Calmon and Graves, 2017; Ponte et al., 2019; Kleber et al., 2020; Cai and Choi, 2021). However, few prior studies have analytically examined the problem of UAC in the fashion industry. Thus, it is important and interesting to investigate the problem of UAC, which contributes to both the extant literature and management of real-world practices. Due to the different features of electronic wastes (and vehicles) and used apparel, our modeling is also different from the literature on waste electronic products or vehicles. For example, waste electronic products or vehicles usually have a higher salvage value than the casual used fashion apparel. Therefore, either compulsory or voluntary remanufacturing may be profitable for electronic wastes or vehicles, but it is not true for used fashion apparel. In addition, apparel donation is a distinctive feature of UAC, which differentiates this paper from others and makes the modeling in this paper unique.

5.1.2. Research Objectives, Questions

Motivated by the observed real-world practices, this paper attempts to explore how commercial UAC operations enhance the profitability and social reputation of a fashion brand. We set up two research objectives: i) To explore the real practice based used apparel collection (UAC) program, which helps to close the loop in the textile and apparel supply chain; ii) To derive possible guidelines for fashion retail companies to efficiently implement UAC so as to achieve socially responsible, yet profitable operations.

To target these goals, we come up with three main research questions: i) What is the optimal promotion effort of the fashion brand for UAC? ii) How could the UAC supply chain be coordinated? iii) How robust are the results when different real-world relevant extended scenarios are examined?

To address these questions, we consider a supply chain with a fashion retail brand, a remanufacturer and a charity organization, and construct a stylized analytical model to identify the optimal operations of the fashion retail brand and the supply chain. To be specific, in our basic model, we consider the case when a fashion retail brand collects the used apparel from consumers in the market by exerting promotion effort. Some of the collected used apparel are in a good shape, which can be directly donated for charity for re-use. However, some of the collected used apparel can only be used for re-manufacturing or recycling. Regarding the benefits for these two different outlets for the collected used apparel, we consider the situation when the re-manufacturer will pay the fashion retail brand some money for each unit of used apparel sent for re-manufacturing. For the donation to charity, even though the charity organization will not “pay the fashion retail brand”, the fashion retail brand actually enjoys a gain in reputation and good name as an ethical company, which in fact should be one important incentive for many of them to engage in UAC. We also explore the supply chain coordination problem in this paper. As the supply chain in this paper contains a charity organization, the coordination problem is different from the traditional supply chain problem (Cachon and Lariviere

2005; Ha and Tong 2008; Govindan and Popiuc 2014). Therefore, we present the "profit" coordination[30] definition as follows. Finally, to check the robustness of managerial findings from the basic model, various UAC practice related extended models, such as i) consumer coupon offering, ii) "no remanufacturing" model, iii) consumer heterogeneity in environmental consciousness, and iv) own-brand collection *vs* any-brand collection, are examined.

Definition (Profit Coordination). *In the supply chain with UAC, it is said to be profit-coordinated if the retailer's optimal promotion effort is the same as the promotion effort that maximizes the supply chain's expected benefit.*

All technical proofs are placed in the Appendix III.

5.2 Basic Model

We consider a fashion retail supply chain consisting of a fashion retail brand, a remanufacturer, a charity organization, and consumers. The fashion retail brand sells fashion products to the consumers and earns an average profit $\bar{p}$ per customer. With the UAC program, the fashion retail brand collects the used apparel for both remanufacturing and donation (P.S.: This is the common case for fashion retail brands like H&M, Marks and Spencer, Zara, etc.). To be specific, some of the collected used apparel may appear in a very good shape, which can be directly donated for charity for re-use. However, some of the collected used apparel are not in a good shape and can only be used for re-manufacturing and recycling. The collected used apparel products are remanufactured or recycled by the third party for other purposes, e.g., carpet production, spinning yarns, etc. Therefore, the remanufactured products do not compete with the originally manufactured fashion product in the fashion brand's retail store. Therefore, they do not affect the market demand. Regarding the benefits for these two different outlets for the collected used apparel, we consider the situation when the re-manufacturer will pay the fashion retail brand for each unit of used apparel sent for remanufacturing. For the donation to charity, even though the charity organization will not "pay the fashion retail brand", the fashion retail brand actually enjoys a gain in reputation as an ethical company and we also quantify this gain by an intangible

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[30] As a remark, the term "profit coordination" is equivalent to the term "supply chain coordination" in this paper.

benefit. Figure 5.1 depicts the whole picture of the basic model.

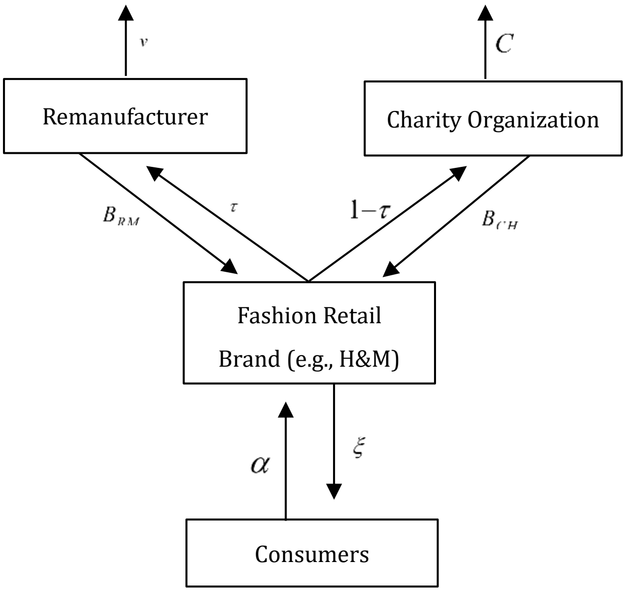

Figure 5.1. The basic model structure of UAC operations.

The potential market size for the fashion retail brand is denoted by N. Suppose that if the fashion retail brand offers the UAC program, it will attract an increased market demand to the store (i.e., it is not the total demand faced by the fashion retail brand, but the increased demand derived from UAC)[31]. Thus, the market demand can be expressed as follows:

$$D = a + b\xi, \tag{5.1}$$

where ξ is the promotion effort of the UAC program, $a > 0$ is the base market demand, and $b > 0$ is the coefficient of promotion effort towards the total market demand.

Note that the linear effort dependent demand function is commonly adopted in the OR literature (see Cachon and Lariviere 2005; Caldieraro and Coughlan 2007; Kovach et al. 2018). It is also in line with the consumer valuation/utility function which is uniformly distributed (such as "Uniform (0,1) distribution"). The promotion effort of UAC program in this paper includes investments in advertisement, the public relations, the training of front-line sellers, and educating consumers, etc. The total market demand on the fashion products has a linear relationship with the promotion effort. We assume exerting the promotion effort incurs a quadratic cost $K(\xi)$, which is defined by: $K(\xi) = k\xi^2/2$

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[31] In our model, we take this increase as deterministic. In fact, even if we include the randomness, it will not affect our qualitative result if we focus on exploring the expected benefit.

. The quadratic cost function is widely adopted in modelling the cost of promotion effort (Jørgensen et al. 2003; Heese and Swaminathan, 2010; Karray 2011; Jørgensen and Zaccour, 2014; Liu et al. 2014; Lu and Navas, 2021). Using it also helps to derive analytically tractable results and enhance the development of managerial insights.

Suppose that from the UAC driven increased demand *D*, only some (i.e., $0<\alpha<1$) but not all consumers will take the used apparel back. In the basic model, we assume that the return rate α to be exogenous in our model. The reason why we consider the return rate α to be exogenous is to generate tractable analytical results. We relax this assumption by considering the return rate α to be endogenous in an extended model and find the main results in the endogenous return rate still hold.

We denote the collected quantity under the UAC program by *Q*, and it is defined below:

$Q=\alpha D$, where $0<\alpha<1$. (5.2)

Observe that some of the collected used apparel may be in a very good shape, which can be directly donated to charity (e.g., Red Cross, Oxfam, etc.) for re-use. However, some of the collected used apparel may be too old or damaged that need to be re-manufactured and recycled. We denote the proportions of collected used apparel that need to be remanufactured by τ, and the ones which can be directly reused and donated for charity by $1-\tau$ (where $0<\tau<1$), respectively. Regarding the benefits for these two different outlets for the collected used apparel, we consider the situation when the re-manufacturer will pay the fashion retail brand B_{RM} for each unit of used apparel sent for re-manufacturing. Thus, the fashion retail brand[32] will gain a benefit of B_{RM} for each unit of collected used apparel for re-manufacturing. For the re-manufacturer, each unit of remanufactured used apparel will yield a value of *v*. For the donation to charity, even though the charity organization will not “pay the fashion retail brand”, the fashion retail brand actually enjoys a gain in reputation as an ethical company. We represent the fashion retail brand’s unit gain for this kind of donation to charity by B_{CH} (called the *unit good-name benefit from donation*), and the charity organization can generate a value of *C* (called the *moral benefit*) from each unit of donated used apparel, where B_{CH} and *C* are exogenous. As a remark, we do not consider the processing cost associated with classifying the

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[32] Unless otherwise specified, the term “fashion retail brand” is equivalent to the term “fashion retailer” in this paper.

collected used apparel, as considering such a cost will not affect any managerial insights while will make the model more complex.

We now consider the operations sequence under UAC. First, the re-manufacturer decides the payment to the fashion retail brand for each unit of used apparel B_{RM}. Then, with given B_{RM}, the fashion retail brand reacts by deciding the optimal promotion effort ξ to support the UAC program. As the charity organization only acts as a recipient of the used apparel, its presence only provides a way for the fashion retail brand to gain B_{CH}, and also generate a value of C for itself. The notation list is shown in Table 5.2.

Table 5.2. Notation Table.

Notations	
a	Base market demand
b	Coefficient of the promotion effort towards demand
ξ	Promotion effort of the fashion retail brand
ξ_R	Promotion effort of the fashion retail brand in the decentralized setting
ξ_{SC}	Promotion effort of the fashion retail brand in the centralized setting
k	Coefficient of the promotion effort towards collection cost
α	Returned rate of used apparel
τ	Proportion of collected used apparel for remanufacturing
B_{RM}	Re-manufacturer's payment to the fashion retail brand for each unit of used apparel sent for re-manufacturing
v	Value generated form each unit of remanufactured used apparel
B_{CH}	Fashion retail brand's unit gain for donation to charity (called the unit good-name benefit from donation)
C	Moral benefit of the charity organization from each unit donation
Z	Social benefits of donation
D	Market demand
$K(\xi)$	Collection cost
Q	Amount of returned used apparel
$\pi_R(\xi)$	Fashion retail brand's profit
$\pi_{RM}(\xi)$	Remanufacturer's profit
$\pi_C(\xi)$	Charity organization's benefit
$\pi_{SC}(\xi)$	Supply chain profit
β	Fashion retail brand's sharing proportion of the promotion effort
ECS	Effort cost sharing
S	Discount coupon (percentage)
η	Coupon redeem rate

γ	Proportion of consumers who are environmental conscious
ρ	Proportion of own brand products among all the collected used apparel

5.3 Equilibrium Decisions and Performance

5.3.1 Decentralized Setting

We start the analysis by exploring the decentralized supply chain. In the decentralized setting, both the fashion retail brand and remanufacturer aim to maximize their profits. The remanufacturer will determine the optimal payment B_{RM} for each unit of used apparel. The fashion retail brand will determine the optimal promotion effort ξ.

For a notational purpose, define:

$\bar{B} = \tau B_{RM} + (1-\tau)B_{CH}$,

$\Omega(B_{RM}) = \bar{p} + \alpha\bar{B}$, and

$\Delta = \frac{ak}{b^2} + \bar{p} + \alpha(1-\tau)B_{CH}$.

From the model in Section 3, we can express the fashion retail brand's profit as follows:

$$\pi_R(\xi) = \bar{p}D + B_{RM}\tau Q + B_{CH}(1-\tau)Q - K(\xi)$$

$$= (\bar{p} + \alpha\bar{B})D - K(\xi). \tag{5.3}$$

It is easy to show that $\pi_R(\xi)$ is a concave function of ξ. Thus, solving the first order condition yields the optimal promotion effort for a given B_{RM}:

$$\hat{\xi}_R = \arg_{\xi}\{\frac{\partial \pi_R(\xi)}{\partial \xi} = 0\} = \frac{(\bar{p} + \alpha\bar{B})b}{k}. \tag{5.4}$$

For the remanufacturer, its profit function when $\xi = \hat{\xi}_R$ is given below:

$$\pi_{RM}(B_{RM}; \xi = \hat{\xi}_R) = (v - B_{RM})\tau Q(\hat{\xi}_R) = (v - B_{RM})\tau\alpha\left(a + \frac{b^2\Omega(B_{RM})}{k}\right). \tag{5.5}$$

Checking the structural properties of $\pi_{RM}(B_{RM}; \xi = \hat{\xi}_R)$ gives Lemma 5.1.

Lemma 5.1. *(a)* $\pi_{RM}(B_{RM};\xi=\hat{\xi}_R)$ *is concave in* B_{RM}. *(b) The equilibrium* B_{RM} *and* ξ *under the decentralized basic model are given by:* $B_{RM}^* = \frac{v}{2} - \frac{\Delta}{2\alpha\tau}$, *and* $\xi_R^* = \frac{b}{k}\left(\bar{p} + \alpha\bar{B}_R^*\right)$, where $\bar{B}_R^* = (\tau B_{RM}^* + (1-\tau)B_{CH})$. *(c)* $B_{RM}^* < v$, *is always true.*

From Lemma 5.1, we can observe several interesting findings. First, Lemma 5.1(b) indicates that if v is sufficiently big, we have $B_{RM}^* > 0$, which means the remanufacturer has to pay the retailer for the used apparel. If v is sufficiently small, the situation becomes different because $B_{RM}^* \le 0$, which implies that the remanufacturer does not need to pay the retailer, but the retailer may even need to sponsor the remanufacturer for remanufacturing the collected used apparel. Since the term Δ increases in *a*, $\bar{p}$, and B_{CH}, but decreases in *b*, we can learn how *a*, $\bar{p}$, B_{CH} and *b* affect B_{RM}^* from the closed-form expression in Lemma 5.1(b). Second, from the expression of the optimal promotion effort ξ_R^*, note that $\bar{B}_R^*$ represents the expected benefit of the collected used-apparel for the retailer, and it plays a crucial role in determining the optimal promotion effort. To be specific, when $\bar{B}_R^*$ is larger, the optimal promotion effort exerted by the fashion retail brand will increase. Furthermore, if the used apparel return rate α is higher, the optimal promotion effort also becomes larger. Lemma 5.1 (c) shows that at the equilibrium, it is always possible for the remanufacturer to make profits by remanufacturing the collected apparel from the fashion retail brand because the value of remanufacturing is always larger than the fees paid to the fashion retail brand.

5.3.2 Centralized Setting

In the centralized setting, the total expected benefit of the supply chain is expressed as follows: $\pi_{SC}(\xi) = \pi_R(\xi) + \pi_{RM}(\xi) + \pi_C(\xi)$, where $\pi_R(\xi)$, $\pi_{RM}(\xi)$ and $\pi_C(\xi)$ represent the profits (or benefits) of the fashion retail brand, the remanufacturer, and the charity organization, respectively.

The benefit gained by the charity organization is expressed below:

$$\pi_C(\xi) = C(1-\tau)Q. \tag{5.6}$$

Thus, we have:

$$\pi_{SC}(\xi) = \bar{p}D + v\tau Q + (B_{CH} + C)(1-\tau)Q - K(\xi) . \tag{5.7}$$

Checking the structural properties of $\pi_{SC}(\xi)$, we have Lemma 5.2.

Lemma 5.2. *In the centralized setting, we have (a)* $\pi_{SC}(\xi)$ *is concave in* ξ *; (b) The optimal* ξ *that maximizes the supply chain's expected benefit is given by:* $\xi_{SC}^{*} = \frac{b}{k}\left[\bar{p} + \alpha\tau v + \alpha(1-\tau)(B_{CH} + C)\right]$.

From Lemma 5.2, we can see that the optimal promotion effort for the whole supply chain follows a similar format as the optimal promotion effort for the fashion retail brand. Combining Lemmas 5.1 and 5.2, we have Proposition 5.1.

Proposition 5.1. *(a)* $\xi_R^{*} < \xi_{SC}^{*}$ *, for any* $B_{RM} \le v$ *. (b)* $\pi_{SC}(\xi_R^{*}) < \pi_{SC}(\xi_{SC}^{*})$.

Proposition 5.1(a) shows that the fashion retail brand's optimal promotion effort is below the supply chain's optimal promotion effort for any $B_{RM} \le v$. A bit surprisingly, observe that this also means that even when the remanufacturer supplies at cost ($B_{RM} = v$), the supply chain is still not coordinated in terms of supply chain profitability. The reason is that, in the supply chain, each donated quantity only gives a value of B_{CH} to the fashion retail brand, but it gives $B_{CH} + C$ to the supply chain (with a unit value C generated for the charity organization). By itself, the decentralized UAC supply chain is hence inefficient and there are rooms for improvement. Proposition 5.1(b) further shows that from the perspective of supply chain, the achieved level of supply chain under the decentralized supply chain setting is lower than the one under the centralized supply chain setting.

Therefore, is there any approach to coordinate the supply chain? We will explore the coordination problem in Section 5.

5.4 Coordination

In the above section, we note that comparing with the centralized supply chain, the decentralized supply chain with UAC is inefficient in both achieving the profit and social welfare. In real world, the supply chain we considered with UAC involves the charity organization, remanufacturer, and fashion retail brand. It is basically impossible for them to be controlled in a centralized manner as they are so different and none of them can naturally be the coordinator. In this section, we examine how a novel effort cost sharing (ECS) contract can overcome this supply chain coordination challenge.

We note that the supply chain with UAC cannot be coordinated even if we set $B_{RM} = v$ to overcome the double marginalization effect. In this sub-section, we propose an innovative measure to help coordinate the supply chain, which requires the help from the charity organization. To be specific, for the charity organization, we consider the scenario when it may help support the UAC program's promotion by sending in some volunteers and workers to help the fashion retail brand. By doing so, it shares a part of the promotion effort cost. To be specific, suppose that the charity organization can help by partially sharing the fashion retailer's promotion effort, with a proportion of $1-\beta$, where $0<\beta\le 1$. The promotion effort in this scenario is denoted as $\xi_{R,\beta}$.

The sequence of the event under the ECS contract is given as follows. First, the remanufacturer decides the payment $B_{RM,\beta}$ to the fashion retail brand for each unit of used apparel, and the charity organization determines to share $1-\beta$ of the promotion cost. Then, with given $B_{RM,\beta}$ and β, the fashion retail brand decides the optimal promotion effort $\xi_{R,\beta}$ to maximize its profit.

The fashion retail brand's profit under the effort cost sharing (ECS) contract is as follows:

$$\pi_R(\xi_{R,\beta}) = \bar{p}D + B_{RM}\tau Q + B_{CH}(1-\tau)Q - \beta\frac{k(\xi_{R,\beta})^2}{2}.$$

Following the same step in Section 4.1, we define $\Delta_\beta = \frac{ak\beta}{b^2} + \bar{p} + \alpha(1-\tau)B_{CH}$ and present Lemma 5.3.

Lemma 5.3. *Under the basic model with the ECS contract: (a) The equilibrium* B_{RM} *and* ξ *under the decentralized supply chain are given by:* $B^*_{RM,\beta} = \frac{v}{2} - \frac{\Delta_\beta}{2\alpha\tau}$, *and* $\xi^*_{R,\beta} = \frac{b}{k\beta}\left(\bar{p} + \alpha\bar{B}^*_{R,\beta}\right)$, *where* $\bar{B}^*_{R,\beta} = B^*_{RM,\beta}\tau + B_{CH}(1-\tau)$. *(b)* $B^*_{RM,\beta} \ge B^*_{RM}$. *(c)* $\xi^*_{R,\beta} \ge \xi^*_R$.

Lemma 5.3 indicates that in the presence of the ECS contract, the equilibrium payment of the remanufacturer and promotion effort the fashion retail brand are both affected and can be larger than the case without ECS. Using the result in Lemma 5.3, we can find the proper way to set the ECS contract to achieve $\xi^*_{R,\beta} = \xi^*_{SC}$, i.e., coordinate the supply chain. We summarize the results in

Proposition 5.2.

Proposition 5.2. *Under the ECS contract, setting* $\beta_{SC} = \frac{\bar{p} + \alpha\tau v + \alpha(1-\tau)B_{CH}}{2\left[\bar{p} + \alpha\tau v + \alpha(1-\tau)(B_{CH} + C)\right] + akb^{-2}}$ *can achieve profit-coordination, where the charity organization has to share* $1-\beta_{SC}$ *proportion of the total UAC promotion cost (e.g., by contributing its team of volunteers).*

Proposition 5.2 indicates that by using the ECS contract, profit-coordination can be achieved which means the supply chain's profitability is maximized. One important and interesting remark is that, many traditional supply chain contracts, including the "powerful" two-part tariff, and revenue sharing contracts, all fail to achieve the supply chain coordination. The reason is due to the presence of the charity organization and the benefit earned through it appears to be different from the revenue derived from conventional business transactions. Finally, we choose the ECS contract, particularly for the coordination problem in this paper. Note that in this paper, we do not model the manufacturer-retailer channel which means the traditional buyback mechanism does not apply here. In fact, for "buyback" scheme, it may be suitable to the reverse logistics problems when the remanufacturer is the original manufacturer. However, in this paper, the remanufacturer acts as a third-party role for remanufacturing or recycling the collected used apparel into carpet, new yarns, etc.

5.5 Extended Models and Analyses

In this section, we extend the basic model analysis by considering various real UAC practice related scenarios. The purpose is to illustrate the robustness of findings derived from the basic model as well as uncover additional insights. As a remark, for each extension, we focus on revealing the respective impacts on supply chain profit under the centralized setting, because we could always achieve SC-coordination by using the properly set ECS contract (P.S.: We have shown in Section 5 and will not analyze it in each case).

5.5.1 Consumer Coupon Offering

In the basic model, we consider the scenario when the consumers only donate the used apparel without any extra incentive offered (e.g., Uniqlo, and Zara). While in the real world, we have witnessed that some fashion brands (e.g., H&M, Marks and Spencer) offer incentives, such as discount coupons, to entice consumers to return used apparel. In this extended model, we explore the situation when the fashion retail brand grants a discount coupon (with the discount rate of "S off" (where S is a percentage)) to the consumers who return the old or unwanted clothes. As in general not all consumers will use the coupon, we denote the coupon redeem rate as η, where $0 \leq \eta \leq 1$. With the coupon, it is rather natural that the same amount of promotion effort will yield a higher impact on demand because there are consumers who are attracted by the presence of coupons. Through modeling and analysis, we conclude the results in Propositions 5.3 and 5.4, which are shown in Appendix III.

We find that with the consumer coupon offering, the optimal fee that the manufacturer pays to the fashion retail brand is rather sensitive to the coupon value S. When S is large, the remanufacturer need pay more to the fashion retail brand; while when S is small, the remanufacturer pays less to the retailer. The reason for this finding is that, in the presence of coupon, the fashion retail brand spends more on the promotion (coupon offering is absent in the basic model) and meanwhile generates a higher revenue. Therefore, it is natural for the fashion retail brand to get more payment from the remanufacturer. Moreover, with coupon offering, the optimal promotion effort of the fashion retail brand will become larger than the case without coupon offering. This is an interesting result because one might predict that with the coupon, the fashion retail brand might not need to work harder to exert a higher effort to collect the used apparel. Our result shows the opposite. In fact, the use of coupon can not only help increase the amount of used apparel collation from the market, it may also generate a higher revenue to the fashion retail brand, which directly explains why the fashion retail brand will increase its promotion effort. Finally, offering coupons is a wise measure for the fashion retail brand because it can help make more profits. This finding partially explains why most fashion retail brands which offer UAC would also grant a discount coupon to consumers (see Table 1.1) as it is beneficial to do so.

In the centralized setting, the optimal promotion effort for the supply chain profit maximization is higher when coupons are offered. With the enhanced promotion effort, the resulting supply chain profit is improved. Therefore, offering "consumer coupons" is a beneficial measure to the supply chain.

5.5.2 “No RM” Model

In the existing UAC programs, regarding the quality requirements of the collected apparel, we observe that there exist two phenomena. For example, H&M collects used apparel in both good and bad shapes and send them for charity donation and commercial remanufacturing, respectively. However, another international fashion brand Uniqlo only takes back used apparel in a good-shape purely for charity donation. Thus, there is no remanufacturing part for Uniqlo’s UAC program and we call it the “No RM” model. In this extended model, we explore the performances of the fashion retail brand, supply chain profit and social welfare under the “No RM” model, as seen in real world by companies such as Uniqlo.

In the basic model, we learn from Lemma 5.1 that if v is sufficiently small, we may have $B_{RM}^{*} \leq 0$, which implies that the remanufacturer does not need to pay the retailer, but the retailer may even need to sponsor the remanufacturer for getting and remanufacturing the used apparel. To this end, it may be wise to for the fashion retail brand to give up RM totally and impose a measure to filter the collected used apparel, all for charity (e.g., the case of Uniqlo). Through modeling and analysis, we conclude the results in Propositions 5.5 and 5.6, which are shown in Appendix III.

Define: $v_{\overline{RM}} = \frac{1}{\alpha\tau}\left[\frac{ak}{b^2} + \bar{p} + \alpha(1-\tau)B_{CH}\right]$, where $v_{\overline{RM}}$ is the threshold for $B_{RM}^{*} = 0$. We find that $v \leq v_{\overline{RM}}$ is equivalent to $B_{RM}^{*} \leq 0$.

Our results reveal that in the decentralized setting, it is wise for the fashion retail brand to give up RM when v is sufficiently small (i.e., $v \leq v_{\overline{RM}}$), and the fashion retail brand will generate more profits than before. Meanwhile, the fashion retail brand needs to exert a higher promotion effort under the “No RM” model.

In the centralized setting, the supply chain profit becomes worse off in the “No RM” model. This result is important because we note that the “No RM” model can be optimal for the fashion retail brand, but it is always harmful to the whole supply chain. As such, there is an inherent conflict between the choice to go for “No RM” between the fashion retail brand and supply chain (as well as the social welfare perspective). Thus, for truly socially responsible fashion retail brands, the “No RM” model seems to be insufficient.

5.5.3 Consumer Heterogeneity in Environmental Consciousness

In the basic model, consumers are assumed to be homogeneous in terms of their environmental consciousness. In this sub-section, we consider the case when among the consumers, γ portion of them are environmental conscious (E), and the remaining (i.e., $1-\gamma$) are non-environmental conscious (NE). To be specific, they are heterogeneous in the following two dimensions. First, environmental conscious consumers are more sensitive to the UAC promotion effort than non-environmental conscious ones. Denote the sensitivity coefficients of environmental and non-environmental conscious consumers by b_E and b_{NE}, respectively. We have $b_E > b_{NE} \geq 0$. Second, the environmental conscious consumers have a higher used apparel donation rate than that of the non-environmental conscious consumers, which are denoted by α_E and α_{NE}, respectively, and $1 \geq \alpha_E > \alpha_{NE} \geq 0$. In particular, when $b_E = b_{NE} = b$ and $\alpha_E = \alpha_{NE} = \alpha$, this model degenerates to the basic one. Let $\bar{\alpha} = \gamma\alpha_E + (1-\gamma)\alpha_{NE}$ and $\bar{b} = \gamma b_E + (1-\gamma) b_{NE}$ denote the average consumer return rate (equal to the average collection rate) and the average sensitivity coefficient, respectively. Exploring the equilibrium with consumer heterogeneity in environmental consciousness, we have Propositions 5.7 and 5.8, which are shown in Appendix III.

We derive the equilibrium results with the consideration of consumer heterogeneity in environmental consciousness in the decentralized supply chain. As the proportion of environmental conscious consumers (γ) increases, the retailer invests more in the UAC promotion effort and the remanufacturer pays more for the collected apparel. These may not increase the demand, but will definitely increase the amount of collected used apparel, which is more environmentally friendly. comparing the equilibrium results with that in the basic model, we find that the interaction effect of the two dimensions of environmental consciousness (sensitivity coefficient and used apparel collection rate) plays a crucial role. As the degree of heterogeneity in consumer environmental consciousness increases, the interaction effect becomes higher. This induces the retailer to invest more in the UAC promotion effort and encourages the remanufacturer to pay more for the used apparel. Both the retailer and the remanufacturer can achieve higher profits.

In the centralized supply chain, we find profit-coordinating promotion effort increases in the proportion of environmental conscious consumers. Our findings in this extended model prove the robustness of that former results in Proposition 4.1: (i) the collecting effort in the decentralized supply chain is lower than those in the centralized supply chain due to the “double marginalization effect” and (ii) the SC-coordinating promotion effort should be higher than that in the decentralized supply chain. Moreover, the consumer heterogeneities in the two dimensions of environmental consciousness, i.e. the sensitivity coefficient and the used apparel collection rate, would amplify their interaction effect ($\bar{\alpha} \cdot \bar{b} > a \cdot b$). This makes the UAC collection effort more effective, and enhances the retailer’s promotion effort and supply chain’s profit.

5.5.4. Own-Brand Collection Versus Any-Brand Collection

The real-world practices reveal that some fashion retail brands only collect their own brands’ used apparel, e.g., Uniqlo, while some other fashion retail brands, such as H&M and Zara, collect used apparel from any brands. Obviously, the any-brand collection (ABC) scheme will collect more used apparel, while the own-brand collection (OBC) scheme will obtain less. Through modeling and analysis, we conclude the results in Propositions 5.9 and 5.10, which are shown in Appendix III.

We find both the optimal B_{RM} and ξ_R in the OBC model are smaller than the ABC model, which means that the fashion retail brand will exert less effort in promoting its own UAC program under OBC, and the remanufacturer will also pay less to get the used apparel for remanufacturing. With the reduced optimal B_{RM} and ξ_R in the OBC model, profits of all supply chain players are reduced. These findings imply that in the OBC model, the market demand will decline with a reduced promotion effort. Worst of all, the supply chain players’ profits also suffer a loss under the OBC model, when compared with the ABC model.

In the centralized setting, the optimal promotion effort which maximizes the supply chain’s profit in the OBC model becomes smaller and the corresponding supply chain’s profit is also reduced. This indicates that from the supply chain perspective, the OBC model is inferior to the ABC model (i.e., basic model).

5.5.5. Summary of Extended Models

To conclude, we summarize the findings from the extended models in Table 5.3. As a remark, all the findings are made under the assumptions (same with those in the basic model): exogenous price and constant collection rate.

Table 5.3. The summary table of the results from extended models (for robustness checking).

Scenarios	*Coordination by ECS?*	*Effects on* ξ_R^* *and* B_{RM}^*	*Key insights*
Consumer coupon offering	Yes	With the consumer coupon offering, ξ_R^* increases and B_{RM}^* is affected by coupon value.	It is wise to offer consumer coupons, because the fashion retail brand, the supply chain and the social welfare benefit from the coupon offering.
"No RM" Model	Yes	In "No RM" model, ξ_R^* becomes larger and B_{RM}^* is zero.	It is wise for the fashion retail brand to give up RM when v is sufficiently small. Thus, the fashion retail brand will generate more profit than before. However, the supply chain benefit and the social welfare are reduced.
Consumer heterogeneity in environmental consciousness	Yes	A higher proportion of environmental conscious consumers will lead to higher ξ_R^* and B_{RM}^*.	The interaction effect of the two dimensions of environmental consciousness. If the degree of consumer heterogeneity in environmental consciousness increases, it could make the UAC program more effective.
Own-brand collection VS Any-brand collection	Yes	"Own-brand collection" model reduces both the ξ_R^* and B_{RM}^*.	It is unwise to perform "own-brand collection", when the fashion retail brand aims to earn more money from UAC program.

5.6 Conclusion Remarks

The commercial used apparel collection (UAC) operations are commonly observed in the real world. In this paper, based on the observed real-world practices, we have analytically explored the UAC operations. First, in the basic model, we have considered the case when a fashion retail brand collects the used apparel from consumers in the market by exerting promotion effort. We have analytically derived in closed-form the optimal promotion efforts for UAC in both decentralized and centralized settings. We have developed a novel contractual mechanism, called effort cost sharing (ECS) contract, in which the charity organization helps the fashion retail brand's UAC operations by sharing partially the promotion cost, e.g., by contributing its team of volunteers to help. We have shown that the ECS contract can successfully achieve supply chain coordination. Finally, to check the robustness of managerial findings from the basic model and also examine various UAC practice related cases, we have examined various extended models and found that the qualitative results from the basic model continue to hold in the extended cases.

From the analytical findings, we have generated a series of important managerial insights and implications. We discuss them in the following.

i) How to maximize the supply chain profit with UAC? Analytical results reveal that in the decentralized setting, the fashion retail brand aims to maximize its own profit and exerts an optimal promotion effort accordingly. However, the decentralized promotion effort fails to coordinate the supply chain (containing the charity organization). Since the supply chain profit would not be maximized automatically, we thus propose an effort cost sharing (ECS) contract to help, in which the charity organization is required to share a part of the UAC promotion cost with the fashion retail brand. In terms of implementation, it can be done by the providing manpower such as volunteers to help promote UAC or to have some joint promotion programs. One important and interesting remark is, many traditional supply contracts, including the "powerful" two-part tariff, and revenue sharing contracts, all fail to achieve profit-coordination. The reason is due to the presence of the charity organization and the benefit earned through it appears to be different from the revenue derived from conventional business transactions.

ii) Is "consumer coupon offering" better than without? Consumer coupon offering is another strategy adopted by some fashion retail brands in the UAC programs. However, not all fashion retail brands provide "coupon" to the consumers who donate the used apparel. For example, fashion retail brands like "H&M" and "Marks & Spencer" give discount coupons to consumers, while fashion retail brands like "Zara" and "Uniqlo" only collect the used clothes without coupon offering. Our analytical findings show that issuing consumer coupons is useful. With the coupon, under the assumption that a proportion of the coupon will be redeemed, it is interesting to note that the fashion retail brand will exert more promotion efforts to collect the used apparel and gain more profits from this strategy. In the centralized setting, with the enhanced promotion effort, the supply chain profit becomes better off. Therefore, offering "consumer coupons" is a beneficial and wise measure to the fashion retail brand, as well as the supply chain.

iii) Is "no remanufacturing" wise for the fashion retail brand? We have observed that in real world, some fashion retail brands only collect used apparel which are in good conditions for donation. They do not collect the severely damaged apparel which can only be used for remanufacturing. If we take a look at Table 5.1, we will find that Uniqlo is such an example for this "No RM" model. When the value of remanufacturing is low, "No RM" model can allow the fashion retail brand to make more profits but lead to a reduction of the supply chain profit. It is important to note that the "No RM" model can be optimal for the fashion retail brand but it is always harmful to the whole supply chain. As such, there is an inherent conflict between the choice to go for "No RM" between the fashion retail brand and the supply chain perspective. Thus, truly socially responsible fashion retail brands should not adopt the "No RM" model.

iv) How to strategically deal with consumer heterogeneity in environmental consciousness? With the increase of consumers' environmental consciousness, the fashion retail brand has to reshape the business strategy to efficiently respond to the emerging demand of the environmental conscious consumers. Our analytical results show that the presence of a higher proportion of environmental conscious consumers will contribute to more profits to both the fashion retail brand and the remanufacturer. As a result, the consumer heterogeneities in the two dimensions of environmental consciousness (sensitivity coefficient and the used apparel collection rate) makes the promotion effort in UAC more effective, and enhances the profits of both the retailer and the supply chain. Thus, it makes sense for the fashion retail brands to promote UAC more specifically towards the environmental conscious consumers as increasing their participation will get more benefits from UAC.

v) Is own-brand collection (OBC) better than any-brand collection (ABC)? The results in our paper reveal that in the OBC model, the market demand will decline with the reduced promotion effort. The fashion retail brand's profit hence becomes worse off in the OBC model, comparing with that in the ABC model. In the centralized setting, the optimal promotion effort which maximizes the supply chain profit in the OBC model becomes smaller and the supply chain profit is reduced. To achieve the profit coordination, note that the charity organization needs to share a higher proportion of the total UAC promotion costs, comparing with the ABC model. Our findings clearly reveal the weakness of

OBC model, and it should be avoided if the fashion retail brand faithfully commits to the UAC program.

Chapter 6

Conclusions and Discussions for Future Research

Sustainability has been given more attention in the fashion industry. Motivated by the new requirements under SDGs, this thesis studies the following three new issues in sustainable fashion supply chain: producer's choice of design-for-environment under environmental taxation, impacts of lead time reduction on fabric sourcing in apparel production with yield and environmental considerations, and commercial used apparel collection operations in retail supply chains. Main results are summarized as follows:

Design-for-Environment: First, different environmental taxation schemes have different impacts on producer's choice of DfE level and the social welfare performance, as well as the environmental impacts. In all cases, the CET scheme in this paper does not encourage the sustainable product design and the ZET scheme is even better than the CET scheme. Thus, using the CET scheme is a big mistake which brings more harm than good. On the contrary, the LET scheme can promote the sustainable product design, which can be regarded as the optimal. Second, from the environment perspective, different environmental tax policies have different impacts on the environment. For example, the CET scheme brings more harm to the environment than the LET and ZET schemes do. When the marginal DfE allowance is small, no tax charge creates the least environmental impacts. However, the LET scheme is optimal for the environment, when the marginal DfE allowance is high. Anyway, a high product's DfE level will do good to the environment. Third, when environmental taxation is designed to balance the DfE level, the stakeholders' benefits, and the environmental impacts, the optimal solution is to choose the LET scheme and make use of the leveraging effect of marginal DfE allowance in the LET scheme. To be specific, if aiming to maximize the social welfare performance, the optimal plan is to set a medium marginal DfE allowance. If aiming to obtain a high social welfare performance and a high government's tax income, a low marginal DfE allowance can be set. If aiming to obtain a high social welfare performance and a high producer's profit, a high marginal DfE allowance is optimal. If aiming to maximize the DfE level of the producer, the best choice is to set a super high marginal DfE allowance and thereby provide a pure environmental sponsorship.

Lead Time Reduction on Fabric Sourcing: In apparel supply chains, manufacturers usually request a short lead time for fabric supplies. However, a short supply lead time would create environmental problems such as insufficient time for proper control of chemicals and material processing operations, and lead to a lower production yield of good quality supplies. Motivated by this observed industrial practice in fabric sourcing and apparel production, we build a stylized analytical model to investigate how lead time reduction in fabric sourcing affects performances of the fabric supplier and apparel manufacturer as well as the environment. To be specific, we first derive the optimal ordering quantity for the apparel manufacturer and find that it is a production yield scaled newsvendor fractile quantity. We then explore the expected values of lead time reduction and derive the respective analytical conditions for the apparel manufacturer, fabric supplier and whole supply chain to be benefited by lead time reduction. From the conditions, we reveal that the prior demand mean (which also implies the relative prior demand uncertainty) plays a critical role in determining whether lead time reduction is beneficial. We illustrate how a win-win situation in the supply chain can be achieved by a properly designed deposit payment scheme. For the environment, we show that when the fabric supplier's profit is improved under lead time reduction, the environment must be hurt. We hence propose the use of an environment tax to help and prove that lead time reduction can even improve the environment if the environment tax is appropriately set. Finally, we show that the product's demand coefficients of variation would mediate how the fabric production yield affects the fabric supplier's expected benefit as well as the expected harm to the environment under lead time reduction.

Used Apparel Collection Operations: First, we analytically derive in closed-form the optimal promotion efforts in both decentralized and centralized settings. We find that the promotion effort in the decentralized setting fails to coordinate the channel. We propose an effort cost sharing (ECS) contract to help, in which the charity organization is required to share partial promotion cost of the fashion retail brand, e.g., by using its team of volunteers to help. Surprisingly, we uncover those traditional contracts like two-part tariff, revenue sharing, and rebates all fail to achieve coordination. Second, to check the robustness of managerial findings from the basic model and also examine various real world related scenarios, we have considered five extensions. Considering consumer coupon offering, we find that the fashion retail brand will exert more promotion effort in collecting the used apparel in the presence of coupon. In the centralized setting, with the enhanced promotion effort, the supply chain profit becomes better off. When there is no used apparel for remanufacturing, we find that used apparel only for donation is not always a good strategy for the fashion retail brand to make more profits. When consumers are heterogenous in environmental consciousness, we find that a higher proportion of environmental conscious consumers will contribute to more profits to both the fashion retail brand and the remanufacturer. When the fashion retail brand only collects its own branded products under UAC, the market demand will decline due to a reduced promotion effort. The supply chain players' profits become worse off, when comparing with the any-brand collection model. Finally, we find that the use of ECS contract for supply chain coordination is robust across all extended models.

6.1 Future research

In the study of DfE, of course, there are other design performance indicators for sustainable product design, but we have not discussed them in this chapter. Secondly, the market price is assumed to keep unchanged with the variable DfE level. In the future research, we may consider the multi-dimensions for modeling the DfE in the basic model, such as raw material options, energy consumption, as well as DfE level and examine how the different dimensions will affect the DfE level and the social welfare. Further, price competition between two producers may be explored by using the non-cooperative game theory. Last but not the least, we will explore the impact of demand uncertainty on the performance of the optical DfE level, producer's profit and the social welfare.

In the study of quick response in fabric sourcing, there are some limitations. For example, we do not consider the possibility of having two orderings, one at Time 1 and one at Time 2. Extending along this direction will require the derivation of a two-stage two-ordering fabric sourcing policy using stochastic dynamic programming. Another probable future research avenue is to explore the level of risk associated with the fabric sourcing decisions (Asian and Nie 2014). It would also be meaningful to further generalize the results and build the effective link between supply chains and regulators so that specific policy suggestions about environment-related problems can be better implemented.

There are a few limitations in the research of used apparel collection operations. First, although we have considered various operations scenarios of UAC, future research can be conducted to examine in more details of different probable configurations of UAC operations. Second, we assume the increased market demand derived from UAC is a linear function of the promotion effort of the fashion retail brand. There may exist other functional forms, which can also be studied in the future. In our analysis, we do not pay attention to the probable impacts brought by UAC on the apparel manufacturers, suppliers and other forward supply chain related operations like sourcing (Calvo and Martínez-de-Albéniz 2015) and supply contracting (Ha and Tong 2008; Govindan and Popiuc 2014). Future research can be conducted to investigate them. The impacts of UAC on environment also deserve investigation in the future.

Moreover, we will study how new technologies (e.g., Blockchain, artificial intelligence, etc.) transform sustainable supply chain in the apparel and textile industry (Cai et al. 2020) and explore possible new business models (e.g., rental, closed loop, etc.) contributing to reducing environmental impacts (Zhang et al. 2021). Last but not the least, we will explore more sustainable issues in textile and apparel industry under new SDGs, especially, the goals of goals of “No Poverty”, “Reduced Inequalities”, “Life below Water” and “Life on Land” (Cai and Choi 2020).

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Appendix I: Proofs for Lemmas and Propositions in Chapter 3

Proof for Lemma 3.1. Under the LET scheme, we have $\bar{\pi}_L = (p-c)\bar{D} - \lambda\bar{D}p + \lambda\bar{D}vm - (1-\lambda)\bar{D}(k-\eta m) - \theta m^2$. By taking the second order derivation of $\bar{\pi}_L$, we have $\frac{\partial^2\bar{\pi}_L}{\partial m^2} = 2\lambda v\sigma + 2(1-\lambda)\eta\sigma - 2\theta$. Arrange $\frac{\partial^2\bar{\pi}_L}{\partial m^2} < 0$, to make sure $\bar{\pi}_L$ is a concave function. Thus, we have $\theta > \lambda v\sigma + (1-\lambda)\sigma\eta$. By arranging $\frac{\partial\bar{\pi}_L}{\partial m} = 0$, we have $m_L^* = \frac{\left((1-\lambda)(p-k)-c\right)\sigma+\lambda v(\alpha-\beta p)+(1-\lambda)(\alpha-\beta p)\eta}{2(\theta-\lambda v\sigma)-2(1-\lambda)\eta\sigma}$. This is the proof of Lemma 3.1 (a).

Similarly, we can prove Lemma 3.1 (b) & (c). (Q.E.D.)

Proof for Proposition 3.1. (a) Comparing m_L^* and m_C^* under the LET and CET schemes (comparing their numerators and denominators), obviously, we have $m_L^* > m_C^*$. (b) Comparing m_0^* and m_{CON}^* under the ZET and CET schemes (comparing their numerators and denominators), obviously, we have $m_0^* > m_C^*$. (c) Comparing m_L^* and m_0^* under the LET and the ZET schemes, a threshold for η is obtained: $\eta_L = \frac{(\theta-\lambda v\sigma)k\sigma}{\theta(\alpha-\beta p)+((1-\lambda)p-c)\sigma^2}$, which makes m_L^* equal to m_0^*. Finally, we have $m_L^* \left(\substack{\geq \\ = \\ <}\right) m_0^*$, if and only if $\eta \left(\substack{\geq \\ = \\ <}\right) \eta_L$.

Thus, this is the proof of Proposition 3.1. (Q.E.D.)

Proof for Proposition 3.2. Based on the analyses in Section 4.1, we learn the optimal modularity level choices of the producer under the three tax schemes. Then, we compare the profits of the producer under the three tax schemes, respectively. The expected profit function of the producer is shown below: $\bar{\pi} = (p-c)\bar{D} - \lambda\bar{D}p + \lambda\bar{D}vm - (1-\lambda)\bar{D}t - \theta m^2$.

In the LET scheme, the optimal expected profit of the producer is denoted by $\bar{\pi}_L^*$ and the environmental tax is $t_L = k - \eta m$. In the CET scheme, the optimal expected profit of the producer is denoted by $\bar{\pi}_C^*$ and the environmental tax is $t_C = k$. In the ZET scheme, the optimal expected profit of the producer is denoted by $\bar{\pi}_0^*$ and the environmental tax is $t_0 = 0$.

In the LET scheme, we have

$\bar{\pi}_L(m) = -(\theta - \lambda v\sigma - (1-\lambda)\eta\sigma)m^2 + \Big(\big((1-\lambda)(p-k)-c\big)\sigma + (\lambda v + (1-\lambda)\eta)(\alpha-\beta p)\Big)m + \big((1-$

$\lambda)(p-k)-c\big)(\alpha-\beta p)$.

In the CET scheme, we have

$$\bar{\pi}_C(m)=-(\theta-\lambda v\sigma)m^2+\Big(\big((1-\lambda)(p-k)-c\big)\sigma+\lambda v(\alpha-\beta p)\Big)m+\big((1-\lambda)(p-k)-c\big)(\alpha-\beta p).$$

In the ZET scheme, we have

$$\bar{\pi}_0(m)=-(\theta-\lambda v\sigma)m^2+\Big(\big((1-\lambda)p-c\big)\sigma+\lambda v(\alpha-\beta p)\Big)m+\big((1-\lambda)p-c\big)(\alpha-\beta p).$$

To facilitate the comparisons of $\bar{\pi}_L^*$, $\bar{\pi}_C^*$ and $\bar{\pi}_0^*$, we draw parabolas to depict $\bar{\pi}_L^*$, $\bar{\pi}_C^*$ and $\bar{\pi}_0^*$. See Figure A1.

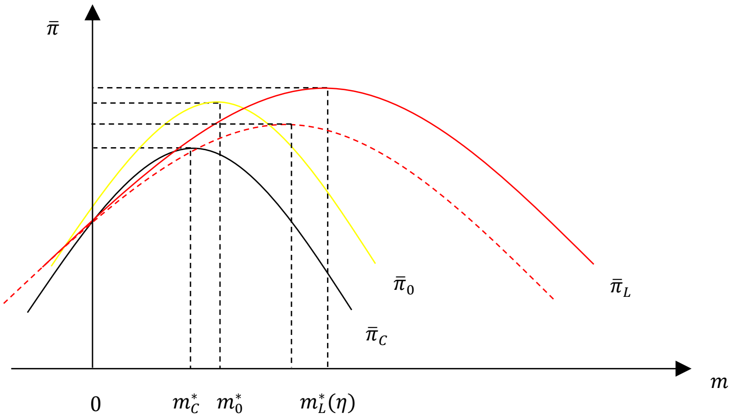

Figure A1. Comparisons of $\bar{\pi}_L^*$, $\bar{\pi}_C^*$ and $\bar{\pi}_0^*$.

First, we compare $\bar{\pi}_C(m_C^*)$ and $\bar{\pi}_0^*(m_0^*)$. From Figure A1, it is intuitive that $\bar{\pi}_0^*(m_0^*) > \bar{\pi}_C^*(m_C^*)$. Second, we compare $\bar{\pi}_L^*(m_L^*)$ and $\bar{\pi}_C^*(m_C^*)$, we have $\bar{\pi}_L^*(m_L^*) > \bar{\pi}_C^*(m_C^*)$. Third, we compare $\bar{\pi}_L^*(m_L^*)$ and $\bar{\pi}_0^*(m_0^*)$, we have $\bar{\pi}_0^*(m_0^*) > \bar{\pi}_L^*(m_L^*) > \bar{\pi}_C^*(m_C^*)$, when $\eta < \eta_p$, while $\bar{\pi}_L^*(m_L^*) \geq \bar{\pi}_0^*(m_0^*) > \bar{\pi}_C^*(m_C^*)$, when $\eta \geq \eta_p$. And $\eta_p = arg_{\eta}\{\bar{\pi}_L(m_L^*) = \bar{\pi}_0(m_0^*)\}$. The relationship between $\bar{\pi}_L^*(m_L^*)$ and $\bar{\pi}_0^*(m_0^*)$, depends on the *marginal DfE allowance* η. When η is large, we can draw the *red solid parabola*, while when η is small, we can draw the *red dashed parabola*. This is the proof of Proposition 3.2 (a).

Similarly, we can prove Proposition 3.2 (b) & (d).

Finally, the consumer surplus increases in m. Therefore, $\overline{CS}(m_0^*) > \overline{CS}(m_L^*) > \overline{CS}(m_C^*)$, when $\eta < \eta_L$; while $\overline{CS}(m_C^*) \geq \overline{CS}(m_0^*) > \overline{CS}(m_C^*)$, when $\eta \geq \eta_L$. This is the proof of Proposition 3.2 (c).

Thus, this is the proof of Proposition 3.2. (Q.E.D.)

Proof for Lemma 3.2. The problem of the social welfare can be expressed as follows:

$$SW = \left((1-\lambda)\left(p + \int_p^{\infty}(u-p)g(u)d(u)\right) - c + \lambda v m - (1-m)\varepsilon\right)\overline{D} - \theta m^2.$$

By taking the second order derivation of SW, we have $\frac{\partial^2 SW}{\partial m^2} = 2(\lambda v + \varepsilon)\sigma - 2\theta$. Arrange $\frac{\partial^2 SW}{\partial m^2} < 0$, to make sure SW is a concave function. Thus, we have $\theta > (\lambda v + \varepsilon)\sigma$. By arranging $\frac{\partial SW}{\partial m} = 0$, we have $m_{SW}^* = \frac{\left((1-\lambda)\left(p+\int_p^{\infty}(u-p)g(u)d(u)\right)-c-\varepsilon\right)\sigma+(\lambda v+\varepsilon)(\alpha-\beta p)}{2\theta-2(\lambda v+\varepsilon)\sigma}$.

Thus, this is the proof of Lemma 3.2. (Q.E.D.)

Proof for Lemma 3.3. (a) Comparing m_{SW}^* and m_0^*, we can easily conclude $m_{SW}^* > m_0^*$. From Lemma 3.1, we learn $m_0^* > m_C^*$. Thus, $m_{SW}^* > m_0^* > m_C^*$. (b) Comparing m_{SW}^* and m_L^*, a threshold for η is obtained: $\eta_S = \frac{(\theta-\lambda v\sigma)\left(k-\frac{\varepsilon}{1-\lambda}+\int_p^{\infty}(u-p)g(u)d(u)\right)\sigma+\frac{\varepsilon\theta}{1-\lambda}(\alpha-\beta p)+\left(p-k-\frac{c}{1-\lambda}\right)\varepsilon\sigma^2}{\theta(\alpha-\beta p)+\left((1-\lambda)\left(p+\int_p^{\infty}(u-p)g(u)d(u)\right)-c-\varepsilon\right)\sigma^2}$, which makes m_{SW}^* equal to m_L^*. And we have $m_{SW}^* \left(\begin{smallmatrix}\geq\\=\\<\end{smallmatrix}\right) m_L^*$, if and only if $\eta \left(\begin{smallmatrix}\geq\\=\\<\end{smallmatrix}\right) \eta_S$. (c) Comparing η_S and η_L, we can conclude that $\eta_S > \eta_L$.

This is the proof of Lemma 3.3. (Q.E.D.)

Proof for Proposition 3.3. To better illustrate the social welfare performance under the environmental taxation schemes, we plot the social welfare performance function in a parabola, with the change of m (see Figure 3.2 in the mainbody).

From Lemma 3.3(a), we learn $m_{SW}^* > m_0^* > m_C^*$. Therefore, the social welfare under the ZET scheme is larger than that under the CET scheme. The ZET scheme and the CET scheme cannot achieve the best social welfare performance. When $m_L^* = m_{SW}^*$, the LET scheme can maximize the social welfare. That is, when $\eta = \eta_S$, the social welfare can attain the highest value.

Comparing the expected social welfare performances under the three environmental tax schemes, we conclude the details in Table 3.2 in the mainbody.

This is the proof of Proposition 3.3. (Q.E.D.)

Proof for Proposition 3.4. When considering investment on technology innovation, with the reduced

$\hat{\theta}$, the optimal modularity level of the producer under the LET scheme is denoted as $m_L^{\hat{\theta}*}$ and $m_L^{\hat{\theta}*} = \frac{\left((1-\lambda)(p-k)-c\right)\sigma+\lambda v(\alpha-\beta p)+(1-\lambda)(\alpha-\beta p)\eta}{2(\hat{\theta}-\lambda v\sigma-(1-\lambda)\eta\sigma)}$.

The social welfare with investment on technology innovation is expressed as

$$SW^{\hat{\theta}}(m) = \left((1-\lambda)\left(p+\int_p^{\infty}(u-p)g(u)d(u)\right)-c+\lambda vm-(1-m)\varepsilon\right)\bar{D}-\hat{\theta}m^2-F.$$

The optimal modularity level for maximizing the social welfare performance is denoted as $m_{SW}^{\hat{\theta}*}$. We have $m_{SW}^{\hat{\theta}*} = \frac{\left((1-\lambda)\left(p+\int_p^{\infty}(u-p)g(u)d(u)\right)-c-\varepsilon\right)\sigma+(\lambda v+\varepsilon)(\alpha-\beta p)}{2\hat{\theta}-2(\lambda v+\varepsilon)\sigma}$. Since $\hat{\theta} < \theta$, we can conclude that $m_{SW}^{\hat{\theta}*} > m_{SW}^{*}$.

To achieve the maximum social welfare performance, the policy maker has to set $\eta = \eta_{\hat{\theta}}$ to make $m_L^{\hat{\theta}*}(\eta_{\hat{\theta}}) = m_{SW}^{\hat{\theta}*}$. Thus, $\eta_{\hat{\theta}} = \frac{(\hat{\theta}-\lambda v\sigma)\left(k-\frac{\varepsilon}{1-\lambda}+\int_p^{\infty}(u-p)g(u)d(u)\right)\sigma+\frac{\varepsilon\hat{\theta}}{1-\lambda}(\alpha-\beta p)+\left(p-k+\frac{c}{1-\lambda}\right)\varepsilon\sigma^2}{\hat{\theta}(\alpha-\beta p)+\left((1-\lambda)\left(p+\int_p^{\infty}(u-p)g(u)d(u)\right)-c-\varepsilon\right)\sigma^2}$.

Due to the complexity of $\eta_{\hat{\theta}}$ and η_S, we compare $\eta_{\hat{\theta}}$ and η_S under the LET scheme with and without investment on technology innovation, by adopting numerical examples. Let $\alpha = 1$, $\beta = 0.1, \lambda = 0.1$, $p = 6$, $\sigma = 0.2$, $c = 1.5$, $v = 4.5$, $u = 6.5$, $k = 0.5$, $\theta = 1.5$, $\varepsilon = 0.5$. We assume $\hat{\theta} = 1$. Then, we have $\eta_{\hat{\theta}} = 0.69$ and $EI^{\hat{\theta}}(m_L^{\hat{\theta}*}(\eta_{\hat{\theta}})) = 0.07$.

From the numerical examples, we have $\eta_{\hat{\theta}} < \eta_S$ and $EI^{\hat{\theta}}(m_L^{\hat{\theta}*}(\eta_{\hat{\theta}})) < EI(m_L^{*}(\eta_S))$.

Comparing the social welfare values under the LET scheme before and after the investment on technology innovation, we have $SW^{\hat{\theta}}\left(m_L^{\hat{\theta}*}(\eta_{\hat{\theta}})\right) > SW\left(m_L^{*}(\eta_S)\right)$ if and only if $F < \tilde{F}$. Define $\tilde{F}$ as the threshold, which allows the equal social welfare performances between with and without investment on technology innovation. That is $SW^{\hat{\theta}}\left(m_L^{\hat{\theta}*}(\eta_{\hat{\theta}})\right) = SW\left(m_L^{*}(\eta_S)\right)$. And $\tilde{F} = arg_F\left\{SW^{\hat{\theta}}\left(m_L^{\hat{\theta}*}(\eta_{\hat{\theta}})\right) - SW\left(m_L^{*}(\eta_S)\right) = 0\right\}$.

This is the proof of Proposition 3.4. (Q.E.D.)

Proof for Proposition 3.5. When considering DLD consumer returns, the expected profit of the producer is expressed as follows:

$$\bar{\pi}_L^{\lambda m}(m) = (p-c)\bar{D}-(1-m)\bar{D}p+(1-m)\bar{D}vm-m\bar{D}(k-\eta m)-\theta m^2.$$

We learn $\bar{\pi}_L^{\lambda}(m)$ is a cubic function in m. Based on the characteristics of a cubic function, we can explore the extreme points and the monotonicity. Taking first order derivative yields:

$$\frac{\partial \bar{\pi}_L^{\lambda m}}{\partial m} = \underbrace{-3(\nu-\eta)\sigma}_{\mu_1} m^2 + \underbrace{(2(p+\nu-k)\sigma - 2(\nu-\eta)(\alpha-\beta p) - 2\theta)}_{\mu_2} m + \underbrace{(p+\nu-k)(\alpha-\beta p) - c\sigma}_{\mu_3},$$

where $\begin{cases} \mu_1 = -3(\nu-\eta)\sigma; \\ \mu_2 = 2(p+\nu-k)\sigma - 2(\nu-\eta)(\alpha-\beta p) - 2\theta; \\ \mu_3 = (p+\nu-k)(\alpha-\beta p) - c\sigma. \end{cases}$

We denote $\frac{\partial \bar{\pi}_L^{\lambda m}}{\partial m}$ as $Z(m)$ and consider ν is larger than η in this paper. Thus, we have $\mu_1 < 0,\ \mu_3 < 0$ and ${\mu_2}^2 - 4\mu_1\mu_3 > 0$. Finally, the solutions for $Z(m) = 0$ can be achieved as:

$$m_L^{\lambda_m *} = \begin{cases} m_{L1}^{\lambda_m *} = \frac{-\mu_2 - \sqrt{{\mu_2}^2 - 4\mu_1\mu_3}}{2\mu_1} \\ m_{L2}^{\lambda_m *} = \frac{-\mu_2 + \sqrt{{\mu_2}^2 - 4\mu_1\mu_3}}{2\mu_1} \end{cases},$$

where $m_{L1}^{\lambda_m *} > m_{L2}^{\lambda_m *}$. It can be concluded that $Z(m)$ is monotonically increasing within the interval $[\frac{-\mu_2 + \sqrt{{\mu_2}^2 - 4\mu_1\mu_3}}{2\mu_1}, \frac{-\mu_2 - \sqrt{{\mu_2}^2 - 4\mu_1\mu_3}}{2\mu_1}]$ and $Z(m)$ reaches the high peak at $m_{L1}^{\lambda_m *}$. Therefore, the effective value for $m_L^{\lambda_m *}$ is $\frac{-\mu_2 - \sqrt{{\mu_2}^2 - 4\mu_1\mu_3}}{2\mu_1}$.

That is $m_L^{\lambda_m *} = \frac{(p+\nu-k)\sigma - (\nu-\eta)(\alpha-\beta p) - \theta + \sqrt{\Delta_L}}{3(\nu-\eta)\sigma}$, where $\Delta_L = ((p+\nu-k)\sigma - (\nu-\eta)(\alpha-\beta p) - \theta)^2 + 3\sigma(\nu-\eta)((p+\nu-k)(\alpha-\beta p) - c\sigma)$.

The social welfare under DLD consumer returns is expressed as:

$$SW^{\lambda_m}(m) = \left(\left(p + \int_p^{\infty}(u-p)g(u)d(u)\right)m - c + (1-m)vm - (1-m)\varepsilon\right)\bar{D} - \theta m^2.$$

To maximize the social welfare under DLD consumer returns, we have $m_{SW}^{\lambda_m *} = \frac{(p+\nu+\varepsilon+\int_p^{\infty}(u-p)g(u)d(u))\sigma - \nu(\alpha-\beta p) - \theta + \sqrt{\Delta_{SW}}}{3\nu\sigma}$, where $\Delta_{SW} = \left(\sigma(p+\nu+\varepsilon+\int_p^{\infty}(u-p)g(u)d(u)) - \nu(\alpha-\beta p) - \theta\right)^2 + 3\nu\sigma\left(\left(p+\nu+\varepsilon+\int_p^{\infty}(u-p)g(u)d(u)\right)(\alpha-\beta p) - (c+\varepsilon)\sigma\right)$. By arranging $m_L^{\lambda_m *}(\eta_{\lambda_m}) = m_{SW}^{\lambda_m *}$, we have $\eta_{\lambda_m} = \frac{(k+\int_p^{\infty}(u-p)g(u)d(u))\nu\sigma + \nu\sqrt{\Delta_{SW}} - \nu\sqrt{\Delta_L}}{(p+\nu+\varepsilon+\int_p^{\infty}(u-p)g(u)d(u))\sigma - \theta + \sqrt{\Delta_{SW}}}$.

Due to the complexity of $m_L^{\lambda_m *}$ and $m_{SW}^{\lambda_m *}$, we adopt the numerical examples to compare the optimal modularity levels and social welfare performances between the case of DLD consumer returns and the benchmark case. Let $\alpha = 1$, $\beta = 0.1, \lambda = 0.1$, $p = 6$, $\sigma = 0.2$, $c = 1.5$, $v = 4.5$, $u =$

6.5, $k = 0.5$, $\theta = 1.5$, $\varepsilon = 0.5$.

Case of DLD Consumer Returns

We first calculate $m_{SW}^{\lambda_m *}$, η_{λ_m}, and $SW^{\lambda_m}(m_L^{\lambda_m *}(\eta_{\lambda_m}))$ under the case of DLD consumer returns. We have $m_{SW}^{\lambda_m *}$= 0.93, η_{λ_m}= 0.84, $SW^{\lambda_m}(m_L^{\lambda_m *}(\eta_{\lambda_m}))$= 1.5172. Thus, we have λ_m= $1 - m_{SW}^{\lambda_m *}$= 0.07. When η_{λ_m}= 0.84, $t_L(\eta_{\lambda_m}) =$ -0.28 per unit. Since $t_L(\eta_{\lambda_m})$ is negative, which implies the government will provide the producer with a pure environmental sponsorship. When η_{λ_m}= 0.84, $EI^{\lambda_m}(m_L^{\lambda_m *}(\eta_{\lambda_m})) = 0.02$.

Benchmark Case (i.e., Fixed Consumer Returns Rate)

We first examine how the results in the benchmark case change with the exogenous λ_F. For notational purpose, λ_F represents the fixed consumer returns rate in the benchmark case. (See Table A2)

Table A2. The change of λ_F in the benchmark case.

λ_F	0	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
$m_L^{\lambda_F *}(\eta_S)$	0.39	0.42	0.44	0.46	0.49	0.52	0.55	0.59	0.63	0.67	0.71
η_S	0.68	0.69	0.71	0.73	0.75	0.78	0.81	0.84	0.88	0.94	1.00
$SW(m_L^{\lambda_F *}(\eta_S))$	2.0161	1.9035	1.7924	1.6829	1.5751	1.4693	1.3657	1.2646	1.1663	1.0711	0.9796

From Table A2, we can see $SW(m_L^{\lambda_F *}(\eta_S))$ is decreasing with λ_F. When λ_F locates at a point between 0.2 and 0.25, we can have $SW^{\lambda_m}(m_L^{\lambda_m *}(\eta_{\lambda_m}))$=$SW(m_L^{\lambda_F *}(\eta_S))$. We find when λ_F= 0.23, and η_S= 0.76, $SW^{\lambda_m}(m_L^{\lambda_m *}(\eta_{\lambda_m}))$=$SW(m_L^{\lambda_F *}(\eta_S))$. When λ_F= 0.23 and η_S= 0.76, we have $t_L(\eta_S) =$ 0.11 per unit. Since $t_L(\eta_S)$ is positive, which implies the producer need pay an environment tax to the government. When λ_F= 0.23 and η_S= 0.76, we have $EI(m_L^{\lambda_F *}(\eta_S))$= 0.12.

Comparison of the Two Cases

The comparison of two cases is shown in Table A3.

Table A3. Comparisons between the two cases when the social welfare performances are equal.

	DLD Consumer Returns	Benchmark Case
λ	0.07	0.23

m	0.93	0.51
η	0.84	0.76
$t_L(\eta_S)$	-0.28	0.11
SW	1.52	1.52
EI	0.02	0.12

From Table A3, we learn that when $SW^{\lambda_m}(m_L^{\lambda_m *}(\eta_{\lambda_m}))$=$SW(m_L^{\lambda_F *}(\eta_S))$, the optimal DfE level of the producer under DLD consumer returns case tends to be high, i.e., $m_L^{\lambda_m *}(\eta_{\lambda_m}) > m_L^{\lambda_F *}(\eta_S)$. The government need provide a much higher *marginal DfE allowance*, i.e., $\eta_{\lambda_m} > \eta_S$. The environmental impacts are reduced, i.e., $EI^{\lambda_m}(m_L^{\lambda_m *}(\eta_{\lambda_m})) < EI(m_L^{\lambda_F *}(\eta_S))$.

Moreover, when λ_F is small, $SW^{\lambda_m}(m_L^{\lambda_m *}(\eta_{\lambda_m})) < SW(m_L^{\lambda_F *}(\eta_S))$. When λ_F is medium $SW^{\lambda_m}(m_L^{\lambda_m *}(\eta_{\lambda_m})) = SW(m_L^{\lambda_F *}(\eta_S))$. When λ_F is sufficiently large, $SW^{\lambda_m}(m_L^{\lambda_m *}(\eta_{\lambda_m})) > SW(m_L^{\lambda_F *}(\eta_S))$. Define λ_F is the fixed consumer return rate and $\tilde{\lambda}_F$ is the threshold, which allows the equal social welfare performances in the DLD consumer returns case and the benchmark case. And $\tilde{\lambda}_F = arg_{\lambda}\left\{SW^{\lambda_m}(m_L^{\lambda_m *}(\eta_{\lambda_m})) - SW(m_L^{\lambda_F *}(\eta_S)) = 0\right\}$. Therefore, $SW^{\lambda_m}(m_L^{\lambda_m *}(\eta_{\lambda_m})) > SW(m_L^{\lambda_F *}(\eta_S))$, *if and only if* $\lambda_F > \tilde{\lambda}_F$.

Thus, this is the proof of Proposition 3.5. (Q.E.D.)

Proof for Proposition 3.6. Considering the revenue tax on the sold products, the expected profit of the producer can be expressed as follows:

$$\bar{\pi}^{\xi}(m) = (p-c)\bar{D} - \lambda\bar{D}p + \lambda\bar{D}vm - (1-\lambda)\bar{D}t - (1-\lambda)\bar{D}\xi p - \theta m^2.$$

Under the LET scheme, $\bar{\pi}_L^{\xi}(m)$ is a concave function in m, if and only if

$\theta > \lambda v\sigma + (1-\lambda)\eta\sigma$. When $\theta > \lambda v\sigma + (1-\lambda)\eta\sigma$, the optimal modularity level is $m_L^{\xi *} = \frac{(1-\lambda)((1-\xi)p-k)\sigma+\lambda v(\alpha-\beta p)+(1-\lambda)(\alpha-\beta p)\eta-c\sigma}{2(\theta-\lambda v\sigma)-2(1-\lambda)\eta\sigma}$.

The expected profit of the social welfare is expressed as follows:

$SW^{\xi}(m) = \left((1-\lambda)\left(p + \int_p^{\infty}(u-p)g(u)d(u)\right) - c + \lambda vm - (1-m)\varepsilon\right)\bar{D} - \theta m^2.$

To maximize the social welfare performance under the revenue tax, we have $m_{SW}^{\xi *} = \frac{\left((1-\lambda)\left(p+\int_p^{\infty}(u-p)g(u)d(u)\right)-c-\varepsilon\right)\sigma+(\lambda v+\varepsilon)(\alpha-\beta p)}{2\theta-2(\lambda v+\varepsilon)\sigma}$. We find $m_{SW}^{\xi *} = m_{SW}^{*}$, and $m_{SW}^{\xi *}$ is not affected by ξ.

To achieve the maximal social welfare performance, the policy maker has to set $\eta = \eta_{\xi}$ to make $m_L^{\xi *} = m_{SW}^{\xi *}$. Thus, $\eta_{\xi} = \frac{(\theta-\lambda v\sigma)\left(\xi p+k-\frac{\varepsilon}{1-\lambda}+\int_p^{\infty}(u-p)g(u)d(u)\right)\sigma+\frac{\varepsilon\theta}{1-\lambda}(\alpha-\beta p)+\left((1-\xi)p-k+\frac{c}{1-\lambda}\right)\varepsilon\sigma^2}{\theta(\alpha-\beta p)+\left((1-\lambda)\left(p+\int_p^{\infty}(u-p)g(u)d(u)\right)-c-\varepsilon\right)\sigma^2}$.

Comparing η_{ξ} and η_S, we have $\eta_{\xi} > \eta_S$. Since $m_{SW}^{\xi *} = m_{SW}^{*}$, we have $SW^{\xi}(m_L^{\xi *}(\eta_{\xi})) = SW(m_L^{*}(\eta_S))$.

This is the proof of Proposition 3.6. (Q.E.D.)

Proof for Proposition 3.7. When considering QET scheme, the expected profit of the producer is expressed as follows:

$\bar{\pi}_Q(m) = (p-c)\bar{D} - \lambda\bar{D}p + \lambda\bar{D}vm - (1-\lambda)\bar{D}(k-\eta m^2) - \theta m^2.$

We learn $\bar{\pi}_Q(m)$ is a cubic function in m. Based on the characteristics of a cubic function, we can explore the extreme points and the monotonicity. Taking first order derivative yields:

$$\frac{\partial\bar{\pi}_Q(m)}{\partial m} = \underbrace{3(1-\lambda)\eta\sigma}_{a_1} m^2 + \underbrace{(2(1-\lambda)(\alpha-\beta p)\eta + 2\lambda v\sigma - 2\theta)}_{a_2} m + \underbrace{(1-\lambda)(p-k)\sigma - c\sigma + \lambda v(\alpha-\beta p)}_{a_3},$$

where $\begin{cases} a_1 = 3(1-\lambda)\eta\sigma; \\ a_2 = 2(1-\lambda)(\alpha-\beta p)\eta + 2\lambda v\sigma - 2\theta; \\ a_3 = (1-\lambda)(p-k)\sigma - c\sigma + \lambda v(\alpha-\beta p). \end{cases}$

We can obviously see that $a_1 > 0$, and $a_3 > 0$. Finally, the solutions for $\frac{\partial\bar{\pi}_Q(m)}{\partial m} = 0$ can be achieved as $m_Q^* = \begin{cases} m_{Q1}^* = \frac{-a_2-\sqrt{{a_2}^2-4a_1a_3}}{2a_1} \\ m_{Q2}^* = \frac{-a_2+\sqrt{{a_2}^2-4a_1a_3}}{2a_1} \end{cases}$, where $m_{Q1}^* < m_{Q2}^*$. Since $a_1 > 0$, we have m_{Q1}^* is the local maximal point and m_{Q2}^* is the local minimal point. Therefore, the effective solution for maximizing the producer's expected profit is $\frac{-a_2-\sqrt{{a_2}^2-4a_1a_3}}{2a_1}$.

When considering QET scheme, the expected social welfare can be expressed as follows:

$SW^{Q}(m) = \left((1-\lambda)\left(p + \int_p^{\infty}(u-p)g(u)d(u)\right) - c + \lambda vm - (1-m)\varepsilon\right)\bar{D} - \theta m^2.$

We can see that the social welfare performance $SW^Q(m)$ is not affected by the form of the environmental tax. The optimal modularity level for maximizing the social welfare performance is denoted as m_{SW}^{Q*} and $m_{SW}^{Q*} = \frac{\left((1-\lambda)\left(p+\int_p^{\infty}(u-p)g(u)d(u)\right)-c-\varepsilon\right)\sigma+(\lambda v+\varepsilon)(\alpha-\beta p)}{2\theta-2(\lambda v+\varepsilon)\sigma}$. We can see $m_{SW}^{Q*} = m_{SW}^{*}$ (i.e., $m_L^*(\eta_S)$). Thus, it is easy to conclude that $SW^Q(m_{SW}^{Q*}) = SW(m_{SW}^{*})$.

To allow $m_Q^*(\eta) = m_{SW}^{Q*}$, the policy maker need provides an appropriate η to achieve the optimal modularity level for maximizing the social welfare performance.

Define η_Q as the threshold, which allows the producer's optimal modularity level under the QET scheme to be equal to the optimal modularity level for maximizing the social welfare under the QET scheme, i.e., $m_Q^*(\eta_Q) = m_{SW}^{Q*}$, and $\eta_Q = arg_{\eta}\{m_Q^*(\eta) - m_{SW}^{Q*} = 0\}$. Finally, we have $SW^Q(m_Q^*(\eta_Q)) = SW(m_L^*(\eta_S))$.

Due to the complexity of the closed-form analytical results in the QET scheme, we adopt numerical analyses to compare η_Q and η_S, in the QET and LET schemes. Let $\alpha = 1$, $\beta = 0.1$, $\lambda = 0.1$, $p = 6$, $\sigma = 0.2$, $c = 1.5$, $v = 4.5$, $u = 6.5$, $k = 0.5$, $\theta = 1.5$, $\varepsilon = 0.5$. We get $\eta_Q = 0.88$ and $\eta_S = 0.71$. Thus, $\eta_Q > \eta_S$.

This is the proof of Proposition 3.7. (Q.E.D.)

Appendix II: Proofs for Lemmas and Propositions in Chapter 4

Proof of Lemma 4.1:

For $i \in (1, 2)$, we have: $\hat{w}_i = \left(\frac{w - a(1-\lambda_i)}{\lambda_i}\right)$. Differentiating $\hat{w}_i$ with respect to λ_i yields $\frac{\partial \hat{w}_i}{\partial \lambda_i} = -\left(\frac{w-a}{\lambda_i^{\,2}}\right)$. Since $w > a$, we have: $\frac{\partial \hat{w}_i}{\partial \lambda_i} < 0$. This proves Part (a). For Part (b), since $s_i = \frac{r - \hat{w}_i}{r + h - v}$ and $\frac{\partial \hat{w}_i}{\partial \lambda_i} < 0$, we have $\frac{\partial s_i}{\partial \lambda_i} > 0$. (Q.E.D.)

Proof of Lemma 4.2: At Time $i, i \in (1, 2)$, it is shown from (4.6) that $\hat{q}_i^* = \mu_i + \sigma_i \Phi^{-1}[s_i]$. From (4.3), we have $\hat{q}_i = \lambda_i q_i$. Thus, the apparel manufacturer's optimal fabric ordering quantity is given by: $q_i^* = \frac{1}{\lambda_i} \hat{q}_i^* = \frac{\mu_i + \sigma_i \Phi^{-1}[s_i]}{\lambda_i}$. (Q.E.D.)

Proof of Lemma 4.3: We learn $EVLR_M = E[\pi_{M,2}]^* - E[\pi_{M,1}]^*$, $EVLR_S = E[\pi_{S,2}]^* - E[\pi_{S,1}]^*$, $EVLR_{SC} = E[\pi_{SC,2}]^* - E[\pi_{SC,1}]^*$. Substituting the analytical expressions into the above equations yields $EVLR_M = T - (\hat{w}_2 - \hat{w}_1)\mu_1$, $EVLR_S = (w-m)(Y\mu_1 - L)$, and $EVLR_{SC} = ((w-m)Y - \hat{w}_2 + \hat{w}_1)\mu_1 + (T - (w-m)L)$. (Q.E.D.)

Proof of Proposition 4.1: (a) Since $EVLR_M = T - (\hat{w}_2 - \hat{w}_1)\mu_1$ and $(\hat{w}_2 - \hat{w}_1 > 0$, simple algebra with rearranging terms easily gives the following relationship: $EVLR_M > 0 \Leftrightarrow \mu_1 < \bar{\mu}_1 \equiv \frac{T}{\hat{w}_2 - \hat{w}_1}$. (b) As $EVLR_S = (w-m)(Y\mu_1 - L)$, $(w-m) > 0$ and $Y > 0$, we can easily see that $EVLR_S > 0 \Leftrightarrow \mu_1 > \underline{\mu}_1 \equiv \frac{L}{Y}$. (Q.E.D.)

Proof of Proposition 4.2:

(a) If $\underline{\mu}_1 < \mu_1 < \bar{\mu}_1$, we have $EVLR_M > 0$ and $EVLR_S > 0$. Since $EVLR_{SC} = EVLR_M + EVLR_S$, we have $EVLR_{SC} > 0$ if $\underline{\mu}_1 < \mu_1 < \bar{\mu}_1$.

(b) Directly checking the closed-form analytical expression of $EVLR_{SC}$, we can see that

$EVLR_{SC} > 0 \Leftrightarrow ((w-m)Y - \hat{w}_2 + \hat{w}_1)\mu_1 + (T-(w-m)L) > 0$. (Q.E.D.)

Proof of Lemma 4.4: As $((w-m)Y - \hat{w}_2 + \hat{w}_1)\mu_1 + (T-(w-m)L) > 0 \Leftrightarrow EVLR_{SC} > 0$ and "$\underline{\mu}_1 < \mu_1 < \overline{\mu}_1$ does not hold" implies that the scenario with "$EVLR_M > 0$ and $EVLR_S > 0$" does not occur (P.S.: Proposition 4.2), we must have either one of the following situation: (i) The apparel manufacturer is benefited but the fabric supplier suffers. (ii) The apparel manufacturer suffers but the fabric supplier is benefited. (Q.E.D.)

Proof of Proposition 5.3:

(a) DP Case 1: In this case, the apparel manufacturer is benefited and the fabric supplier suffers. Thus, the apparel manufacturer should contribute $DP_{M\to S}$ and the respective interest generated amounts to $\xi DP_{M\to S}$. For the apparel manufacturer, after contributing this deposit payment, its benefit after adopting the lead time reduction scenario is: $\Delta_{SC} - l_S - \xi DP$ and we require it to be positive. Thus, we have:

$\Delta_{SC} - l_S - \xi DP_{M\to S} > 0$. (A1)

For the fabric supplier, to ensure it does not suffer a loss after lead time reduction, we require: $\xi DP > l_S$. (A2)

Combining (A1) and (A2) yields $\frac{l_S}{\xi} < DP_{M\to S} < \frac{\Delta_{SC} - l_S}{\xi}$, which is the analytical condition for the establishment of the win-win situation. Part (b), similarly, in DP Case 2, we can prove that the condition for win-win is $\frac{l_M}{\xi} < DP_{S\to M} < \frac{\Delta_{SC} - l_M}{\xi}$. (Q.E.D.)

Proof of Proposition 5.4:

(a) We have $EHTE^{(LTR)} = TP_2 - TP_1$, $TP_1 = \left(\frac{\mu_1 + \sigma_1\Phi^{-1}[s_1]}{\lambda_1}\right)Q_1$ and $TP_2 = \left(\frac{\mu_1 + \sigma_2\Phi^{-1}[s_2]}{\lambda_2}\right)Q_2$.

Putting TP_1 and TP_2 into $EHTE^{(LTR)}$ immediately gives $EHTE^{(LTR)}$ $= \left(\frac{Q_2}{\lambda_2}\right)(\mu_1 + \sigma_2\Phi^{-1}[s_2]) - \left(\frac{Q_1}{\lambda_1}\right)(\mu_1 + \sigma_1\Phi^{-1}[s_1])$.

(b) From the analytical expression of $EHTE^{(LTR)}$, we can easily find that if $\mu_1 > \underline{\mu}_1$, we have $EHTE^{(LTR)} > 0$. Furthermore, when $\mu_1 \leq \underline{\mu}_1$, we can prove by rearranging terms that (i) $EHTE^{(LTR)} > 0$ if and only if $\frac{Q_2}{Q_1} > \left(\frac{\lambda_2(\mu_1 + \sigma_1\Phi^{-1}[s_1])}{\lambda_1(\mu_1 + \sigma_2\Phi^{-1}[s_2])}\right)$, and (ii) $EHTE^{(LTR)} \leq 0$ if and only if $\frac{Q_2}{Q_1} \leq \left(\frac{\lambda_2(\mu_1 + \sigma_1\Phi^{-1}[s_1])}{\lambda_1(\mu_1 + \sigma_2\Phi^{-1}[s_2])}\right)$. (Q.E.D.)

Proof of Proposition 5.5:

(a) Under the lead time reduction ordering scenario (i.e. ordering at Time 2), in the presence of the environment taxation scheme as well as the ability to reduce Q_2 from the original Q_2 to $\hat{Q}_2$, we denote the EVLR for the fabric supplier by $EVLR_S{}^{(ET)}(\hat{Q}_2)$, and we can easily see that it is given as follows.

$$EVLR_S{}^{(ET)}(\hat{Q}_2)$$

$$= (w-m)(Y\mu_1 - L) - \left(\left(\frac{\hat{Q}_2}{\lambda_2}\right)(\mu_1 + \sigma_2\Phi^{-1}[s_2]) - \left(\frac{Q_1}{\lambda_1}\right)(\mu_1 + \sigma_1\Phi^{-1}[s_1])\right) - \frac{\varepsilon(Q_2 - \hat{Q}_2)^2}{2}.$$

Checking the 2nd order derivative shows that $\frac{\partial^2 EVLR_S{}^{(ET)}(\hat{Q}_2)}{\partial \hat{Q}_2{}^2} < 0$ which means it is a concave function. Solving $\frac{\partial EVLR_S{}^{(ET)}(\hat{Q}_2)}{\partial \hat{Q}_2} = 0$ yields $\hat{Q}_2^* = Q_2 - \frac{t}{\varepsilon}\left(\frac{\mu_1 + \sigma_2\Phi^{-1}[s_2]}{\lambda_2}\right)$.

(b) In the presence of the environment tax, it is optimal to reduce Q_2 to $\hat{Q}_2^*$. Thus, we have

$$EHTE^{(LTR)}(\hat{Q}_2^*) = \left(\frac{\hat{Q}_2^*}{\lambda_2}\right)(\mu_1 + \sigma_2\Phi^{-1}[s_2]) - \left(\frac{Q_1}{\lambda_1}\right)(\mu_1 + \sigma_1\Phi^{-1}[s_1]).$$

It is easy to find that $EHTE^{(LTR)}(\hat{Q}_2^*) = 0$ if and only if $t = \varepsilon(Q_2 - \beta Q_1) = \hat{t}$. A further checking reveals that $EHTE^{(LTR)}(\hat{Q}_2^*)\begin{cases} > 0, if\ t < \hat{t} \\ = 0\ if\ t = \hat{t} \\ < 0, if\ t > \hat{t} \end{cases}$. (Q.E.D.)

Appendix III: Proofs for Lemmas and Propositions in Chapter 5

Proof of Lemma 5.1: In the decentralized setting, the sequence of the event is: i) the remanufacturer first determines B_{RM}; ii) For given B_{RM}, the fashion retail brand determines the optimal promotion effort. $\pi_R(\xi)$ is a concave function of ξ. Thus, by solving the first order condition, we have the optimal fashion retail brand's promotion effort for a given B_{RM}: $\hat{\xi}_R = \arg_{\xi}\{\frac{\partial \pi_R(\xi)}{\partial \xi} = 0\} = \frac{(\bar{p} + \alpha \bar{B})b}{k}$. For the remanufacturer, $\pi_{RM}(B_{RM}; \xi = \hat{\xi}_R)$ is concave in B_{RM}. The optimal B_{RM} and ξ under the decentralized basic model are given by: $B_{RM}^* = \frac{v}{2} - \frac{\Delta}{2\alpha\tau}$, and $\xi_R^* = \frac{b}{k}\left(\bar{p} + \alpha \bar{B}_R^*\right)$, where $\Delta = \frac{ak}{b^2} + \bar{p} + \alpha(1-\tau)B_{CH}$ and $\bar{B}_R^* = (B_{RM}^*\tau + B_{CH}(1-\tau))$. $B_{RM}^* < v$, is always true. Thus, we have Lemma 5.1. (Q.E.D.)

Proof of Lemma 5.2: In the centralized setting, the total expected benefit of the supply chain is expressed as $\pi_{SC}(\xi) = \pi_R(\xi) + \pi_{RM}(\xi) + \pi_C(\xi)$. Checking the structural property of $\pi_{SC}(\xi)$, we learn that $\pi_{SC}(\xi)$ is concave in ξ. The optimal ξ which maximizes the supply chain's expected benefit under the centralized basic model is given by: $\xi_{SC}^* = \frac{b}{k}\left[\bar{p} + \alpha\tau v + \alpha(1-\tau)(B_{CH} + C)\right]$. We have proven Lemma 5.2. (Q.E.D.)

Proof of Proposition 5.1: Combining Lemmas 5.1 and 5.2, we can compare the relationships among ξ_R^*, and ξ_{SC}^*. From Lemma 4.1, we have $\xi_R^* = \frac{b}{k}\left(\bar{p} + \alpha \bar{B}_R^*\right)$, where $\alpha \bar{B}_R^* = \alpha\tau B_{RM}^* + \alpha(1-\tau)B_{CH}$. Obviously, $\alpha \bar{B}_R^* < \alpha\tau v + \alpha(1-\tau)(B_{CH} + C)$. Thus, we have $\xi_R^* < \xi_{SC}^*$, for any $B_{RM} \leq v$. After further checking, we have $\pi_{SC}(\xi_R^*) < \pi_{SC}(\xi_{SC}^*)$, and hence Proposition 5.1 is proven. (Q.E.D.)

Proof of Lemma 5.3: In coordination, the charity organization will help share the promotion cost of the fashion retail brand. The fashion retail brand has to spend $\beta\frac{k(\xi_{R,\beta})^2}{2}$ and $0 < \beta \leq 1$, while the charity organization shares $(1-\beta)\frac{k(\xi_{R,\beta})^2}{2}$. The fashion retail brand's profit under the (collection) effort cost sharing (ECS) contract is $\pi_R(\xi_{R,\beta}) = \overline{p}D + B_{RM}\tau Q + B_{CH}(1-\tau)Q - \beta\frac{k(\xi_{R,\beta})^2}{2}$. The supply chain profit function remains unchanged. Following the same step of Lemma 5.1, we define $\Delta_\beta = \frac{ak\beta}{b^2} + \overline{p} + \alpha(1-\tau)B_{CH}$. The equilibrium B_{RM} and promotion effort under the decentralized supply chain are given by: $B^*_{RM,\beta} = \frac{v}{2} - \frac{\Delta_\beta}{2\alpha\tau}$, and $\xi^*_{R,\beta} = \frac{b}{k}\left(\overline{p} + \alpha\overline{B}^*_{R,\beta}\right)$, where $\overline{B}^*_{R,\beta} = B^*_{RM,\beta}\tau + B_{CH}(1-\tau)$. Since $0 < \beta \leq 1$, we have $\Delta_\beta \geq \Delta$, where $\Delta = \frac{ak}{b^2} + \overline{p} + \alpha(1-\tau)B_{CH}$ (see Lemma 5.1). Therefore, we have $B^*_{RM,\beta} \geq B^*_{RM}$ and $\xi^*_{R,\beta} \geq \xi^*_R$. Thus, we have Lemma 5.3. (Q.E.D.)

Proof of Proposition 5.2: For profit-coordination, we set the ECS contract to achieve $\xi^*_{R,\beta} = \xi^*_{SC}$. That is $\frac{b}{k}\left(\overline{p} + \alpha\overline{B}^*_{R,\beta}\right) = \frac{b}{k}\left[\overline{p} + \alpha\tau v + \alpha(1-\tau)(B_{CH} + C)\right]$, where $\Delta_\beta = \frac{ak\beta}{b^2} + \overline{p} + \alpha(1-\tau)B_{CH}$, $B^*_{RM,\beta} = \frac{v}{2} - \frac{\Delta_\beta}{2\alpha\tau}$, $\overline{B}^*_{R,\beta} = \tau B^*_{RM,\beta} + (1-\tau)B_{CH}$. Solving the above function yields $\beta = \frac{\overline{p} + \alpha\tau v + \alpha(1-\tau)B_{CH}}{2\left[\overline{p} + \alpha\tau v + \alpha(1-\tau)(B_{CH} + C)\right] + akb^{-2}}$. Thus, the charity organization has to share $1-\beta$ proportion of the total UAC promotion cost to achieve profit coordination. (Q.E.D)

Proposition 5.3. *With the coupon offering, we have: (a)* $B^*_{RM,S} \begin{pmatrix} > \\ = \\ < \end{pmatrix} B^*_{RM}$ *if and only if* $S \begin{pmatrix} > \\ = \\ < \end{pmatrix} 1 - \frac{ak}{\alpha\eta\overline{p}}\left(\frac{\hat{b}^2 - b^2}{\hat{b}^2 b^2}\right)$. *(b)* $\xi^*_{R,S} > \xi^*_R$. *(c)* $\pi_{R,S}(\xi^*_{R,S}) > \pi_{R,S}(\xi^*_R)$.

Proposition 5.4. *(a)The optimal* ξ *which maximizes the supply chain's expected profit under the centralized setting is given by:* $\xi^*_{SC,S} = \frac{\hat{b}}{k}\left[(1+\alpha\eta)\overline{p} + \alpha\tau v + \alpha(1-\tau)(B_{CH} + C)\right]$. *(b) When comparing with the basic model, we have* $\xi^*_{SC,S} > \xi^*_{SC}$ *and* $\pi_{SC,S}(\xi^*_{SC,S}) > \pi_{SC}(\xi^*_{SC})$.

Proofs of Propositions 5.3 and 5.4:

We denote the market demand attracted by UAC in this scenario by $\hat{D}$ which is expressed in the following:

$\hat{D} = a + \hat{b}\xi$,

where $\hat{b} > b$ is the parameter which captures the increased sensitivity of promotion effort towards market demand under the case with coupon offering.

Since the coupon can benefit the consumers, we define the extra consumer surplus (denoted as $EXCS$) as follows:

$EXCS = \eta QS\overline{p}$, where $\hat{Q} = \alpha(a + \hat{b}\xi)$.

Observe that $\alpha(a + \hat{b}\xi)$ is the expected amount of collected used apparel in the presence of coupon, η is the redeem rate, and $S \cdot \overline{p}$ is the unit benefit to the consumers who give the used apparel to the fashion retail brand.

The fashion retail brand's profit under the coupon offering scenario is expressed as:

$$\pi_{R,S}(\xi) = \overline{p}D + B_{RM}\tau Q + B_{CH}(1-\tau)Q - K(\xi) + \eta Q(1-S)\overline{p}$$

$$= (1+\eta\alpha(1-S))\overline{p}D + B_{RM}\tau Q + B_{CH}(1-\tau)Q - K(\xi) .$$

The remanufacturer's profit under the coupon offering scenario is given in the following:

$$\pi_{RM,S}(\xi) = (v - B_{RM})\tau\hat{Q} .$$

The supply chain's benefit under the coupon offering scenario is shown below:

$$\pi_{SC,S}(\xi) = \overline{p}D + (B_{CH} + C)(1-\tau)Q + v\tau Q + \eta Q\overline{p} - K(\xi) .$$

Define: $\Delta_S = \frac{ak}{\hat{b}^2} + (1+\alpha\eta(1-S))\overline{p} + \alpha(1-\tau)B_{CH}$.

Under the coupon offering scenario, denote the re-manufacturer's payment to the fashion retail brand for each unit of used apparel sent for re-manufacturing and the fashion retail brand's unit good-name benefit from donation by $\xi_{R,S}$ and $B_{RM,S}$, respectively. It is easy to find that the optimal $\xi_{R,S}$ and $B_{RM,S}$ are given as follows:

$$B^*_{RM,S} = \frac{v}{2} - \frac{\Delta_S}{2\alpha\tau} ,$$

$$\xi^*_{R,S} = \frac{\hat{b}}{k}\left((1+\alpha\eta(1-S))\,\overline{p} + \alpha\overline{B}^*_{R,S}\right) ,$$

where $\bar{B}^*_{R,S} = (\tau B^*_{RM,S} + (1-\tau)B_{CH})$.

We learn from Lemma 5.1 that $B^*_{RM} = \frac{v}{2} - \frac{\Delta}{2\alpha\tau}$ and $\Delta = \frac{ak}{b^2} + \bar{p} + \alpha(1-\tau)B_{CH}$. By comparing $B^*_{RM,S}$ and B^*_{RM}, we have $B^*_{RM,S} - B^*_{RM} = \frac{1}{2\alpha\tau}(\frac{ak}{b^2} - \frac{ak}{\hat{b}^2} - \alpha\eta(1-S)\bar{p})$. Therefore, $B^*_{RM,S} \begin{pmatrix} > \\ = \\ < \end{pmatrix} B^*_{RM}$ if and only if $S \begin{pmatrix} > \\ = \\ < \end{pmatrix} 1 - \frac{ak}{\alpha\eta\bar{p}}(\frac{\hat{b}^2 - b^2}{\hat{b}^2 b^2})$.

From Lemma 5.1, we have $\xi^*_R = \frac{b}{k}\left(\bar{p} + \alpha\bar{B}^*_R\right)$ and $\bar{B}^*_R = (\tau B^*_{RM} + (1-\tau)B_{CH})$. Putting $\bar{B}^*_R$ into ξ^*_R yields $\xi^*_R = \frac{b}{2k}\left[\bar{p} + \alpha\tau v + \alpha(1-\tau)B_{CH}\right] - \frac{a}{2b}$. Similarly, putting $\bar{B}^*_{R,S}$ into $\xi^*_{R,S}$, we have $\xi^*_{R,S} = \frac{\hat{b}}{2k}\left[(1+\alpha\eta(1-S))\bar{p} + \alpha\tau v + \alpha(1-\tau)B_{CH}\right] - \frac{a}{2\hat{b}}$. By comparing $\xi^*_{R,S}$ and ξ^*_R, we have:

$\xi^*_{R,S} - \xi^*_R = \frac{\hat{b}}{2k}\left[\bar{p} + \alpha\tau v + \alpha(1-\tau)B_{CH}\right] - \frac{b}{2k}\left[\bar{p} + \alpha\tau v + \alpha(1-\tau)B_{CH}\right] + \frac{a}{2b} - \frac{a}{2\hat{b}} + \frac{\hat{b}}{2k}\left[\alpha\eta(1-S)\bar{p}\right]$. Since $\hat{b} > b$, we have $\frac{\hat{b}}{2k}\left[\bar{p} + \alpha\tau v + \alpha(1-\tau)B_{CH}\right] > \frac{b}{2k}\left[\bar{p} + \alpha\tau v + \alpha(1-\tau)B_{CH}\right]$ and $\frac{a}{2b} > \frac{a}{2\hat{b}}$. Obviously, we have $\xi^*_{R,S} - \xi^*_R > 0$.

From $\pi_{R,S}(\xi) = (1 + \eta\alpha(1-S))\bar{p}D + B_{RM}\tau Q + B_{CH}(1-\tau)Q - K(\xi)$, we learn that the fashion retail brand will acquire an extra income from consumer coupon offering and the extra income is $\eta\alpha(1-S)\bar{p}D$. Comparing the maximal profits with and without consumer coupon offering, it is easy to find that $\pi_{R,S}(\xi^*_{R,S}) > \pi_{R,S}(\xi^*_R)$. This completes the proof of Proposition 5.3.

Following the proof of Proposition 5.2, we can prove Proposition 5.4. (Q.E.D.)

Proposition 5.5. *If* $v \le v_{\overline{RM}}$*, we have: (a) The equilibrium* $\xi^*_{R(\overline{RM})}$ *under the decentralized setting is given by* $\xi^*_{R(\overline{RM})} = \frac{b}{k}\left[\bar{p} + \alpha(1-\tau)B_{CH}\right]$. *(b)* $\xi^*_{R(\overline{RM})} > \xi^*_R$. *(c)* $\pi_R(\xi^*_{R(\overline{RM})}) > \pi_R(\xi^*_R)$.

Proposition 5.6. *(a)The optimal* ξ *which maximizes the supply chain's expected profit under the centralized setting is given by:* $\xi^*_{SC(\overline{RM})} = \frac{b}{k}\left[\bar{p} + \alpha(1-\tau)(B_{CH} + C)\right]$. *(b) When comparing with the basic model, we have* $\xi^*_{SC(\overline{RM})} < \xi^*_{SC}$*, and* $\pi_{SC}(\xi^*_{R(\overline{RM})}) < \pi_{SC}(\xi^*_R)$.

Proofs of Propositions 5.5 and 5.6:

Profit functions of the fashion retail brand and the supply chain under "No RM" model are respectively expressed as follows (we use the subscribe $(\overline{RM})$ to denote the case with "No RM"):

$\pi_{R(\overline{RM})}(\xi) = \bar{p}D + B_{CH}(1-\tau)Q - K(\xi)$.

$\pi_{SC(\overline{RM})}(\xi) = \bar{p}D + (B_{CH}+C)(1-\tau)Q - K(\xi)$.

Define: $v_{\overline{RM}} = \dfrac{1}{\alpha\tau}\left[\dfrac{ak}{b^2} + \bar{p} + \alpha(1-\tau)B_{CH}\right]$, where $v_{\overline{RM}}$ is the threshold for $B^*_{RM} = 0$. Following the same logic of Propositions 5.3 and 5.4, we can prove Propositions 5.5 and 5.6. (Q.E.D)

Proposition 5.7. *In the decentralized supply chain, we have (a) is* $B^*_{RM,EC} = \dfrac{v}{2} - \dfrac{1}{2\tau}\left[(1-\tau)B_{CH} + \dfrac{\bar{b}\cdot\bar{p}}{\bar{\alpha}\cdot\bar{b}} + \dfrac{ak\bar{\alpha}}{\bar{\alpha}\cdot\bar{b}^2}\right]$ *and* $\xi^*_{R,EC} = \dfrac{1}{k}\left(\bar{b}\cdot\bar{p} + \bar{\alpha}\cdot\bar{b}B^*_R\right)$*, where* $B^*_{R,EC} = B^*_{RM,EC}\tau + B_{CH}(1-\tau)$ *; (b)* $\dfrac{\partial\xi^*_{R,EC}}{\partial\gamma} > 0$, $\dfrac{\partial B^*_{RM,EC}}{\partial\gamma} > 0$, $\dfrac{\partial D_{EC}}{\partial\gamma} > 0$ *if* $B_{CH} < v$ *and* $\gamma < \dfrac{\sqrt{r}-r}{1-r}$ *where* $r = \dfrac{\alpha_{NE}b_{NE}}{\alpha_E b_E}$*, and* $\dfrac{\partial Q_{EC}}{\partial\gamma} > 0$*; (c) when* $\bar{\alpha} = \alpha$ *and* $\bar{b} = b$*,* $B^*_{RM,EC}$*,* $\xi^*_{R,EC}$*,* $\pi^*_{RM,EC}$ *and* $\pi^*_{R,EC}$ *increase in* $\bar{\alpha}\cdot\bar{b}$*, and* $B^*_{RM,EC} > B^*_{RM}$*,* $\xi^*_{R,EC} > \xi^*_R$*,* $\pi^*_{RM,EC} > \pi^*_{RM}$ *and* $\pi^*_{R,EC} > \pi^*_R$*.*

Proposition 5.8. *In the centralized supply chain, (a) the optimal* ξ *that maximizes the supply chain profit is* $\xi^*_{SC,EC} = \dfrac{1}{k}\left\{\bar{b}\cdot\bar{p} + \bar{\alpha}\cdot\bar{b}\left[\tau v + (1-\tau)(C + B_{CH})\right]\right\}$ *where* $\dfrac{\partial\xi^*_{SC,EC}}{\partial\gamma} > 0$ *; (b)* $\xi^*_{R,EC} < \xi^*_{SC,EC}$ *for any* $B_{RM} \le v$*; (c) when* $\bar{\alpha} = \alpha$ *and* $\bar{b} = b$*,* $\xi^*_{SC,EC}$ *and* $\pi^*_{SC,EC}$ *increase in the interaction effect* $\bar{\alpha}\cdot\bar{b}$*, and we have* $\xi^*_{SC,EC} > \xi^*_{SC}$*, and* $\pi^*_{SC,EC} > \pi^*_{SC}$*.*

Proofs of Propositions 5.7 and 5.8:

The increase of market demand functions (derived from UAC) of the environmental and non-environmental conscious consumers are

$D_E = \gamma\left(a + b_E\xi\right)$,

$D_{NE} = \left(1-\gamma\right)\left(a + b_{NE}\xi\right)$.

The total increase in market demand brought by UAC is

$D = D_E + D_{NE} = a + \bar{b}\xi$.

The collected quantities of used apparel from the environmental and non-environmental conscious consumers are $\alpha_E D_E$ and $\alpha_{NE} D_{NE}$, respectively. The total collected quantity of the used apparel is

$Q = \alpha_E D_E + \alpha_{NE} D_{NE} = a\bar{\alpha} + \bar{\alpha}\cdot\bar{b}\xi$,

where $\bar{\alpha}\cdot\bar{b} = \gamma\alpha_E b_E + \left(1-\gamma\right)\alpha_{NE} b_{NE}$ measures the interaction effect of the two-dimensional environmental consciousness, i.e. the consumer sensitivity towards the UAC promotion effort and the consumer return rate of used apparel. If $\bar{\alpha}\cdot\bar{b} = a\cdot b$, the interaction effect equals that in the basic model. Holding the average values of the return rate and the sensitivity coefficient equal to those in the basic model (i.e., $\bar{\alpha} = \alpha$ and $\bar{b} = b$), we have $\bar{\alpha}\cdot\bar{b} > \alpha b$. This indicates that the consumer heterogeneities in both dimensions of environmental consciousness amplifies their interaction effect. Moreover, we find that the interaction effect is larger as the degree of consumer heterogeneity increases (α_E and b_E become extremely high, and α_{NE} and b_{NE} become extremely low).

The fashion retailer's profit is

$\pi_{R,EC}(\xi) = \bar{p}D + \left[B_{RM}\tau + B_{CH}(1-\tau)\right]Q - K(\xi)$.

The remanufacturer's profit is

$\pi_{RM,EC}(B_{RM}) = (v - B_{RM})\tau Q$.

Same as the basic model, the remanufacturer decides B_{RM} first and the retailer decides ξ next. We can derive the equilibrium by backward induction and present the result in Proposition 5.9.

First, we prove Proposition 5.7 (a) by deriving the equilibrium by backward induction.

In the second stage, given B_{RM}, the fashion retailer sets ξ to maximize its profit given by

$\pi_{R,EC}(\xi) = \overline{p}D + \overline{B}Q - K(\xi) = \overline{p}\left(a + \overline{b}\xi\right) + \overline{B}\left(a\overline{\alpha} + \overline{\alpha b}\xi\right) - \frac{k\xi^2}{2}$.

Since $\pi_{R,EC}(\xi)$ is concave in ξ ($\frac{\partial^2 \pi_{R,EC}(\xi)}{\partial \xi^2} < 0$), the optimal decision can be obtained by the first order condition: $\frac{\partial \pi_{R,EC}(\xi)}{\partial \xi} = 0$ i.e., $\xi^*_{R,EC} = \frac{1}{k}\left(b\overline{p} + \overline{\alpha b}\overline{B}\right)$.

In the first stage, with the estimated best response of the retailer, the remanufacturer decides B_{RM} to maximize its profit given by $\pi_{RM,EC}(B_{RM}) = (v - B_{RM})\tau Q\left(\xi^*_{R,EC}\right)$. Since $\pi_{RM,EC}(B_{RM})$ is concave in B_{RM} ($\frac{\partial^2 \pi_{RM,EC}(B_{RM})}{\partial {B_{RM}}^2} < 0$), the optimal decision can be obtained by the first order condition $\frac{\partial \pi_{RM,EC}(B_{RM})}{\partial B_{RM}} = 0$ i.e., $B^*_{RM,EC} = \frac{v}{2} - \frac{1}{2\tau}\left[\left(1-\tau\right)B_{CH} + \frac{b\overline{p}}{\overline{\alpha b}} + \frac{k\alpha a}{\overline{\alpha b}^2}\right]$ .Then, Proposition 5.7(b) can be obtained by differentiating the equilibrium with respect to θ and Proposition 5.7(c) can be obtained straightforwardly by comparing the equilibrium with and without the consideration of consumer heterogeneity in environmental consciousness. This completes the proof of Proposition 5.7.

Consequently, we analyze the centralized supply chain. The supply chain's profit is given as follows:

$\pi_{SC,EC}(\xi) = \overline{p}D + \left[v\tau + (1-\tau)\left(C + B_{CH}\right)\right]Q - K(\xi)$.

As the supply chain's profit $\pi_{SC,EC}(\xi)$ is concave in ξ. The optimal ξ for coordinating the supply chain can be determined by the first order conditions, respectively. Proposition 5.8 (b) and (c) are straightforward. This completes the proof of Proposition 5.8. (Q.E.D.)

Proposition 5.9. *In the decentralized setting, we have (a)* $B^*_{RM,O} < B^*_{RM}$ *, and* $\xi^*_{R,O} < \xi^*_R$ *. (b)* $\pi_R(\xi^*_{R,O}) < \pi_R(\xi^*_R)$ *, and* $\pi_{RM}(\xi^*_{R,O}) < \pi_{RM}(\xi^*_R)$.

Proposition 5.10. *For profit coordination, we have* $\xi^*_{SC,O} < \xi^*_{SC}$ *, and* $\pi_{SC,O}(\xi^*_{SC,O}) < \pi_{SC}(\xi^*_{SC})$.

Proofs of Propositions 5.19 and 5.10:

In the ABC model, which is the basic model, the amount of collected used apparel is $Q = \alpha D$. We denote Q_O as the amount of collected used apparel in the OBC model, and the respective increased demand driven by the UAC program is D_O. It is obvious that $D_O < D$ as we consider the case in which only a proportion of the originally “UAC driven increased demand” *D* will have own brand products to donate. Thus, $D_O = \rho D$, where $0 < \rho < 1$. As a result, we have: $Q_O = \alpha D_O = \alpha(\rho D)$.

We denote $\rho\alpha$ as α_O. Then, we have $Q_O = \alpha_O D$ and $\alpha_{obc} < \alpha$, and present Proposition 6.9. As a remark, we use the subscribe “O” to represent the OBC case.

The fashion retail brand’s profit under “own-brand collection (OBC) scheme” is expressed as $\pi_{R,O}(\xi) = \bar{p}D_O + B_{RM}\tau Q_O + B_{CH}(1-\tau)Q_O - K(\xi)$, where $Q_O = \alpha_{obc}D$ and $\alpha_{obc} < \alpha$.

Thus, the optimal $B^*_{RM}\,|_{\alpha_{obc}}$ and $\xi^*_R\,|_{\alpha_{obc}}$ are shown below:

$$B^*_{RM}\,|_{\alpha_{obc}} = \frac{v}{2} - \frac{1}{2\alpha_{obc}\tau}\left(\frac{ak}{b^2} + \bar{p} + \alpha_{obc}(1-\tau)B_{CH}\right),$$

$$\xi^*_R\,|_{\alpha_{obc}} = \frac{b}{2k}\left[\bar{p} + \alpha_{obc}\tau v + \alpha_{obc}(1-\tau)B_{CH}\right] - \frac{a}{2b}.$$

Since $\alpha_{obc} < \alpha$, we have $B^*_{RM}\,|_{\alpha_{obc}} < B^*_{RM}\,|_{\alpha}$ and $\xi^*_R\,|_{\alpha_{obc}} < \xi^*_R\,|_{\alpha}$.

When comparing $\pi_R(\xi^*_{R,O})$ and $\pi_R(\xi^*_R)$, we have $\pi_R(\xi^*_{R,O}) - \pi_R(\xi^*_R) < 0$. Therefore, $\pi_R(\xi^*_{R,O}) < \pi_R(\xi^*_R)$. Similarly, we have $\pi_{RM}(\xi^*_{R,O}) < \pi_{RM}(\xi^*_R)$, and $\pi_C(\xi^*_{R,O}) < \pi_C(\xi^*_R)$. This completes the proof of Proposition 5.9.

Following the same logic of the proof of Proposition 5.2, we can prove Proposition 5.10. (Q.E.D.)