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Essays on Strategic Interactions in Remanufacturing, Environmental Quality Investments, and Greenwashing

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Résumé

Nous étudions les interactions stratégiques dans les problèmes environnementaux avec plusieurs joueurs en utilisant des modèles théoriques de jeux. Nous nous concentrons sur des stratégies compétitives de réutilisation des produits dans une industrie innovante, des investissements compétitifs en matière de qualité environnementale avec l'écoblanchiment et la collaboration de la chaîne d'approvisionnement pour améliorer la qualité environnementale avec l'écoblanchiment. Dans cette thèse, nous répondons à ces problèmes en trois essais.

Dans le premier essai, notre objectif est d'explorer la stratégie de remise à neuf optimale pour le fabricant d'équipement d'origine (OEM) et le remanufactureur indépendant (IR) dans une industrie innovante. Nous étudions également comment la stratégie optimale varie en fonction de l'identité du remanufactureur. L'innovation diffère de la qualité du produit en présence de remanufacturing, en incluant activement les caractéristiques innovantes dans les produits remanufacturés, par opposition au transfert passif de la qualité du produit vers les produits remanufacturés. Nous examinons trois stratégies de refabrication distinctes : (i) sans refabrication, (ii) refabrication sans ajout de fonctionnalités innovantes et (iii) refabrication avec ajout de fonctionnalités innovantes (mise à niveau).

Dans le deuxième essai, nous analysons les effets du greenwashing sur les stratégies et les résultats des entreprises et sur les consommateurs. Nous considérons un cadre de jeu en deux étapes, où un opérateur historique monopolistique prend des décisions concernant la tarification et l'investissement dans la qualité de l'environnement dans la première étape. Dans la deuxième étape, l'opérateur historique est en concurrence avec un entrant.

L'opérateur historique est identifié comme une entreprise verte qui représente fidèlement la qualité environnementale de son produit, tandis que l'entrant peut recourir à des pratiques d'écoblanchiment. Nous supposons que le greenwashing ne peut attirer que des consommateurs inexpérimentés, c'est-à-dire ceux qui n'ont pas acheté le produit auparavant dans la première période. Notre enquête se concentre sur la compréhension des conditions qui font de l'écoblanchiment une stratégie rentable pour l'entrant, comment l'opérateur historique réagit à l'écoblanchiment et l'impact global de l'écoblanchiment sur l'environnement et les clients.

Dans le troisième essai, nous étudions l'interaction stratégique entre un détaillant, un fabricant et un fournisseur dans une chaîne d'approvisionnement à trois échelons avec un modèle de théorie des jeux en présence du développement des fournisseurs et du greenwashing. Le détaillant et le fabricant sont respectueux de l'environnement et cherchent à améliorer l'image environnementale de leurs produits en améliorant la qualité environnementale du fournisseur. Cette amélioration vise à tirer parti de la conscience environnementale des consommateurs et à accroître la demande. Pour atteindre cet objectif, le fabricant ou le distributeur propose de partager les coûts d'investissement supportés par le fournisseur, tandis que le distributeur fait la promotion de la qualité environnementale des produits. Cependant, il existe un risque de greenwashing lorsque la qualité annoncée dépasse la qualité réelle du produit. Si le greenwashing est exposé, les consommateurs réagissent en pénalisant la chaîne d'approvisionnement et en s'abstenant d'acheter le produit.

Mots-clés

Remise à neuf, Innovation, Prix compétitifs, Théorie des jeux, Écoblanchiment, Investissements dans la qualité environnementale, Approvisionnement responsable, Développement durable, Chaîne d'approvisionnement, Développement des fournisseurs

Méthodes de recherche

Recherche quantitative, Analyse numérique

Abstract

We investigate the strategic interactions in environmental problems with multiple players using game theoretical models. Our focus is on competitive product reuse strategies in an innovative industry, competitive environmental quality investments with greenwashing, and supply chain collaboration to enhance environmental quality with greenwashing.

In the first essay, our aim is to explore the optimal remanufacturing strategy for both an original equipment manufacturer (OEM) and an independent remanufacturer (IR) in an innovative industry. We also investigate how the optimal strategy varies depending on the identity of the remanufacturer. Innovation differs from product quality in the presence of remanufacturing, by actively including the innovative features in the remanufactured products, as opposed to passively carrying over product quality to the remanufactured products. We examine three distinct remanufacturing strategies: (i) not remanufacturing, (ii) remanufacturing without adding innovative features, and (iii) remanufacturing with the addition of innovative features (upgrading).

In the second essay, we analyze the effects of greenwashing on firms' strategies and outcomes and on consumers. We consider a two-stage game framework, where a monopolistic incumbent makes decisions regarding pricing and environmental quality investment in the first stage. In the second stage, the incumbent competes with an entrant. The incumbent is identified as a green firm that accurately represents the environmental quality of its product, while the entrant may resort to greenwashing practices. We assume that greenwashing can only attract inexperienced consumers, meaning those who have not previously purchased the product in the first period. Our investigation focuses on under-

standing the conditions that make greenwashing a profitable strategy for the entrant, how the incumbent responds to greenwashing, and the overall impact of greenwashing on the environment and customers.

In the third essay, we investigate the strategic interaction between a retailer, a manufacturer, and a supplier in a three-echelon supply chain with a game-theoretical model in the presence of supplier development and greenwashing. Both the retailer and manufacturer are environmentally sustainable and seek to enhance the environmental image of their products by improving the supplier's environmental quality. This improvement aims to leverage consumers' environmental consciousness and increase demand. To achieve this objective, the manufacturer or the retailer proposes to share the investment costs incurred by the supplier, while the retailer advertises the environmental quality of the products. However, there is a risk of greenwashing when the advertised quality surpasses the actual quality of the product. If greenwashing is exposed, consumers respond by penalizing the supply chain and abstaining from purchasing the product.

Keywords

Remanufacturing, Innovation, Competitive Pricing, Game Theory, Greenwashing, Environmental Quality Investments, Responsible Sourcing, Supply Chain, Sustainability, Supplier Development

Research methods

Quantitative Research, Numerical Analysis

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Preface

This thesis consists of three essays and the first one is accepted for publication.

- Cetin, C. B. and Zaccour, G. (2023). Remanufacturing with innovative features: A strategic analysis. *European Journal of Operational Research*, 310 (2): 655-669
- Cetin, C. B., Mukherjee, A. and Zaccour, G., Strategic Pricing and Investment in Environmental Quality by an Incumbent Facing a Greenwasher Entrant.
- Cetin, C. B., Karaer, Ö. and Zaccour, G., Supplier Environmental Development with Green-washing Activities of the Retailer.

General Introduction

Firms are rational profit maximizers and do not focus on their environmental impact. Even when they look like acting altruistically, they usually have an indirect economical benefit. That is why it is very important to detect the cases that are beneficial for the firms and the environment at the same time. In this thesis, we focus on the settings where the firm can increase its profit while doing good for the environment. The economic and environmental objectives can be aligned in two ways, either the end-of-use products carry some value that can be recovered, which is investigated in *closed-loop supply chains* and *product reuse economics* articles, or the environmental performance of the product can attract customer demand, which is investigated in *green supply chains* and *environmental economics* articles. We contribute to *closed-loop supply chains* and *product reuse economics* literature with the first essay by investigating the profitability and environmental impact of remanufacturing in an innovative industry and to *green supply chains* and *environmental economics* literature with the second and third essays by examining the relationship between environmental quality investments and greenwashing in a competitive setting and in a supply chain, respectively.

In the first essay, we investigate the product reuse strategies of an original equipment manufacturer (OEM) and an independent remanufacturer (IR) in an innovative industry. An OEM should carefully evaluate the benefits and costs of remanufacturing, especially in an innovative industry (An innovative feature can be exemplified as a better camera for a cellphone.). Although remanufacturing can generate additional profits, it also has the potential to reduce the demand for new products, ultimately leading to a decline in overall profitability. This cannibalization effect is particularly significant for innovative new products, as they offer higher profit margins due to their value-adding features. Furthermore, if the OEM chooses not to remanufacture its end-of-use products, IRs can seize the opportunity and utilize those products to compete directly with the OEM.

In the context of an innovative industry, the original equipment manufacturer and possibly the independent remanufacturers face two crucial decisions regarding remanufacturing. Firstly, they must determine whether to introduce remanufactured products into the market. Secondly, they need to decide whether these remanufactured products should incorporate innovative features to enhance consumer valuation. We first analytically examine the conditions for the profitability of remanufacturing or upgrading with a given level of innovation for both the OEM and the IR. Additionally, we perform numerical optimization to determine the optimal innovation level for the OEM and investigate the profitability conditions of remanufacturing or upgrading. Subsequently, we expand our model to investigate aspects such as innovation sharing between the players and the preemptive strategies employed by the OEM.

To address the research questions mentioned earlier, we examine two settings. In the first setting, the market consists solely of the OEM without any participation from the IR. In the second setting, the OEM chooses not to engage in remanufacturing, thereby creating an opportunity for the IR to enter the market. In this case, we aim to identify a Nash equilibrium in terms of quantities and innovative investment, considering that the level of innovation is endogenous.

In summary, our research distinguishes itself from previous studies by incorporating the OEM's innovation improvement investments, taking into account the possibility of an entry into the market by an IR. Additionally, we examine two distinct remanufacturing strategies: the decision to remanufacture and the decision to incorporate innovative features in the remanufactured products.

We showed that the consumer perception toward remanufactured products and the cost advantage of remanufacturing are the most important factors for both the OEM and the IR to introduce remanufactured products. Considering the OEM's concern about the potential decrease in demand for new products resulting from the introduction of remanufactured ones, the OEM expects higher valuations for remanufactured products and greater cost advantage in remanufacturing compared to the IR. Similar to the decision of whether or not to engage in remanufacturing, the OEM is more conservative than the IR when it comes to incorporating innovative features into remanufactured products. This cautious approach is driven by the recognition of potential negative effects on demand for new products caused by the inclusion of such features. As anticipated, the overall profit is higher in a monopoly scenario compared to a duopoly scenario. However, surprisingly, competition does not always yield benefits for consumers. Contrary to popular belief, remanufacturing of end-of-use products does not always guarantee environmental advantages. While remanufactured products tend to use less raw materials compared to new products, the potential expansion of the market can overshadow this advantage of remanufacturing.

In the second essay, we investigate the environmental quality investment and greenwashing strategies of a green incumbent and a greenwasher entrant. With the improved environmental consciousness of the consumers, the firms have another drive to improve their environmental quality apart from government regulations, that customers prefer green products over non-green ones and are willing to pay more for green products (McKinsey and NielsenIQ, 2023). However, firms are not always honest regarding their true environmental performance and can overstate their environmental quality to gain a competitive advantage. The act of positively projecting a firm's environmental performance when it is not truly up to the mark is greenwashing. Volkswagen's "low emission" and " environmentally friendly" claims for its diesel engine turned out to be misleading and the firm agreed to pay $96.5 million in penalties to settle the case (Shepardson, 2016).

Greenwashing is an increasingly important issue in today's business world. It refers to the practice of making false or misleading claims about a company's environmental practices in order to appear more sustainable and socially responsible than it actually is. In our paper, we aim to explore the importance of greenwashing from a firm's perspective, particularly in terms of its competitive advantage and the associated risks. For many companies, greenwashing has become a crucial tool for gaining a competitive edge, as consumers become more environmentally conscious and demand sustainable products and practices. However, the risks of greenwashing are also significant, as consumers and stakeholders can quickly see through false claims and expose a company's lack of genuine commitment to sustainability, leading to reputational damage and lost trust. Therefore, understanding the importance of greenwashing is crucial for companies looking to succeed in today's increasingly environmentally conscious market.

This research paper examines the impact of greenwashing on the strategies and outcomes of companies, as well as its effect on consumers. We propose a two-stage game scenario where a monopolistic company makes decisions regarding pricing and environmental quality in the first stage, and then competes with a new entrant in the second stage. The incumbent company acts responsibly and accurately represents the environmental quality of its product, while the entrant may be enticed to engage in greenwashing. We assume that only inexperienced consumers, those who have not purchased the product before, can be influenced by greenwashing. Consequently, our model captures two important dynamic features, namely, the change in the competitive structure and the presence of a "learning" effect in the market.

Our research differentiates from the existing articles by investigating the environmental quality investment to enhance the demand instead of trying to achieve government-mandated environmental targets and the level of greenwashing of the entrant firm instead of mimicking the green firm's environmental quality in a competitive environment where consumers knowledge on environmental performance evolves with experience.

We found that the incumbent creates an appropriate environment for greenwashing by increasing its first-period price and decreasing environmental quality investment to decrease the number of experienced customers. This can also interpreted as the conditions that allow the entrant to greenwash become more strict if the incumbent firm overlooks greenwashing. These adjustments of the incumbent may cause the entrant to lose profit with greenwashing. As the entrant replaces the costly environmental quality investments with cheaper greenwashing, the environmental quality investments of the two firms usually decrease with greenwashing. The environment and consumers are better off if greenwashing is overlooked. Consumer surplus always decreases with greenwashing.

In the third essay, we examine the strategic interactions in a supply chain to build up the environmental quality and the conditions causing greenwashing. Although companies in developed nations have ceased their environmental wrongdoings and enhanced their environmental practices due to market pressure and government regulations, their international suppliers may still lack adequate environmental standards. Non-governmental organizations (NGOs) play a role in informing customers and holding global corporations accountable for the environmental performance of their suppliers. Nestlé, for instance, has been targeted by Greenpeace for the environmental misconduct of its secondary supplier, which involves deforestation to expand palm oil production. As a result, Nestle has been compelled by its customers to switch suppliers (The Economist, 2010).

If a purchasing company desires superior environmental practices from all of its partners within the supply chain, it must either seek out environmentally responsible partners or assist its current partners in enhancing their environmental performance. While the supplier's environmental performance may enhance due to the fear of losing business or thanks to support from downstream partners, the resulting environmental quality may still fall short of meeting the buying firm's expectations for market differentiation and increased demand. Given the difficulty for customers to verify the claimed environmental performance of a supplier, a buying firm may choose to exaggerate the environmental quality of the product in such situations.

To gain insight into the cooperative dynamics among supply chain partners, the investment behavior of suppliers in environmental quality, and the greenwashing strategies employed by retailers (buying firms), we developed a sequential move game model. This model considers a three-echelon supply chain consisting of a retailer, a manufacturer, and a supplier, where both the retailer and the manufacturer are environmentally responsible, while the supplier is expected to enhance its environmental performance.

Even though we approach the problem profit maximization perspective of the supply chain members, our results are also beneficial to understand the effects of greenwashing and the identity of the cost-sharing firm on the environment and consumers.

Our findings indicate that the retailer's greenwashing strategy is dependent on the environmental quality of the supplier. If the supplier's environmental quality falls below a certain threshold, the retailer engages in greenwashing; otherwise, greenwashing is not employed. Both the reduction in greenwashing and the improvement in environmental quality are influenced by the rate of cost-sharing. As the cost-sharing rate increases, the level of greenwashing decreases, while the environmental quality level increases. Furthermore, the manufacturer's cost-sharing rate is higher than that of the retailer. Consequently, when the retailer shares the supplier's investment cost, both the likelihood and level of greenwashing are higher. It is important to note that while greenwashing is ultimately the retailer's decision, it is not consistently beneficial, particularly when the manufacturer supports the supplier, resulting in a decline in the supplier's environmental quality level.

This thesis contributes to the literature by investigating remanufacturing strategies in an innovative industry and the impact of competition by an independent remanufacturing with the first essay, by examining competitive environmental quality investments of a green incumbent and a greenwasher entrant with the second essay, and by analyzing the supplier development efforts of downstream firms in the presence of greenwashing with the third essay.

Chapter 1

Remanufacturing with Innovative Features: A Strategic Analysis[1]

Abstract

In this study, we investigate the best remanufacturing strategy for the original equipment manufacturer (OEM) and independent remanufacturer (IR) in an innovative industry where the consumer valuation of the products increases with the level of innovation, and we characterize how the best strategy changes with the identity of the remanufacturer. Our work differs from existing articles that investigate the remanufacturing strategy in the presence of quality decisions, by actively including the innovative features in the remanufactured products, as opposed to passively carrying over product quality to the remanufactured products. We consider three remanufacturing strategies: (i) not remanufacturing, (ii) remanufacturing without adding innovative features, and (iii) remanufacturing adding innovative features (upgrading). To analyze the problem, we create a single-period model where the OEM determines the level of innovation and the quantity of new products, in both competitive settings, and either the OEM or IR determines the remanufacturing quantity depending on the competitive setting. We investigate how the firms' environmental

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impact and the consumer surplus are affected by the competition and the remanufacturing strategy.

1.1 Introduction

Remanufacturing means bringing used products to a like-new condition by disassembling the whole product, inspecting all parts and modules, and replacing those that cannot satisfy like-new quality standards (Thierry et al., 1995). Even though remanufactured products are functionally equivalent to new products, they might be perceived as inferior alternatives to new products by the consumers (Ferguson and Toktay, 2006; Guide and Li, 2010; Galbreth et al., 2013; Örsdemir et al., 2014). Nevertheless, the remanufacturing industry is growing daily and cannot be overlooked by firms. According to United States International Trade Commission (2012), the remanufacturing industry grew by 15% between 2009 and 2011, and reaching US$43 billion, and provided 180,000 jobs in 2011 in the US. Environment and Climate Change Canada (2019) states that remanufacturing and other value recovery operations created C$44 billion in total revenues and provided 375,000 direct jobs in 2019 in Canada.

Product reuse has been a controversial subject among decision makers, and its economic benefits have been considered ambiguous. In some cases, firms have been forced by regulatory bodies to handle the waste generated by their products at the end of the product life cycle (WEEE, 2012). In other cases, companies have seen the potential economic benefits of product reuse and took this direction even in the absence of regulation (see De Giovanni and Zaccour (2014); Atasu et al. (2008); Ferrer and Swaminathan (2006)).

An original equipment manufacturer (OEM) should carefully assess the advantages and disadvantages of remanufacturing, especially in an innovative industry. While remanufacturing can create a new profit stream, it can also cannibalize the demand for new products, resulting in a loss of profit, overall. This cannibalization effect is more important for innovative new products due to the improved profit margin with the value-adding innovative features. Those innovative features can be exemplified as a more efficient battery for cell phones or higher printing speed for photocopiers. Moreover, when the OEM does not remanufacture its end-of-use products, independent remanufacturers (IRs) can use those end-of-use products and compete with the OEM. While Hewlett-Packard, whose products compete with the remanufactured products of an IR, and Xerox who remanufactures its own used products are the historically cited examples of remanufacturing in literature (Li et al., 2018; Subramanian et al., 2013), Samsung and Apple are examples of innovative firms who refurbish their own end-of-use products without including innovative features (Bliszczyk, 2021). (Refurbishing is the inferior form of value recovery, as compared to remanufacturing, making no claim of as-good-as new functionality (Thierry et al., 1995).). Even though Apple and Samsung, as OEMs, do not include innovative features in their refurbished products, Inrego, as an IR, remanufactures end-of-use electronics including cell phones with innovative features (`inrego.com`). Inrego shows us that including innovative features in remanufactured products can be a profitable remanufacturing strategy for an IR and its profitability for OEMs should be investigated.

The OEM, and potentially the IR, has two fundamental choices to make regarding remanufacturing: whether to introduce remanufactured products and whether to include innovative features in the remanufactured products to improve (upgrade) the consumer valuation. Our main objective is to help OEMs make these decisions in an innovative industry. Our research questions are as follows:

1. Assuming that the investment in innovative features is exogenously given, then

    a) Under what conditions is it profitable for the OEM to remanufacture (or upgrade)? What are the optimal quantities of new and remanufactured (or upgraded) products?

    b) If the OEM produces only new products, should the IR remanufacture (or upgrade)? What are the resulting equilibrium quantities of new and remanufactured (or upgraded) products?

2. Assuming that the level of innovative features is endogenous, that is, a decision by the OEM, then

    a) Under what conditions is it profitable for the OEM to remanufacture (or upgrade)? How do the optimal quantities, innovation level, profit, consumer surplus, and material use vary with the main parameter values?

    b) If the OEM produces only new products, should the IR remanufacture (or upgrade)? How do the equilibrium quantities, innovation level, profit, consumer surplus, and material use vary with the main parameter values?

    c) How do the equilibrium (or optimal) profit, consumer surplus, and material use vary with the identity of remanufacturer?

3. Suppose that the OEM can fully appropriate the innovative features, then under what conditions should the OEM share this information with the IR?

4. Should an OEM that does not want to remanufacture preempt an IR from remanufacturing?

To answer the above research questions, we consider two setups. In the first, the OEM is alone in the market. In the second setup, the OEM does not want to remanufacture, which leaves the door open for the IR to enter the market. In both scenarios, the assumption is that the market is in a steady state and a static model can therefore accurately represent the context. When the OEM does not remanufacture, we seek a Nash equilibrium in quantities and also in innovative investment when its level is endogenous. In any event, the remanufacturing quantity is limited by the new-product quantity, a natural assumption that, however, complicates the analysis. One reason for the OEM not to remanufacture is if the remanufactured products negatively affect the perceived value of its new products (Agrawal et al., 2015).[2]

[2] We do not consider a setting where entrance of one player prevents the entry of the other player in remanufacturing market. Instead, we focus on two distinct settings where there is only one player who considers whether to remanufacture and whether to include the innovative features in remanufactured products and we compare the results of those two settings to understand the effects of those settings on the performance measures. We added the idea of an entry game in the extensions in the conclusion.

Even though we approach the problem from the OEM's point of view, our results also have important implications for the IR. The OEM and the IR can better assess the economic outcome of introducing remanufactured products and of including, or not, innovative features. Understanding the implications of the remanufacturing strategy will help the OEM better align remanufacturing with innovation.

The remainder of this article is organized as follows: Section 1.2 briefly reviews the relevant literature, and Section 1.3 introduces the model. In Sections 1.4 and 1.5, we provide comprehensive analytical and numerical results for the monopoly and duopoly settings when innovation is exogenous and endogenous, respectively. In Section 1.6, we investigate the scenario where the OEM sells innovation information to the IR, and preemptive recycling. We conclude with a summary of our findings in Section 1.7. Appendices A, B and C provide all proofs, the derivations of demand functions, consumer surplus expressions and the equilibrium (or optimal) profits of the firms in all settings.

1.2 Literature review

Our work draws from the literature on pricing of new and remanufactured products, and competition in product quality or innovation.

Abbey et al. (2015) look into whether there are customers who prefer new products regardless of the price of remanufactured products, customers who perceive new and remanufactured products as equivalent, and customers who prefer remanufactured products over new products for environmental reasons. The empirical answer is that the first two customer segments exist. Agrawal et al. (2015) hypothesize that the offer of remanufactured products may influence the customer valuation of the new products. Interestingly, they find that such an offer has a negative effect when it is made by the OEM but a positive effect when it comes from the IR. Guide and Li (2010) show that customer valuation of remanufactured products is affected by product type. For a B2B product, this valuation is not different for remanufactured products. However, if the buyer is the final consumer, then remanufactured products are perceived as inferior.

Debo et al. (2005) answer whether the opportunity to reach low-end consumers outweighs the high cost of producing a remanufacturable product. Customers are differentiated in their valuation of the product, and remanufactured products are perceived as inferior. Ferrer and Swaminathan (2010) answer the same question with a similar utility function, without considering remanufacturability, but while considering the remanufacturing supply, which is dependent on the production quantity of new products. Jin et al. (2016) extend those works by allowing the sale of new products as remanufactured products. In this way, they eliminate the supply limitation of the remanufacturing process. Shi et al. (2016) do not consider a product's useful life as one period; instead, a more detailed utility function is created, and here, again remanufactured products are considered inferior. Customers have a positive utility from a used product in the second period. However, its utility is less than new and remanufactured products.

Competition in the presence of remanufactured products is generally investigated in settings where one or more OEMs compete with an IR. Heese et al. (2005); Atasu et al. (2008); and Mitra (2016) are the exceptions in this stream. They investigate the competition between the OEMs with remanufacturing capability and the OEMs without remanufacturing capability. Heese et al. (2005) consider a setup with two OEMs that share the market potential in a constant proportion. The remanufactured product is seen as the equivalent of the new products. Consequently, they can be seen as a cost reduction opportunity. Atasu et al. (2008) split the customers into two groups: regular and green customers. Regular customers see remanufactured products as inferior, whereas green customers see them as equivalent to the new products. The OEM without remanufacturing produces low-end products, but these are viewed as preferable to remanufactured products by regular customers.

Majumder and Groenevelt (2001) is the first paper that investigates OEM and IR competition. Products remanufactured by the OEM are considered a perfect substitute for new products, whereas those remanufactured by the IR are perceived as inferior by consumers. Ferguson and Toktay (2006) extend the previous work by considering cases where even though offering remanufactured products to the market is not profitable in a monopolistic market structure, an OEM may opt to remanufacture to deter the entry of an IR. Ferguson and Toktay (2006) differ from Majumder and Groenevelt (2001) in their assumption about the customers' perceptions of the remanufactured products. The environment considered in Ferrer and Swaminathan (2006) is the same as in Majumder and Groenevelt (2001). However, the models differ: the latter paper considers not only the two-period model but also multi-period and infinite-horizon models. Mitra and Webster (2008) incorporate a government subsidy for remanufactured products into their models and the effect of the subsidy is evaluated. Oraiopoulos et al. (2012) investigate the effects of competition between an OEM and IR(s), where the OEM takes a relicensing fee from the IRs for each unit remanufactured. Wu (2012b) and Wu (2013) take disassemblability as an additional aspect. (Disassemblability is the easiness of remanufacturing operations.) They differ from each other through their customer segmentation assumptions. Wu (2012b) considers a market with two distinct segments, regular and green customers, whereas the market considered in Wu (2013) only consists of regular customers. Subramanian et al. (2013) investigate the interaction between remanufacturing and component commonality decisions. Both OEM remanufacturing and IR remanufacturing cases are investigated. Li et al. (2015) use the empirical findings of Agrawal et al. (2015) in their analysis. If OEM is the one that remanufactures, the perceived value of the new products decreases. Whereas, if an IR remanufactures, customers perceive new products as more valuable compared to the case without remanufacturing. Wu and Zhou (2016) investigate the effects of the entry of IR(s) into a market with two OEMs that are vertically differentiated. Different purchasing preferences of regular and green customer segments are considered in this article.

The articles that consider remanufacturing and product quality at the same time are quite new. Wu (2012a) investigates the effects of after-sale service quality in a system that consists of an OEM that only produces new products, an IR, and a common retailer. The OEM and the IR compete in their service level and the wholesale price, and the retailer determines the market price of each product type. Customers perceive remanufactured products as inferior. In Atasu and Souza (2013), three alternative scenarios are investigated in a monopolistic market where customer willingness to pay increases with the quality level and is equal for the new and remanufactured products: profitable remanufacturing, profitable recycling, and costly recycling. Örsdemir et al. (2014) investigate how an OEM can use product quality along with quantity as a competitive lever against an IR. The OEM can choose to remanufacture or not, and can collect the used products to preempt the IR. Cui et al. (2017) depart from previous articles that investigate remanufacturing and quality decisions from an OEM's point of view. Instead, their IR is the only player of concern, and the OEM's decisions are taken as given parameters. Galbreth et al. (2013) consider three alternative products: new products, upgraded products, and remanufactured products. A constant rate of product innovation is assumed. While remanufacturing the used products, the producer can use innovative parts to replace worn-out parts, or old technology parts, resulting in either upgraded products or remanufactured products, respectively. The question of concern is what type of products the firm should produce to maximize its profits. Consumer utility is the lowest for remanufactured products and the highest for new products. Li et al. (2018) extend the previous work by taking innovation level as a decision variable and find the optimum innovation level. However, their paper omits some parts of its predecessor by not considering two alternative remanufacturing options, i.e., upgraded products and remanufactured products. Instead, it defines the innovation level as a tool to increase the valuation of the new products.

In a nutshell, our work differs from the existing literature by considering the investments of an OEM to enhance innovation, in the face of a potential entry onto the market by an IR, together with two remanufacturing strategies: whether or not to remanufacture and whether or not to include innovative features in the remanufactured products.

1.3 The model

We consider a market with an original equipment manufacturer (OEM) and an independent remanufacturer (IR). The OEM is the only firm that can produce goods from raw materials, whereas both the OEM and IR can remanufacture the OEM's end-of-use products.

As in, e.g., Subramanian et al. (2013); Örsdemir et al. (2014); Atasu and Souza (2013), we assume that the product life cycle is long enough so that we can retain a single-period model to investigate the steady-state behavior of the two firms. After use, the products are returned to either the OEM (player O) or the IR (player I). As our focus is not investigating the collection and acquisition of the end-of-use products, we do not account for the corresponding costs. (These costs could be added to the remanufacturing cost without altering any of our qualitative results.) Further, we suppose that used products can only be exploited once as an input for remanufacturing. Since there will not be an accumulation of used products in the steady-state, the remanufacturing quantity, q_{xr}, (or upgrading quantity, q_{xu}) is constrained by the new product manufacturing quantity, q_{On}. To keep it simple, we assume that all end-of-use products are available to the remanufacturer $q_{xr}(or\ q_{xu}) \leq q_{On},\ x \in \{O, I\}$. If the OEM does not recover the value remaining in its end-of-use products, then the IR can remanufacture and sell them on the same market.

The OEM can make an investment to add new features in order to create additional value for its products. The innovation level i defines the proportion of the innovative parts in the whole product. The customers' valuation of a product is increasing in the innovation (investment) level i. The investment cost is convex increasing and given by $k_f i^2$, with $k_f > 0$. When only new products are considered, quality and innovation are synonymous in terms of their (increasing) effects on customer valuation. However, this is not the case when it comes to remanufactured products. While the quality of the new product is carried to the remanufactured product passively (Atasu and Souza, 2013; Örsdemir et al., 2014), the remanufacturing firm can decide to update the outdated modules to make the remanufactured product innovative (Galbreth et al., 2013), or not. Taking this decision into account, three alternative products can be supplied to the market:

New product (n) manufactured with raw materials and including innovative features.

Remanufactured product (r) made with end-of-use products, without innovative fea-

Table 1.1: Notation

	Parameters
θ	Customer willingness-to-pay
δ	Relative WTP of customers for remanufactured products with respect to new products
c_0	Base manufacturing cost
γ	Proportional remanufacturing cost
k_v	Per unit additional cost proportional to the level of innovation
k_f	Innovation investment cost coefficient
α	Spillover rate
p_{xy}^z	Price of product type y of producer x in setting z
U_{xy}^z	Utility of a customer from purchasing product type y of producer x in setting z
π_x^z	Profit of producer x in setting z
	Decision and state variables
q_{xy}^z	Production level of product type y of producer x in setting z
i^z	Innovation level in setting z
	Indices
x	Index for producers, O: OEM, I: IR
y	Index for product type, n: new product, u: upgraded product, r: remanufactured product
z	Index for settings, NR: no remanufacturing, R: the OEM remanufactures, U: the OEM upgrades, IR: the IR remanufactures, IU: the IR upgrades

tures.

Upgraded product (u) made with end-of-use products, and its outdated modules are replaced with innovative ones.

The decision of the OEM and the IR is whether to remanufacture and what type of remanufactured good to produce. The prices of the new, upgraded, and remanufactured products are denoted by p_{On}, p_{xu}, and p_{xr}, respectively, with $x = O, I$.

The sequence of the events is as follows:

1. The OEM determines the level of innovation i and makes the investment to achieve

that level.

2. The OEM and the IR (if IR is the remanufacturer) simultaneously determine production quantities (new product and remanufactured/upgraded, respectively) and whether to include innovative features in remanufactured products.

The market size is fixed and normalized to 1. The customers make their purchasing decisions based on their utility maximization, and are differentiated in their willingness-to-pay (WTP), θ, which is distributed uniformly in $[0,1]$ (Ferguson and Toktay, 2006; Ferrer and Swaminathan, 2010; Galbreth et al., 2013; Shi et al., 2016). Utility of a new, upgraded, or remanufactured product is denoted by U_{On}, U_{xu}, and U_{xr}, respectively, with $x = O, I$.

The OEM can influence customer valuation by adding innovative features to its products, leading to utility $U_{On} = \theta(1+i) - p_{On}$. The customer WTP for a remanufactured product that does not contain any innovative features is given by $\delta\theta$, where $\delta \in (0,1)$, with a resulting utility $U_{xr} = \delta\theta - p_{xr}$. It is assumed that customers' WTP for a remanufactured product is not affected by the identity of the remanufacturer. If some innovative features have been added, then the customer valuation becomes $(1+i)\delta\theta$ and the utility $U_{Ou} = (1+i)\delta\theta - p_{Ou}$. The OEM's innovative advances cannot be fully appropriated, as a portion involuntarily spillovers to the IR. Denote by $\alpha \in [0,1]$ the spillover rate, assumed to be constant for all innovation efforts. The customer's utility when purchasing an upgraded product of the IR is $U_{Iu} = (1+\alpha i)\delta\theta - p_{Iu}$.

Given the pricing system and the OEM's innovation level, the maximization of the consumer utility function yields the following four price functions (see Appendix A for details):

$$
\begin{aligned}
p_{On} &= (1+i)(1-q_{On}) - (1+i)\delta q_{Ou} - (1+\alpha i)\delta q_{Iu} - \delta q_{xr}, \\
p_{Ou} &= (1+i)\delta(1-q_{On}-q_{Ou}) - (1+\alpha i)\delta q_{Iu} - \delta q_{xr}, \\
p_{Iu} &= (1+\alpha i)\delta(1-q_{On}-q_{Ou}-q_{Iu}) - \delta q_{xr}, \\
p_{xr} &= \delta(1-q_{On}-q_{Ou}-q_{Iu}-q_{xr}).
\end{aligned}
$$

Denote by $c_0 < 1$ the constant marginal cost of producing a good with raw materials, without innovative features. The unit cost of adding such features is linear increasing in i, and given by $k_v i$, where k_v is a positive parameter. Therefore, the total unit-production cost of a new product becomes $c_n = c_0 + k_v i$. As in Abbey et al. (2015), Jin et al. (2016), and Wu (2013), we assume that the remanufacturing cost is lower than the cost of producing with new materials; otherwise, there is no incentive to remanufacture, unless it is required by law. The savings are due to the use of parts and modules extracted from collected products that comply with quality standards. The cost to remanufacture is given by $c_r = \gamma c_0$, where $\gamma \in (0,1)$, which means that the rate of cost-saving is $(1-\gamma)c_0$. Finally, adding the cost of the innovative features, the unit cost of an upgraded product is $c_u = \gamma c_0 + k_v i$. Table 1.1 summarizes our notation.

1.4 Exogenous innovation level

To get some hints about the decision process, we first consider the simpler case where the innovation level is given. The effects of the OEM's remanufacturing strategy are assessed by the consumer surplus (CS) and total material usage (M). Total material usage for new products and remanufacturing activities is given by $M = q_{On} + \gamma q_{xy}$, $x \in \{O, I\}$ and $y \in \{r, u\}$ (Galbreth et al., 2013) [3]. The derivation of the consumer surplus is provided in Appendix A.

For $z \in \{R, U, IR, IU\}$, define by

S_0^z : the region where remanufacturing (or upgrading) is not profitable;

S_u^z : the region where remanufacturing (or upgrading) is profitable and the resource constraint is satisfied;

S_c^z : the region where remanufacturing (or upgrading) is profitable but the constraint is not satisfied.

[3] The robustness of the qualitative results for this metric has been checked for more general case where $M = q_{On} + \gamma\omega q_{xy}$. ω represents the portion of remanufacturing cost incurred by material usage and $1-\omega$ represents the portion of remanufacturing cost incurred disassembly and sorting costs. Even though this affects the quantitative results, managerial insights are not sensitive to this change.

1.4.1 Case with OEM as the remanufacturer

In the following three propositions, we characterize the optimal solution when the OEM does not remanufacture, remanufactures end-of-use products, and upgrades end-of-use products, respectively.

OEM does not remanufacture

In this scenario, the price and profit functions reduce to

$$\begin{aligned} p_{On}(q_{On}) &= (1+i)(1-q_{On}), \\ \pi_O(q_{On}) &= q_{On}((1+i)(1-q_{On})-c_0-k_v i)-k_f i^2. \end{aligned}$$

Proposition 1 *When the OEM does not remanufacture, the optimal new-product quantity and price are given by*

$$q_{On}^{NR} = \tfrac{1-c_0+i(1-k_v)}{2(1+i)}, \text{ and } p_{On}^{NR} = \frac{1+c_0+i(1+k_v)}{2}.$$

The higher are c_0, k_v, and i, the higher the price, while the quantity decreases in the cost parameters c_0 and k_v. The quantity increases in i, only if $k_v < c_0$, which is realistic to assume, as the unit cost of adding some features should be lower than the production cost.

OEM remanufactures

The inverse-demand functions of the new and remanufactured products are given by $p_{On} = (1+i)(1-q_{On}) - \delta q_{Or}$, and $p_{Or} = \delta(1-q_{On}-q_{Or})$, respectively. The OEM's optimization problem is as follows:

$$\begin{aligned} \pi_O(q_{On}, q_{Or}) = q_{On}&((1+i)(1-q_{On}) - \delta q_{Or} - c_0 - k_v i) \\ &+ q_{Or}(\delta(1-q_{On}-q_{Or}) - \gamma c_0) - k_f i^2 \\ \text{subject to}: 0 \leq q_{Or} &\leq q_{On}. \end{aligned}$$

The regions defining remanufacturing strategy are given by

$$S_0^R = \{(\delta - (1+i)\gamma)c_0 + \delta k_v i < 0\},$$
$$S_u^R = \{0 \le (\delta - (1+i)\gamma)c_0 + \delta k_v i < \delta(1-\delta-(1-\gamma)\,c_0 + (1-k_v)\,i)\},$$
$$S_c^R = \{\delta(1-\delta-(1-\gamma)\,c_0 + (1-k_v)\,i) \le (\delta - (1+i)\gamma)c_0 + \delta k_v i\}.$$

Proposition 2 *When the OEM produces the new product and remanufactures the end-of-use products, the optimal quantities and prices are given by*

$$q_{On}^R = \begin{cases} \frac{1-c_0+i(1-k_v)}{2(1+i)}, & S_0^R, \\ \frac{1-\delta-(1-\gamma)c_0+(1-k_v)i}{2(1+i-\delta)}, & S_u^R, \\ \frac{1+\delta-(1+\gamma)c_0+(1-k_v)i}{2(1+i+3\delta)}, & S_c^R, \end{cases} \quad \text{and} \quad q_{Or}^R = \begin{cases} 0, & S_0^R, \\ \frac{(\delta-\gamma)c_0+(\delta k_v-\gamma c_0)i}{2\delta(1+i-\delta)}, & S_u^R, \\ \frac{1+\delta-(1+\gamma)c_0+(1-k_v)i}{2(1+i+3\delta)}, & S_c^R. \end{cases}$$

$$p_{On}^R = \begin{cases} \frac{1+c_0+(1+k_v)i}{2}, & S_0^R \;\&\; S_u^R, \\ \frac{2(1+i)(1+i+3\delta)-(1+i+\delta)^2+(1+i+\delta)((1+\gamma)c_0+k_v i)}{2(1+i+3\delta)}, & S_c^R. \end{cases}$$

$$p_{Or}^R = \begin{cases} NA, & S_0^R, \\ \frac{\delta+\gamma c_0}{2}, & S_u^R, \\ \frac{\delta(2\delta+(1+\gamma)c_0+k_v i)}{(1+i+3\delta)}, & S_c^R. \end{cases}$$

Table 1.2: Parameter sensitivity when the OEM remanufactures and innovation is exogenous

	Non-binding				Binding		
	q_{On}^R	q_{Or}^R	p_{On}^R	p_{Or}^R	$q_{On}^R = q_{Or}^R$	p_{On}^R	p_{Or}^R
i	?	?	$+$	0	?	$+$	?
δ	$-$	$+$	0	$+$	?	$-$	$+$
γ	$+$	$-$	0	$+$	$-$	$+$	$+$
c_0	$-$	?	$+$	$+$	$-$	$+$	$+$
k_v	$-$	$+$	$+$	0	$-$	$+$	$+$

Remanufacturing is profitable for the OEM if $(\delta-(1+i)\gamma)c_0 + \delta k_v i > 0$. The cost advantage of remanufacturing $(1-\gamma)$ should be sufficiently large that the OEM can make a profit by selling a remanufactured product with an inferior perceived quality δ. The price of the new products is not affected by the introduction of the remanufactured products, whereas the optimal quantity of the new products q_{On}^{R} is lower when the remanufactured products are supplied to the market.

When the remanufacturing resource constraint is not binding, the impact of the innovation level i on q_{On}^{R} and q_{Or}^{R} depends on the term $c_0(1-\gamma)-k_v(1-\delta)$. If this term is positive, then $q_{On}^{R}(q_{Or}^{R})$ increases (decreases) with i; otherwise, the impacts go in the opposite direction. As can be seen in Table 1.2, the higher is δ or k_v, the higher is q_{Or}^{R} and the lower is q_{On}^{R}; whereas γ has the opposite effect on q_{On}^{R} and q_{Or}^{R}. Further, q_{On}^{R} is decreasing in c_0, which is expected. On the other hand, the effect of c_0 on q_{Or}^{R} is not straightforward. The ratio of the WTP for the remanufactured products to the WTP for new products should be higher than the ratio of the base production costs of those two product types, that is, $\frac{\delta}{1+i} > \gamma$, for q_{Or}^{R} to be increasing in c_0. The prices of new and remanufactured products are increasing in their WTPs, i and δ, respectively, and in the cost terms, c_0, k_v, and δ, when the constraint is not binding.

When the constraint is binding, the optimal production quantity increases with i if k_v is not higher than $\frac{2\delta+c_0(1+\gamma)}{1+3\delta}$, and the changes in q_{On}^{R} and q_{Or}^{R} are monotonically decreasing in the cost parameters, i.e., γ, c_0, or k_v. Further, the prices p_{On}^{R} and p_{Or}^{R} are increasing in their own WTPs, i and δ, respectively, whereas the cross-price effects of their WTPs are not straightforward. If $\frac{c_0(1+\gamma)+k_v i}{1+i+\delta} < \frac{1+i-3\delta}{2(1+i)}$, then a higher WTP of the remanufactured products δ leads to an increase in the price of the new products. Similarly, if $\frac{2\delta+c_o(1+\gamma)}{1+3\delta} < k_v$, a higher innovation level i also increases the price of the remanufactured products because of the decrease in the remanufacturing quantity due to the decrease in the new-product quantity.

OEM upgrades

When the products on the market are the OEM's new and upgraded products, the price functions reduce to $p_{On} = (1+i)(1-q_{On}-\delta q_{Ou})$ and $p_{Ou} = \delta(1+i)(1-q_{On}-q_{Ou})$, respectively. Consequently, the OEM's optimization problem is as follows:

$$
\begin{aligned}
\pi_O(q_{On}, q_{Ou}) = {} & q_{On}((1+i)(1-q_{On}-\delta q_{Ou}) - c_0 - k_v i) \\
& + q_{Ou}((1+i)\delta(1-q_{On}-q_{Ou}) - \gamma c_0 - k_v i) - k_f i^2, \\
\text{subject to} : {} & 0 \le q_{Ou} \le q_{On}.
\end{aligned}
$$

The regions defining upgrading strategy are given by

$$
\begin{aligned}
S_0^U &= \{(\delta-\gamma)c_0 - (1-\delta)k_v i < 0\}, \\
S_u^U &= \{0 \le (\delta-\gamma)c_0 - (1-\delta)k_v i < \delta((1-\delta)(1+i) - (1-\gamma)c_0)\}, \\
S_c^U &= \{\delta((1-\delta)(1+i) - (1-\gamma)c_0) \le (\delta-\gamma)c_0 - (1-\delta)k_v i\}.
\end{aligned}
$$

Proposition 3 *When the OEM offers new and upgraded end-of-use products, the optimal quantities and prices are given by*

$$
q_{On}^U = \begin{cases} \frac{1-c_0+i(1-k_v)}{2(1+i)}, & S_0^U, \\ \frac{(1-\delta)(1+i)-(1-\gamma)c_0}{2(1+i)(1-\delta)}, & S_u^U, \\ \frac{(1+i)(1+\delta)-(1+\gamma)c_0-2k_v i}{2(1+i)(1+3\delta)}, & S_c^U, \end{cases} \quad \text{and} \quad q_{Ou}^U = \begin{cases} 0, & S_0^U, \\ \frac{(\delta-\gamma)c_0-(1-\delta)k_v i}{2\delta(1+i)(1-\delta)}, & S_u^U, \\ \frac{(1+i)(1+\delta)-(1+\gamma)c_0-2k_v i}{2(1+i)(1+3\delta)}, & S_c^U. \end{cases}
$$

$$
p_{On}^U = \begin{cases} \frac{1+c_0+i(1+k_v)}{2}, & S_0^U \ \& \ S_u^U, \\ \frac{(1+i)\left(1+4\delta-\delta^2\right)+(1+\delta)((1+\gamma)c_0+2k_v i)}{2(1+3\delta)}, & S_c^U. \end{cases}
$$

$$
p_{Ou}^U = \begin{cases} NA, & S_0^U, \\ \frac{(1+i)\delta+\gamma c_0+k_v i}{2}, & S_u^U, \\ \frac{\delta(2(1+i)+(1+\gamma)c_0+2k_v i)}{(1+3\delta)}, & S_c^U. \end{cases}
$$

Upgrading is profitable when the cost of adding innovative features is lower than a certain threshold, $k_v < \frac{\delta-\gamma}{(1-\delta)i}$. Note that this condition gets tighter with an increase in i, but looser with an increase in δ. With respect to no remanufacturing, remanufacturing and upgrading do not affect the price of new products, and yields lower optimal quantities of new products (see Table 1.3). When the remanufacturing resource constraint is not binding, both new and upgraded products benefit from a WTP increase, with an increase in

Table 1.3: Parameter sensitivity when the OEM upgrades and innovation is exogenous

	Non-binding				Binding		
	q^U_{On}	q^U_{Ou}	p^U_{On}	p^U_{Ou}	$q^U_{On} = q^U_{Ou}$	p^U_{On}	p^U_{Ou}
i	$+$	$-$	$+$	$+$	?	$+$	$+$
δ	$-$	$+$	0	$+$	?	?	$+$
γ	$+$	$-$	0	$+$	$-$	$+$	$+$
c_0	$-$	$+$	$+$	$+$	$-$	$+$	$+$
k_v	0	$-$	$+$	$+$	$-$	$+$	$+$

the innovation level i; however, the WTP difference between new and upgraded products $(1+i)(1-\delta)$ is increasing in i. As a result, q^U_{On} is increasing in i, while q^U_{Ou} is decreasing in i. The parameters δ and γ have opposite effects on the optimal quantities of new and upgraded products. While an increase in δ (a decrease in γ) decreases the new-product quantity, it increases the upgrading quantity.

A higher unit cost c_0 leads to a lower new-product quantity q^U_{On} and higher upgraded-product quantity q^U_{Ou}. Further, an increase in k_v has a decreasing effect on q^U_{Ou}, whereas it has no effect on q^U_{On} since the negative effect of an increase in the cost is compensated for by a decrease in the upgrading quantity for new products. The prices p^U_{On} and p^U_{Ou} are increasing in i, which is due to the increase in the WTP. Similarly, a higher δ leads to a higher p^U_{Ou}. The higher are the cost parameters c_0, γ, and k_v, the higher p^U_{On} and p^U_{Ou}, independently of the remanufacturing resource constraint.

When the constraint is binding, q^U_{On} increases with i if $k_v < \frac{(1+\gamma)c_0}{2}$. When the sum of the unit cost of producing new products and the unit cost of upgrading end-of-use products, $(1+\gamma)c_0 + 2k_v$, is higher than $\frac{2(1+i)}{3}$, then a higher relative valuation for the upgraded products increases the optimal production quantity. The higher are the cost parameters c_0, γ, and k_v, the lower q^U_{On} and q^U_{Ou} when the resource constraint is binding. The price of the new (upgraded) product increases with i (with i and δ).

Profit, consumer surplus, and environmental benefits

We wrap up the profitability results in the no competition case.

Proposition 4 *The OEM*

1. *remanufactures if* $(\delta-\gamma)c_0+(\delta k_v-\gamma c_0)i>0$*;*

2. *upgrades if* $(\delta-\gamma)c_0-(1-\delta)k_v i>0$*;*

3. *prefers upgrading over remanufacturing if* $\frac{\gamma c_0-k_v}{(\delta-\gamma)c_0+(\delta k_v-\gamma c_0)i}>\frac{-1}{(1-\delta)+\sqrt{(1-\delta)(1+i-\delta)}}$.

Table 1.4: Profit of the OEM in monopoly settings

	Profit of the OEM (π_O)
NR	$\frac{(1-c_0+i(1-k_v))^2}{4(1+i)}-k_f i^2$
R	$\pi^{NR}+\frac{((\delta-\gamma)c_0+(\delta k_v-\gamma c_0)i)^2}{4\delta(1+i)(1+i-\delta)}$
U	$\pi^{NR}+\frac{((\delta-\gamma)c_0-(1-\delta)k_v i)^2}{4\delta(1+i)(1-\delta)}$

The profitability of remanufacturing requires that the rate of the unit production cost to the WTP for new products should be higher than that for remanufactured products, i.e., $\frac{c_n}{1+i}>\frac{c_r}{\delta}$, which is equivalent to $(\delta-\gamma)c_0+(\delta k_v-\gamma c_0)i>0$. In other words, to be introduced, remanufactured products should be more cost-efficient than new products. Similarly, in order for the OEM to introduce upgraded products, they should be more cost-efficient than new products, i.e., $\frac{c_n}{1+i}>\frac{c_u}{(1+i)\delta}$, or $(\delta-\gamma)c_0-(1-\delta)k_v i>0$. When both remanufacturing and upgrading end-of-use products are profitable, upgrading is more profitable for the OEM if $\frac{\gamma c_0-k_v}{(\delta-\gamma)c_0+(\delta k_v-\gamma c_0)i}>\frac{-1}{(1-\delta)+\sqrt{(1-\delta)(1+i-\delta)}}$. Given that upgrading is more profitable, if $\gamma c_0>k_v$, the profit difference decreases with the relative WTP of remanufactured products δ and increases with innovation level i; otherwise, the profit difference increases with δ and decreases with i. If $\gamma c_0>k_v$, whenever remanufacturing is profitable, upgrading is profitable too. Similarly, if $\gamma c_0<k_v$, whenever upgrading is profitable, remanufacturing is profitable too. The regions where optimal remanufacturing and upgrading quantities satisfy the remanufacturing resource constraint are already defined as S_r^u and S_u^u, respectively. If $\frac{\delta-\gamma c_0}{\delta-k_v}>1+\delta$, S_u^u is larger than S_r^u.

As shown in Table 1.4 and Table 1.5, consumer preferences are aligned with the OEM's preference. When remanufacturing (upgrading) is profitable for the OEM, the

Table 1.5: Summary of monopoly OEM settings

	Consumer Surplus (CS)	Material Usage (M)
NR	$\frac{(1-c_0+i(1-k_v))^2}{8(1+i)}$	$\frac{1-c_0+i(1-k_v)}{2(1+i)}$
R	$CS^{NR}+\frac{((\delta-\gamma)c_0+(\delta k_v-\gamma c_0)i)^2}{8\delta(1+i)(1+i-\delta)}$	$M^{NR}-\frac{((\delta-\gamma)c_0+(\delta k_v-\gamma c_0)i)(\delta-\gamma(1+i))}{2\delta(1+i-\delta)(1+i)}$
U	$CS^{NR}+\frac{((\delta-\gamma)c_0-(1-\delta)k_v i)^2}{8\delta(1+i)(1-\delta)}$	$M^{NR}-\frac{(\delta-\gamma)((\delta-\gamma)c_0-(1-\delta)k_v i)}{2\delta(1-\delta)(1+i)}$

consumer surplus with remanufacturing CS^R (the consumer surplus with upgrading CS^U) is higher than the consumer surplus without remanufacturing CS^{NR}. When upgrading is more profitable for the OEM than remanufacturing, the consumer surplus with upgrading CS^U is higher than the consumer surplus with remanufacturing CS^R.

The conditions that make upgrading profitable also guarantee that upgrading is better for the environment than not remanufacturing, $M^U < M^{NR}$. When $\frac{\delta-\gamma}{(1-\delta)i} > k_v$, introducing upgraded products is beneficial for the OEM, the consumers, and the environment. The only exception to the environmental superiority of upgrading is when the remanufacturing resource constraint is binding and $\frac{1+i-c_0-k_v}{\delta-\gamma} < \frac{(\delta-\gamma)c_0-(1-\delta)k_v}{(\delta-\gamma)+\delta(1-\gamma)}$. In order for remanufacturing to be more environmental friendly compared to not remanufacturing, $M^R < M^{NR}$, the ratio of the WTP for remanufactured products δ to the WTP for new products $(1+i)$ should be higher than the base manufacturing cost ratio γ, i.e., $\frac{\delta}{1+i} > \gamma$. When this condition is satisfied, introducing remanufactured products is beneficial for the OEM, the consumers, and the environment. When the innovation level is sufficiently high, $i > \frac{(\delta-\gamma)(c_0\delta(1-\gamma)+(1-\delta)(\gamma c_0-k_v))}{(1-\delta)(k_v\delta(1-\gamma)+\gamma(\gamma c_0-k_v))}$, upgrading is more environmental friendly than remanufacturing, $M^U < M^R$.

1.4.2 Case with IR as the remanufacturer

In the following two propositions, we characterize the equilibrium solution when the OEM only produces new products and the IR remanufactures end-of-use products and upgrades end-of-use products, respectively.

IR remanufactures

When the OEM chooses not to remanufacture end-of-use products and the IR uses them for remanufacturing, the inverse-demand functions are given by $p_{On} = (1+i)(1-q_{On}) - \delta q_{Ir}$ and $p_{Ir} = \delta(1-q_{On}-q_{Ir})$, respectively. The OEM's and the IR's optimization problems are as follows:

$$\begin{aligned}
\pi_O(q_{On}) &= q_{On}((1+i)(1-q_{On}) - \delta q_{Ir} - c_0 - k_v i) - k_f i^2, \\
\pi_I(q_{Ir}) &= q_{Ir}(\delta(1-q_{On}-q_{Ir}) - \gamma c_0), \\
\text{subject to} &: 0 \leq q_{Ir} \leq q_{On}.
\end{aligned}$$

The IR's remanufacturing strategy are defined by the following regions:

$$\begin{aligned}
S_0^{IR} &= \{(1+i)\delta - (2(1+i)\gamma - \delta)c_0 + \delta k_v i < 0\}, \\
S_u^{IR} &= \{0 \leq (1+i)\delta - (2(1+i)\gamma - \delta)c_0 + \delta k_v i < \delta(2+2i-\delta-(2-\gamma)c_0 - 2k_v i)\}, \\
S_c^{IR} &= \{\delta(2+2i-\delta-(2-\gamma)c_0 - 2k_v i) \leq (1+i)\delta - (2(1+i)\gamma - \delta)c_0 + \delta k_v i\}.
\end{aligned}$$

Proposition 5 *When the OEM chooses not to remanufacture or upgrade end-of-use products and the IR uses them for remanufacturing, the equilibrium quantities and prices are given by*

$$q_{On}^{IR} = \begin{cases} \frac{1-c_0+i(1-k_v)}{2(1+i)}, & S_0^{IR}, \\ \frac{2-\delta-(2-\gamma)c_0+2(1-k_v)i}{(4+4i-\delta)}, & S_u^{IR}, \\ \frac{1-c_0+i(1-k_v)}{2(1+i+\delta)}, & S_c^{IR}, \end{cases} \quad \textit{and} \quad q_{Ir}^{IR} = \begin{cases} 0, & S_0^{IR}, \\ \frac{(1+i)\delta-(2(1+i)\gamma-\delta)c_0+\delta k_v i}{\delta(4+4i-\delta)}, & S_u^{IR}, \\ \frac{1-c_0+i(1-k_v)}{2(1+i+\delta)}, & S_c^{IR}. \end{cases}$$

$$p_{On}^{IR} = \begin{cases} \frac{1+c_0+(1+k_v)i}{2}, & S_0^{IR} \\ \frac{(2+2i-\delta)(1+i)+(2+2i-\delta)(c_0+k_v i)+(1+i)\gamma c_0}{4+4i-\delta}, & S_u^{IR} \\ \frac{1+c_0+(1+k_v)i}{2}, & S_c^{IR} \end{cases}$$

$$p_{Ir}^{IR} = \begin{cases} NA, & S_0^{IR} \\ \frac{\delta(1+i)+(2+2i-\delta)\gamma c_0+\delta(c_0+k_v i)}{4+4i-\delta}, & S_u^{IR} \\ \frac{\delta(\delta+c_0+k_v i)}{1+i+\delta}, & S_c^{IR} \end{cases}$$

Table 1.6: Parameter sensitivity when the IR remanufactures and innovation is exogenous

	Non-binding				Binding		
	q_{On}^{IR}	q_{Ir}^{IR}	p_{On}^{IR}	p_{Ir}^{IR}	$q_{On}^{IR}=q_{Ir}^{IR}$	p_{On}^{IR}	p_{Ir}^{IR}
i	?	?	$+$	?	?	$+$	?
δ	$-$	$+$	$-$	$+$	$-$	0	$+$
γ	$+$	$-$	$+$	$+$	0	0	0
c_0	$-$	?	$+$	$+$	$-$	$+$	$+$
k_v	$-$	$+$	$+$	$+$	$-$	$+$	$+$

For the IR to remanufacture, the ratio of the maximum profit margin of remanufacturing to the WTP for remanufactured products should be at least half the ratio of the maximum profit margin of new products to the WTP for new products, that is, $\frac{(\delta-\gamma c_0)}{\delta} > \frac{(1-c_0+(1-k_v)i)}{2(1+i)}$. The equilibrium quantity and price of new products (q_{On}^{IR} and p_{On}^{IR}) decrease with the entrance of the IR.

The effect of the increase in the innovation level i on q_{On}^{IR} and q_{Ir}^{IR} depends on the market conditions. When the remanufacturing resource constraint is non-binding and $\frac{\delta+(2-\gamma)c_0}{4-\delta} > k_v$, the variations in q_{On}^{IR} and q_{Ir}^{IR} with a change in i are as expected, namely, an increase in i increases q_{On}^{IR} but decreases q_{Ir}^{IR}. If $\frac{\delta+(2-\gamma)c_0}{4-\delta} < k_v$, then the changes in the production quantities are opposite as the innovation level i increases. Contrary to the costly added value of the innovation level i, δ increases the valuation of the remanufactured products without any cost. Consequently, an increase in δ leads to lower q_{On}^{IR} and higher q_{Ir}^{IR} (see Table 1.6).

The OEM's equilibrium quantity of new products decreases with its cost terms, c_0 and k_v, and increases with the cost term of the IR, γ. If the relative cost of remanufacturing to the cost of producing new products is lower than the threshold, i.e., $\gamma < \frac{\delta}{2(1+i)}$, then an increase in c_0 affects more the OEM than on the IR, so that the IR's equilibrium remanufacturing quantity increases with c_0. As presented in Table 1.6, a higher γ or a lower k_v decreases the remanufacturing quantity. The higher the cost terms c_0, k_v, and γ, or the lower the WTP terms i and δ, the lower are the prices of the new and remanufactured products.

When the constraint is binding, q_{On}^{IR} increases with i and decreases with δ. Even though the remanufacturing quantity decreases with δ due to the reduction in remanufacturing resources, the increase in price compensates for the decrease in the remanufacturing quantity, and the IR's profit increases. If $k_v > \frac{\delta+c_0}{1+\delta}$, then this cost dominates the effect of the increased valuation for the new products and q_{On}^{IR}decreases with i. If that condition holds, the price of the remanufactured products decreases with i due to less strict competition.

IR upgrades

When the OEM chooses not to remanufacture or upgrade end-of-use products but the IR uses them for upgrading, the inverse-demand functions are given by $p_{On} = (1+i)(1-q_{On}) - (1+\alpha i)\,\delta q_{Iu}$ and $p_{Iu} = \delta(1+\alpha i)(1-q_{On}-q_{Iu})$, respectively. The OEM's and the IR's optimization problems are as follows:

$$
\begin{aligned}
\pi_O(q_{On}) &= q_{On}((1+i)(1-q_{On}) - (1+\alpha i)\,\delta q_{Iu} - c_0 - k_v i) - k_f i^2,\\
\pi_I(q_{Iu}) &= q_{Iu}(\delta(1+\alpha i)(1-q_{On}-q_{Iu}) - \gamma c_0 - k_v \alpha i),\\
&\text{subject to} : 0 \le q_{Iu} \le q_{On}.
\end{aligned}
$$

Formally, the regions defining the upgrading strategy are given by

$$
\begin{aligned}
S_0^{IU} &= \left\{ \frac{\delta(1+\alpha i) - (\gamma c_0 + k_v i)}{\delta(1+\alpha i)} \le \frac{1+i-(c_0+k_v i)}{2(1+i)} \right\}.\\
S_u^{IU} &= \left\{ \frac{1+i-(c_0+k_v i)}{2(1+i)} < \frac{\delta(1+\alpha i) - (\gamma c_0 + k_v i)}{\delta(1+\alpha i)} \; \& \right.\\
&\quad 3\delta(1+\alpha i)(1-\gamma)c_0 < ((1+i) - \delta(1+\alpha i))(\delta(1+\alpha i) + 2(\gamma c_0 + k_v i))\},\\
S_c^{IU} &= \{((1+i) - \delta(1+\alpha i))(\delta(1+\alpha i) + 2(\gamma c_0 + k_v i)) < 3\delta(1+\alpha i)(1-\gamma)c_0\}.
\end{aligned}
$$

Let $K_{On}(i)$, K_{xr} and $K_{xu}(i)$, $x \in \{O, I\}$ be the maximum profit margins for new, remanufactured, and upgraded products, respectively. They are given by

$$\begin{aligned}
K_{On}(i) &= (1+i) - c_0 - k_v i, \\
K_{Ou}(i) &= \delta(1+i) - \gamma c_0 - k_v i, \\
K_{Iu}(i) &= \delta(1+\alpha i) - \gamma c_0 - k_v \alpha i, \\
K_{xr} &= \delta - \gamma c_0.
\end{aligned}$$

Proposition 6 *When the OEM chooses not to remanufacture end-of-use products but the IR uses them for upgrading, the equilibrium quantities and prices are given by*

$$q_{On}^{IU} = \begin{cases} \frac{K_{On}(i)}{2(1+i)}, & S_0^{IU}, \\ \frac{2K_{On}(i)-K_{Iu}(i)}{4(1+i)-\delta(1+\alpha i)}, & S_u^{IU}, \\ \frac{K_{On}(i)}{2((1+i)+\delta(1+\alpha i))}, & S_c^{IU}, \end{cases} \quad and \;\; q_{Iu}^{IU} = \begin{cases} 0, & S_0^{IU}, \\ \frac{2(1+i)K_{Iu}(i)-\delta(1+\alpha i)K_{On}(i)}{\delta(1+\alpha i)(4(1+i)-\delta(1+\alpha i))}, & S_u^{IU}, \\ \frac{K_{On}(i)}{2((1+i)+\delta(1+\alpha i))}, & S_c^{IU}. \end{cases}$$

$$p_{On}^{IU} = \begin{cases} \frac{1+c_0+i(1+k_v)}{2}, & S_0^{IU}, \\ \frac{(2(1+i)-\delta(1+\alpha i))(1+c_0+i(1+k_v))+(1+i)(\gamma c_0+k_v\alpha i)}{4(1+i)-\delta(1+\alpha i)}, & S_u^{IU}, \\ \frac{1+c_0+i(1+k_v)}{2}, & S_c^{IU}. \end{cases}$$

$$p_{Iu}^{IU} = \begin{cases} NA, & S_0^{IU}, \\ \frac{\delta(1+\alpha i)(1+c_0+i(1+k_v))+2((1+i)-\delta(1+\alpha i))(\gamma c_0+k_v\alpha i)}{4(1+i)-\delta(1+\alpha i)}, & S_u^{IU}, \\ \frac{\delta(1+\alpha i)((1+\alpha i)+c_0+k_v i)}{(1+i)+\delta(1+\alpha i)}, & S_c^{IU} \end{cases}$$

Table 1.7: Parameter sensitivity when the IR upgrades and innovation is exogenous

	Non-binding				**Binding**		
	q_{On}^{IU}	q_{Iu}^{IU}	p_{On}^{IU}	p_{Iu}^{IU}	$q_{On}^{IU}=q_{Iu}^{IU}$	p_{On}^{IU}	p_{Iu}^{IU}
i	?	?	+	?	?	+	?
δ	−	+	−	+	−	0	+
γ	+	−	+	+	0	0	0
α	?	?	?	+	−	0	+
c_0	−	?	+	+	−	+	+
k_v	−	?	+	+	−	+	+

For the IR to upgrade end-of-use products, the ratio of the maximum profit margin of upgrading to the WTP for upgraded products should be at least half the ratio of the maximum profit margin of new products to the WTP for new products, $\frac{K_{Iu}(i)}{\delta(1+\alpha i)} > \frac{K_{On}(i)}{2(1+i)}$. When the IR upgrades products, the quantity of the new products decreases, and the price increases. When the remanufacturing resource constraint is non-binding, the effect of the innovation level i depends on the value of the cost of adding innovative features k_v. If $\frac{2\delta(1-\alpha)+(2-\gamma)(4-\alpha\delta)c_0}{(4-\delta)(2-\alpha)} > k_v$, then an increase in i leads to a higher quantity of new products. As shown in Table 1.7, while an increase in δ decreases the equilibrium new-product quantity q_{On}^{IU}, it increases the upgrading quantity q_{Iu}^{IU}. The higher are the OEM's cost terms, c_0 and k_v, the lower q_{On}^{IU}. If the ratio of the remanufacturing cost to the manufacturing cost γ increases, the advantage of the IR diminishes, the equilibrium upgrading quantity of the IR q_{Iu}^{IU} decreases, and the new-product quantity q_{On}^{IU} increases. A higher c_0 is not always bad for the IR. If γ is low enough, $\gamma < \frac{\delta(1+\alpha i)}{2(1+i)}$, the higher cost's negative impact on the IR is less than the benefits, thanks to the decrease of q_{On}^{IU} and increase of q_{Iu}^{IU} in γ. Similarly, if the spillover rate α is lower than $\frac{\delta}{2+2i-\delta}$, the higher cost of adding innovative features k_v increases the upgrading quantity due to a large decrease in the new-product quantity. Further, if

$$k_v > \frac{\delta^2(1+i)(1+\alpha i)^2 + c_0(\delta^2 - 4\delta\gamma(1+i)(1+\alpha i) + 8\gamma(1+i)^2)}{8(1+i)^2 - 2\delta(1-\alpha^2 i^2)(1+i) - \delta^2 i(1+\alpha i)^2},$$

an increase in the spillover rate α decreases the upgrading quantity q_{Iu}^{IU}. The higher the spillover rate, the higher the price of the upgraded products p_{Iu}^{IU}. If $\frac{\delta(2(1+i)+c_0(2-\gamma))}{4(1+i)-\delta(1+2i)} < k_v$, an increase in α boosts q_{On}^{IU} and decreases p_{On}^{IU}. A higher relative WTP for the remanufactured products δ decreases p_{On}^{IU} and increases p_{Iu}^{IU}. The higher the cost terms, c_0, γ, and k_v, the higher the equilibrium prices for both product types.

When the constraint is binding, if $k_v < \frac{\delta(1-\alpha)+c_0(1+\alpha\delta)}{1-\delta}$, then q_{On}^{IU} increases with i. With higher δ or α, customers value the upgraded products more, and the superiority of new products diminishes. As a result, q_{On}^{IU} decreases, and the price of the upgraded products p_{Iu}^{IU} increases with δ or α. As shown in Table 1.7, the higher c_0 or k_v, the lower q_{On}^{IU}. The price of the new products p_{On}^{IU} increases with the innovation level i.

Profit, consumer surplus, and environmental benefits

Table 1.8: Profits under duopoly setting

	Profit of the OEM (π_O)	Profit of the IR (π_I)
NR	$\frac{(K_{On}(i))^2}{4(1+i)} - k_f i^2$	NA
IR	$\frac{(i+1)(2K^n(i)-K_{Ir})^2}{(4+4i-\delta)^2} - k_f i^2$	$\frac{(2(1+i)K_{Ir}-\delta K_{On}(i))^2}{\delta(4+4i-\delta)^2}$
IU	$\frac{(i+1)(2K^n(i)-K_{Iu}(i))^2}{(4(1+i)-\delta(1+\alpha i))^2} - k_f i^2$	$\frac{(2(1+i)K_{Iu}(i)-\delta(1+\alpha i)K_{On}(i))^2}{\delta(1+\alpha i)(4(1+i)-\delta(1+\alpha i))^2}$

For remanufacturing to be profitable to the IR, the ratio of the maximum profit margin of remanufacturing to the WTP for remanufactured products should be at least half that of the new products, $\frac{K_{Ir}}{\delta} > \frac{K_{On}(i)}{2(1+i)}$,. Similarly, in order for upgrading to be profitable to the IR, the ratio of the maximum profit margin from upgrading to the WTP for the upgraded product should be at least half that of the new products, $\frac{K_{Iu}(i)}{\delta(1+\alpha i)} > \frac{K_{On}(i)}{2(1+i)}$. Upgrading is more profitable than remanufacturing for the IR if $q_{On}^{IU} > \frac{2(1+i)\alpha i(k_v-\gamma c_0)}{(4+4i-\delta)\sqrt{1+\alpha i}}$ is satisfied. If the cost of adding innovative features k_v is less than the cost of remanufacturing γc_0, upgrading is always more profitable for the IR. The profit of the OEM decreases with competition from either a remanufacturing IR or an upgrading IR. The OEM prefers for the IR to upgrade rather than remanufacture if $k_v > \frac{\delta(2(1+i)+c_0(2-\gamma))}{4(1+i)-\delta(1+2i)}$. We wrap up the profitability results in

Proposition 7 *The IR*

1. *remanufactures if* $\frac{K_{Ir}}{K_{On}(i)} > \frac{\delta}{2(1+i)}$*;*
2. *upgrades if* $\frac{K_{Iu}(i)}{K_{On}(i)} > \frac{\delta(1+\alpha i)}{2(1+i)}$*;*
3. *prefers upgrading over remanufacturing if* $\frac{2K_{On}(i)-K_{Iu}(i)}{4(1+i)-\delta(1+\alpha i)} > \frac{2(1+i)\alpha i(k_v-\gamma c_0)}{(4+4i-\delta)\sqrt{1+\alpha i}}$.

As summarized in Table 1.9, material usage increases with the entrance of the IR onto the market with remanufacturing (upgrading) if the material usage rate for remanufacturing γ is higher than $\frac{\delta}{2(1+i)}$ $\left(\frac{\delta(1+\alpha i)}{2(1+i)}\right)$. The condition for remanufacturing to be more

Table 1.9: Material usage under duopoly setting

	Material Usage (M)
NR	$\frac{1-c_0+i(1-k_v)}{2(1+i)}$
IR	$M^{NR} - \frac{(\delta-2\gamma(1+i))}{2(1+i)} q_{Ir}^{IR}$
IU	$M^{NR} - \frac{(\delta(1+\alpha i)-2\gamma(1+i))}{2(1+i)} q_{Iu}^{IU}$

environmentally friendly compared to not remanufacturing is more strict than that of upgrading; whenever remanufacturing is beneficial for the environment, upgrading is too. If $\frac{\delta}{2(1+i)} < \gamma < \frac{\delta}{(1+i)} \left(\frac{\delta(1+\alpha i)}{2(1+i)} < \gamma\right)$, then remanufacturing (upgrading) by the OEM is beneficial for the environment while remanufacturing (upgrading) by the IR is not beneficial for the environment.

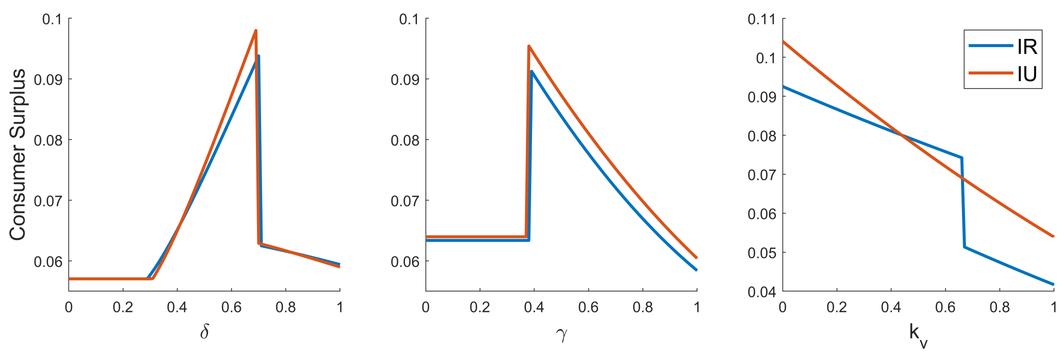

Figure 1.1: Change in the consumer surplus when innovation is not a decision variable

We can observe that the consumer surplus increases with the improvement in the IR's competitive position when the remanufacturing resource constraint is not binding. As illustrated in Figure 1.1, an increase in the relative WTP for the remanufactured or upgraded products δ and a decrease in the ratio of the remanufacturing cost to the manufacturing cost γ raises the consumer surplus. However, when the remanufacturing resource constraint is binding, the OEM decreases the new product quantity, and CS decreases with the increase in δ. Since the new product quantity is independent of γ when the resource constraint is binding, CS does not change with it. As expected, an increase in a cost term k_v decreases the quantity supplied to the market, so consumers suffer from that cost increase as well. From Figure 1.1, we can observe that consumers prefer the IR to upgrade more than to remanufacture except when δ is low or k_v is moderate.

1.4.3 Summary of remanufacturing strategy

We wrap up what we have obtained so far on who remanufactures/upgrades. Let

$$X = \left\{ \frac{\gamma c_0 - k_v}{(\delta-\gamma)c_0 + (\delta k_v - \gamma c_0)i} > \frac{-1}{(1-\delta)+\sqrt{(1-\delta)(1+i-\delta)}} \right\},$$
$$Y = \left\{ \frac{2K^n(i) - K^u(i)}{4(1+i)-\delta(1+\alpha i)} > \frac{2(1+i)\alpha i(k_v - \gamma c_0)}{(4+4i-\delta)\sqrt{1+\alpha i}} \right\},$$

and denote by X' (respectively, Y'), the complement of region X (respectively, Y). X (Y) defines the region where the OEM (the IR) prefers upgrading over remanufacturing. The following table summarizes the results obtained in the five considered settings, namely, the OEM does not remanufacture (*NR*), remanufactures (*R*), and upgrades (*U*) the end-of-use products; and the IR remanufactures (*IR*) and upgrades (*IU*) the end-of-use products. (The spillover rate α is taken as 1 for the ease of comparison of the OEM's and the IR's remanufacturing strategies, hence $K_{Iu}(i) = K_{Ou}(i)$)

$\frac{K_{xr}}{K_{On}(i)}, \frac{K_{xu}(i)}{K_{On}(i)} \in$	$\left[0, \frac{\delta}{2(1+i)}\right]$	$\left[\frac{\delta}{2(1+i)}, \frac{\delta}{2}\right]$	$\left[\frac{\delta}{2}, \frac{\delta}{(1+i)}\right]$	$\left[\frac{\delta}{(1+i)}, \delta\right]$	$[\delta, 1]$
X	*NR*	*NR*	*NR*	*NR*	*U*
X'	*NR*	*NR*	*NR*	*R*	*R*
Y	*NR*	*NR*	*IU*	*IU*	*IU*
Y'	*NR*	*IR*	*IR*	*IR*	*IR*

We can observe that the IR is more greedy to remanufacture and to include the innovative features to remanufactured products compared to the OEM with lower maximum profit margin ratio of remanufactured products with respect to new products. Even though remanufactured/upgraded products can be sold with a positive profit margin, the OEM should also consider the demand decrease in new products due the introduction of remanufactured/upgraded products. This consideration is behind the difference in the remanufacturing strategies of the OEM and the IR.

1.5 Endogenous innovation level

Up to now, we have assumed that the innovation level is given. In this section, we endogenize it, which comes with the cost of having to proceed with a numerical analysis, because it is not possible to get any qualitative insight analytically. We find the profit-maximizing innovation level for the OEM by comparing the OEM's profit with discretized innovation levels in $[0,1]$ with 0.001 step size for a given parameter set. First, to observe the individual effects of the parameters for the base parameter set, we find equilibrium outcome for each parameter varying in $[0,1]$ with 0.001 step size while keeping the rest unchanged. Then, to check whether those individual effects are robust to changes in other parameters, we repeat this process by combining low, base and high values of the other parameters (see Table 1.10). If the effect of a parameter on the outcome depends on other parameters, the related discussion is provided in detail. As before, we start by considering that only the OEM is in the market, and then the IR enters.

Table 1.10: The levels of the parameters used in numerical analysis for robustness check

	low	base	high
δ	0.3	0.6	0.9
γ	0.2	0.5	0.8
α	0.5	0.8	1
c_0	0.2	0.4	0.6
k_v	0.1	0.3	0.5
k_f	0.3	0.5	0.8

The diagonal arrows, $\nearrow$ and $\searrow$, represent incremental increases and decreases in the results and the vertical arrows, $\uparrow$ and $\downarrow$, represent jumps and drops in the results. The jumps and drops in the outcome that are represented with the vertical arrows are caused by the remanufacturing resource constraint becoming binding or non-binding with a change in a parameter. Multiple arrows in a cell means that the effect of the parameter on the outcome is not monotone. Question mark defines the cases where the effect of the parameter in concern is dependent on other parameters. If the effect of a parameter on a performance is different when the remanufacturing resource constraint is binding, then we indicate the effect of parameter with bold arrows to distinguish.

1.5.1 Case with IR as the remanufacturer

Table 1.11: Parameter sensitivity when the OEM and the IR do not remanufacture

	i^{NR}	π_O^{NR}	q_{On}^{NR}	M^{NR}	CS^{NR}
c_0	$\nearrow\searrow$	$\searrow$	$\searrow$	$\searrow$	$\searrow$
k_v	$\searrow$	$\searrow$	$\searrow\nearrow$	$\searrow\nearrow$	$\searrow$
k_f	$\searrow$	$\searrow$	$\searrow$	$\searrow$	$\searrow$

The optimal innovation level i^{NR} is decreasing in the cost of adding innovative features k_v and in the innovation investment cost k_f. If $k_v > c_0$, the optimal new product quantity q_{On}^{NR} is decreasing in i, hence it increases with k_v. The OEM chooses a higher level of innovation with an increase in c_0 to compensate for the revenue loss due to the decrease in q_{On}^{NR}, whereas, with a further increase in c_0, q_{On}^{NR} is not large enough to bring additional revenue that compensates for the cost of innovation investment, and hence, i^{NR} decreases with c_0. The profit of the OEM π_O^{NR} decreases with any of the cost terms, c_0, k_v, or k_f. Even though there is an increase in the optimal innovation level with a higher base manufacturing cost up to a point, the increase in the innovation level is not sufficient to generate a higher profit for the OEM π_O^{NR} and a higher consumer surplus CS^{NR}.

Table 1.12: Parameter sensitivity when the OEM remanufactures

	i^R	π_O^R	q_{On}^R	q_{Or}^R	M^R	CS^R
δ	$\nearrow\searrow\boldsymbol{?}$	$\nearrow$	$\searrow\boldsymbol{?}$	$\nearrow\boldsymbol{?}$	$\nearrow\searrow?$	$\searrow\nearrow$
γ	$\boldsymbol{\searrow}\nearrow$	$\searrow$	$\boldsymbol{\searrow}\nearrow$	$\searrow$	$\nearrow$	$\searrow$
c_0	$\nearrow\searrow$	$\searrow$	$\searrow$	$\nearrow\boldsymbol{\searrow}$	$\searrow$	$\searrow$
k_v	$\searrow$	$\searrow$	$\searrow\nearrow$	$\nearrow\searrow$	$\searrow\nearrow$	$\searrow$
k_f	$\searrow$	$\searrow$	?	?	$\searrow$	$\searrow$

As shown in Table 1.12, when the remanufacturing resource constraint is non-binding, the optimal innovation level i^R first increases then decreases with the relative WTP for remanufactured products δ. If the base manufacturing cost is higher than the cost of adding innovative features, $c_0 > k_v$, then δ should be higher for remanufacturing to be profitable, and we cannot see the part that innovation increases with δ. When the constraint is binding, i^R decreases (increases) with a higher δ if c_0 is low (high). When the remanufacturing resource constraint is non-binding, q^R_{On} (q^R_{Or}) decreases (increases) with δ. The improvement in consumer perception toward remanufactured products is usually beneficial for all parties, that is, a larger δ increases the OEM's profit π^R_O, increases the consumer surplus CS, and decreases the material usage M^R. Only when remanufacturing is just becoming profitable, can M increase, and CS^R decrease with δ. When the constraint is non-binding (binding), i^R and q^R_{On} increase (decrease) with the ratio of the remanufacturing cost to the manufacturing cost γ. The optimal remanufacturing quantity q^R_{Or} is always decreasing in γ. The loss in the OEM's profit and in the consumer surplus cannot be compensated for by the increase in the new product quantity q^R_{On} when γ increases. Only when the cost of developing innovative features k_f and the cost of adding them to the products k_v are low enough, are the negative effects of the decrease in remanufacturing quantity q^R_{Or} due to an increase in γ compensated by the increases in the innovation level and the new product quantity with a further increase in γ. Only when c_0 is too high and the remanufacturing constraint is binding, does a decrease in γ increase the material usage M. As can be seen in Table 1.12, an increase in c_0, k_f, or k_v is always detrimental for the OEM and the consumers, and usually beneficial for the environment.

Table 1.13: Parameter sensitivity when the OEM upgrades

	i^U	π^U_O	q^U_{On}	q^U_{Ou}	M^U	CS^U
δ	$\searrow\boldsymbol{\nearrow}$**?**	$\nearrow$	$\searrow$**?**	$\nearrow$**?**	$\searrow$**?**	$\searrow\boldsymbol{\nearrow}$
γ	**?**$\nearrow$	$\searrow$	$\boldsymbol{\searrow}\nearrow$	$\searrow$	**?**$\nearrow$	$\boldsymbol{\searrow}\nearrow$
c_0	$\nearrow\searrow$	$\searrow$	$\searrow$	$\nearrow\boldsymbol{\searrow}$	$\searrow$	$\searrow$
k_v	$\searrow$	$\searrow$	$\searrow$	$\searrow$	$\searrow\nearrow$	$\searrow$
k_f	$\searrow$	$\searrow$	?	$\nearrow$**?**	?	$\searrow$

If the remanufacturing resource constraint is non-binding, then i^U decreases with the relative WTP for the remanufactured products δ; otherwise, it increases when the OEM upgrades the end-of-use products. An increase in δ or a decrease in γ always improves the OEM's profit and the environmental performance if the constraint is non-binding.

However, the increase in δ does not always mean an improvement for the consumers, as the consumer surplus CS^U may decrease with δ due to a lower innovation level i^U and new-product quantity q_{On}^U. As reported in Table 1.13, when the constraint is non-binding, i^U increases with the ratio of the remanufacturing cost to the manufacturing cost of new products γ. When the constraint is binding, the impact of γ on i^U depends on c_0 and k_v. With a high c_0 or low k_v, i^U decreases with γ; otherwise, it increases with γ. When the constraint is non-binding, the material usage M^U increases with γ. When the constraint is binding and c_0 is too high, the effect of an increase in γ on production quantities is very high, so the material usage decreases with γ. As can be seen from Table 1.12 and Table 1.13, the effects of the base manufacturing cost c_0 and the cost of adding innovative features k_v on the performance measures, π_O, CS, and M, are the same in settings where the OEM remanufactures and where the OEM upgrades. If the base manufacturing cost c_0 is low enough, then the lower the innovation investment cost coefficient k_f, the higher the profit of the OEM π_O^U and consumer surplus CS^U, and the lower the material usage M^U; otherwise M^U increases as k_f goes down.

1.5.2 Case with IR as the remanufacturer

With an increase in the customer valuation toward remanufactured products δ, the OEM loses its advantageous position and obtains a lower market share. With a higher δ and an increase in the remanufacturing quantity q_{Ir}^{IR}, the consumer surplus CS^{IR} increases until the remanufacturing supply constraint becomes binding. Since the increase in q_{Ir}^{IR} is larger than the decrease in the new product quantity, the material usage goes up with δ. When the remanufacturing resource constraint is binding, the OEM decreases its new product quantity q_{On}^{IR} and indirectly decreases the remanufacturing quantity of the IR q_{Ir}^{IR} with a higher δ. The decrease in production quantities is beneficial for the environment but detrimental to the consumers.

The equilibrium innovation level i^{IR} is increasing (decreasing) in δ if c_0 is low (high) or the cost of adding innovative features k_v is high (low). The outcomes of an increase

Table 1.14: Parameter sensitivity when the IR remanufactures

	i^{IR}	π_O^{IR}	π_I^{IR}	q_{On}^{IR}	q_{Ir}^{IR}	M^{IR}	CS^{IR}
δ	**?**↓↗↘	↘↑**↘**	↗↑**↗**	↘↓**↗↘**	↗↓**↗↘**	↗↘↓**↗↘**	↗↓**↗↘**
γ	**↘**↑?	**↘**↗	**↘**↓↘	**↘**↓↗	**↘**↑↘	**↗**↑↗↘	**↘**↑↘
c_0	↗↘↓**↗↘**	↘	↘↑**↘**	↘↓**↘**	↘↓**↘**	↘↓**↘**	↘↓**↘**
k_v	↘↓**↗↘**	↘	↗↑**↘↗**	↘↓**↗↘**	↗↓**↗↘**	↘↓**↗↘**	↘↓**↗↘**
k_f	↘	↘	↗↑**↗**	↘↓**↘**	↗↓**↘**	↘↓**↘**	↘↓**↘**

in δ and a decrease in γ are very similar. The first difference of the decrease in γ is that it can increase the profit of the IR π_I^{IR} without decreasing the profit of the OEM π_O^{IR} and the consumer surplus CS^{IR}. The second difference is that the equilibrium innovation level i^{IR} does not change with γ when the constraint is binding. The equilibrium innovation level i^{IR} is a concave function of the base manufacturing cost when the remanufacturing resource constraint is either binding or non-binding. When the constraint becomes binding with an increase in c_0, the OEM reduces its new product quantity to decrease the IR's remanufacturing quantity as shown in Table 1.14. The IR benefits from that drop in the quantities supplied to the market thanks to the increase in the remanufactured product price p_{Ir}^{IR}. Since the number of new products that will include innovative features decreases with that reduction, the cost of innovation investment per product unit increases, and the equilibrium innovation level goes down. Consumers lose with reductions in quantities and innovation level. With the decreases in q_{On}^{IR} and q_{Ir}^{IR}, the material usage decreases. An increase in k_v or k_f decreases the OEM's profit π_O^{IR}, material usage M^{IR}, and consumer surplus CS^{IR}; and it increases the IR's profit π_I^{IR}. Only just after the constraint becomes binding with an increase in k_v, the OEM increases its innovation level to limit its losses. As a result of this enhanced innovation, the impact of an increase in k_v reverses the signs of changes in π_I^{IR}, M^{IR}, and CS^{IR}. When the remanufacturing resource constraint becomes binding with an increase in k_f, the OEM produces fewer new product to limit the IR's remanufacturing supply; nevertheless, this drop in both quantities benefits the IR most and the IR realizes a positive jump in its profit, as indicated in Table 1.14. After a certain threshold, an increase in k_v hurts both players since the OEM tries to compensate for the revenue loss due to the decrease in innovation level, with an increase in the new-product quantity, and a higher new-product quantity decreases the IR's profit.

Table 1.15: Parameter sensitivity when the IR upgrades

	i^{IU}	π_O^{IU}	π_I^{IU}	q_{On}^{IU}	q_{Iu}^{IU}	M^{IU}	CS^{IU}
δ	$?\downarrow\boldsymbol{\nearrow}\boldsymbol{\searrow}$	$\searrow\uparrow\boldsymbol{\searrow}$	$\nearrow\uparrow\boldsymbol{\nearrow}$	$\searrow\downarrow\boldsymbol{\nearrow}\boldsymbol{\searrow}$	$\nearrow\downarrow\boldsymbol{\nearrow}\boldsymbol{\searrow}$	$\nearrow\searrow\downarrow\boldsymbol{\nearrow}\boldsymbol{\searrow}$	$\nearrow\downarrow\boldsymbol{\nearrow}\boldsymbol{\searrow}$
γ	$\boldsymbol{\searrow}\uparrow?$	$\boldsymbol{\searrow}\nearrow$	$\boldsymbol{\searrow}\downarrow\searrow$	$\boldsymbol{\searrow}\uparrow\nearrow$	$\boldsymbol{\searrow}\uparrow\searrow$	$\boldsymbol{\nearrow}\uparrow\nearrow\searrow$	$\boldsymbol{\searrow}\uparrow\searrow$
c_0	$\nearrow\searrow\downarrow\boldsymbol{\nearrow}\boldsymbol{\searrow}$	$\searrow$	$\searrow\uparrow\boldsymbol{\searrow}$	$\searrow\downarrow\boldsymbol{\searrow}$	$\searrow\downarrow\boldsymbol{\searrow}$	$\searrow\downarrow\boldsymbol{\searrow}$	$\searrow\downarrow\boldsymbol{\searrow}$
k_v	$\searrow\downarrow\boldsymbol{\searrow}$	$\searrow$	$\searrow\downarrow\boldsymbol{\searrow}\boldsymbol{\nearrow}$	$\searrow\downarrow\boldsymbol{\searrow}\boldsymbol{\nearrow}$	$\searrow\downarrow\boldsymbol{\searrow}\boldsymbol{\nearrow}$	$\searrow\downarrow\boldsymbol{\searrow}\boldsymbol{\nearrow}$	$\searrow\downarrow\boldsymbol{\searrow}$
k_f	$\searrow$	$\searrow$	?	$\searrow\downarrow\boldsymbol{\searrow}$	$\nearrow\downarrow\boldsymbol{\searrow}$	$\searrow\downarrow\boldsymbol{\searrow}$	$\searrow\downarrow\boldsymbol{\searrow}$
α	?	?	?	?	?	$\searrow$	$\searrow$

By checking tables 1.14 and 1.15 together, we can see that the behaviors of the performance measures usually stay the same when the IR decides to add innovative features to its remanufactured products, in other words, when the IR switches from remanufacturing to upgrading, even though the values of those performance measures change. The only difference is the change in the upgrading quantity q_{Iu}^{IU} and the profit of the IR π_I^{IU}, with an increase in the cost of adding innovative features to products k_v. The equilibrium upgrading quantity q_{Iu}^{IU} and the IR's profit π_I^{IU} first decrease, and then increase with k_v, unlike the setting where IR remanufactures. Since the cost of adding innovative features k_v constitutes a higher proportion of the upgrading cost, compared to the production cost of new products, the increase in k_v hurts the IR more than the OEM. With a further increase in k_v, the OEM decreases the innovation investment and the negative effects of a high k_v diminishes for the IR, and its upgrading quantity and profit increase. When k_v is very low, the benefit of the improved valuation for upgraded products with a higher innovation level i exceeds the cost of adding innovative features. Therefore, the IR's profit decreases with the innovation investment cost coefficient k_f. Since the effect of the spillover rate α is proportional to the level of innovation i, the signs of the changes in the performance measures, π_O^{IU}, π_I^{IU}, M^{IU}, and CS^{IU}, with α, are determined by the other parameters when i is low. If the WTP-to-cost ratio of the upgraded products is low, i.e., when the cost of adding innovative features k_v is high or the relative valuation for the remanufactured products δ is low, the equilibrium innovation level i^{IU} and the OEM's profit π_O^{IU} increase and the IR's profit π_I^{IU} decreases with the spillover rate α; otherwise, the outcome of the increase in α is reversed. As seen in Table 1.15, even though the effects of α on the new-product quantity q_{On}^{IU} and upgrading quantity q_{Iu}^{IU} are not consistent, the combined effect of the changes on production quantities is beneficial for the environment but detrimental to the consumers. For the cases where an increase in α makes the constraint binding, there is a jump in performance measures at the equilibrium. When the constraint becomes binding, the innovation level i^{IU}, new product quantity q_{On}^{IU} and upgrading quantity q_{Iu}^{IU} drop. Since the decrease in the new product quantity q_{On}^{IU} is higher than the decrease in the upgrading quantity q_{Iu}^{IU}, the IR's profit increases with a jump. With the drops in production quantities, the material usage M^{IU} and consumer surplus CS^{IU} also drop.

1.5.3 Comparison

The objective of this subsection is to compare the results when the OEM is alone in the market to those obtained when the IR enters the market. The results are presented in Figures 1.2 and 1.3, where we denote by R and U (IR and IU) the regions where remanufacturing and upgrading are profitable for the OEM (the IR) when the remanufacturing resource constraint is non-binding, respectively. The underlined regions, $\underline{R}$, $\underline{U}$, $\underline{IR}$, and $\underline{IU}$, refer to the same regions when the remanufacturing resource constraint is binding.

Figure 1.2 shows that the regions where the OEM remanufactures and does not, are separated, roughly speaking, by the line defined by the ratio $\frac{\delta}{\gamma} = 1$. So, the rule of thumb is that the OEM remanufactures when $\frac{\delta}{\gamma} > 1$, which is equivalent to $\frac{c_r}{c_0} < \delta$, that is, the ratio of the remanufacturing cost to the manufacturing cost is less than the customer valuation of remanufactured products. We can observe from Figure 1.3 that $\frac{\delta}{\gamma}$ is also an important factor for the IR too to enter the market via remanufacturing. However, the value that makes remanufacturing profitable for the IR is lower than the value for the OEM, because the IR does not manufacture new products. The OEM's lost profits in new-product sales cannot be compensated for through remanufacturing or upgrading if $\frac{\delta}{\gamma}$ is not sufficiently high, whereas the IR remanufactures with a lower threshold. Unlike for the OEM, the ratio for the IR is affected more by the changes in other problem parameters. We can

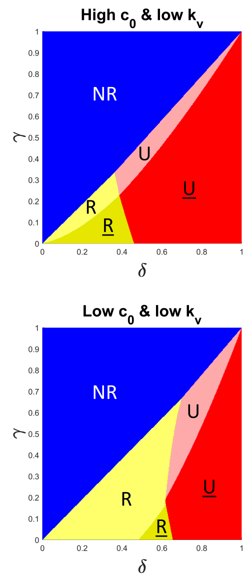

Figure 1.2: The remanufacturing strategy of the OEM in monopolistic settings

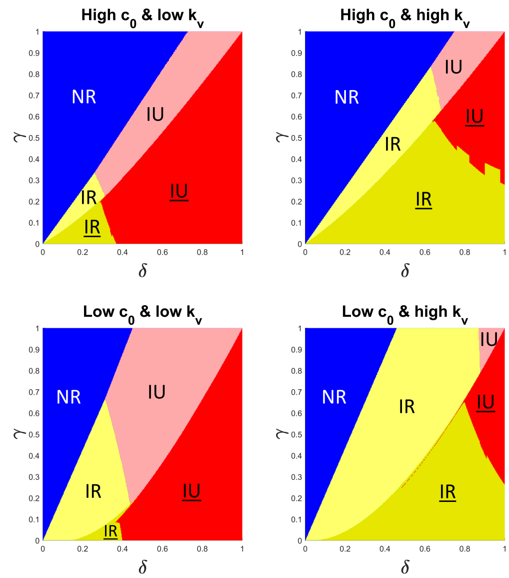

Figure 1.3: The remanufacturing strategy of the IR in duopolistic settings

observe that the ratio is smaller when the base manufacturing cost c_0 is low but is not significantly affected by the change in k_v.

While the increase in δ always motivates the OEM and the IR to include innovative features in the remanufactured products, the effects of an increase in γ depend on the other problem parameters and whether the constraint is binding for the OEM. When the remanufacturing constraint is binding, an increase in γ always makes upgrading preferable compared to remanufacturing, whereas c_0 must be low and k_v high for that to be true when the constraint is non-binding for the OEM. For the IR, an increase in γ always motivates it to switch from remanufacturing to upgrading.

From Figure 1.2 and Figure 1.3, we can observe that the regions where remanufacturing is more profitable for the OEM, $R+\underline{R}$, and for the IR, $IR+\underline{IR}$ get smaller with an increase in c_0 since the cost advantage of upgrading over manufacturing from raw materials increases, while the value advantage of upgrading over remanufacturing stays the same. The effect of k_v on the remanufacturing strategies of the OEM and the IR is straightforward, as the cost of adding innovative features k_v decreases, the motivation for the OEM and the IR to include them in the remanufactured products increases, both $U+\underline{U}$

and $IU + \underline{IU}$ get larger.

When we compare Figure 1.2 and Figure 1.3, we see that the IR chooses upgrading more than the OEM does. The rationale is the same as for why the OEM does not conduct either type of remanufacturing with low $\frac{\delta}{\gamma}$ values. In order for the OEM to remanufacture, it needs higher profits than the IR does to compensate for the loss due to the demand decrease for new products. Similarly, in order for the OEM to include the innovative features, i.e., to supply closer substitutes to the new products, the additional profits obtained by switching from remanufacturing to upgrading should be higher than those for the IR, to compensate for the loss in the demand decrease from new products.

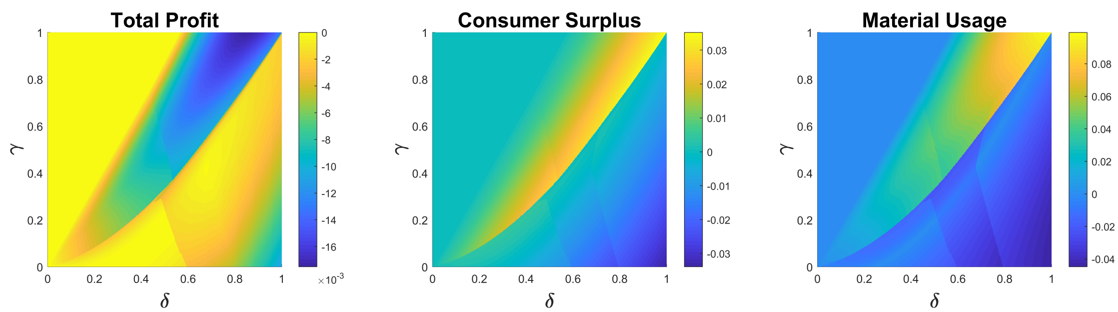

Figure 1.4: Absolute changes in performance measures when the IR remanufactures instead of the OEM

Figure 1.4 shows the changes in the performance measures when the IR remanufactures instead of the OEM. The total profit generated in the market $\pi_T = \pi_O + \pi_I$ is always less when the IR remanufactures than when the OEM remanufactures end-of-use products, as expected. When the remanufacturing resource constraint is non-binding, the remanufacturing (or upgrading) quantity cannot be manipulated by the OEM via the new-product quantity; hence the competition between the two parties is more intense and the profit loss due to the competition is more severe compared to the case where the constraint is binding. The loss in the total profit is higher when the IR includes the innovative features since the upgraded products are closer substitutes to the new products and have a larger impact on the demand for the new products. With a larger δ or smaller γ, remanufacturing and upgrading become more advantageous and the market position of the IR improves. As the market position of the IR improves, the competitive intensity escalates and the profit loss increases.

While competition is always beneficial for consumers when the remanufacturing resource constraint is non-binding, it is usually harmful when the constraint is binding. When the constraint is non-binding, the innovation and the remanufacturing/upgrading quantity are high enough to compensate for the decrease in the new product quantity so that CS is higher. When the constraint is binding, the OEM decreases the new product quantity, and the remanufacturing/upgrading quantity decreases with it; hence CS decreases with competition. When the constraint is non-binding, the consumers' benefit from competition increases, and when the constraint is binding, it decreases with a larger δ or smaller γ. The loss in CS is higher when the OEM remanufactures and the IR upgrades in the same conditions.

The change in raw material usage with competition follows a similar pattern to the consumer surplus. However, we want to minimize the raw material usage for the benefit of the environment, while we want to maximize CS. While the consumers benefit, the environment suffers, and while consumers suffer, the environment benefits from competition. While the effect of δ on the material usage depends on whether the remanufacturing resource constraint is binding: as in CS, a decrease in γ is beneficial for the environment since it also decreases the raw material requirement of the remanufactured/upgraded products.

The three pillars of sustainable development are environmental, social, and economic pillars (`www.un.org/ecosoc/en/sustainable-development`). We do not touch the social pillar, but we believe that our work can contribute to the other two facets by raising the following research question: should competition between the OEM and the IR be promoted or discouraged in an innovative market?

The raw material usage M is the environmental performance measure in our problem, while the economic performance is measured by the sum of profits and consumer surplus, i.e., $E = \pi_O + \pi_I + CS$.

From Figure 1.4, we can see that the objectives do not align for every parameter set.

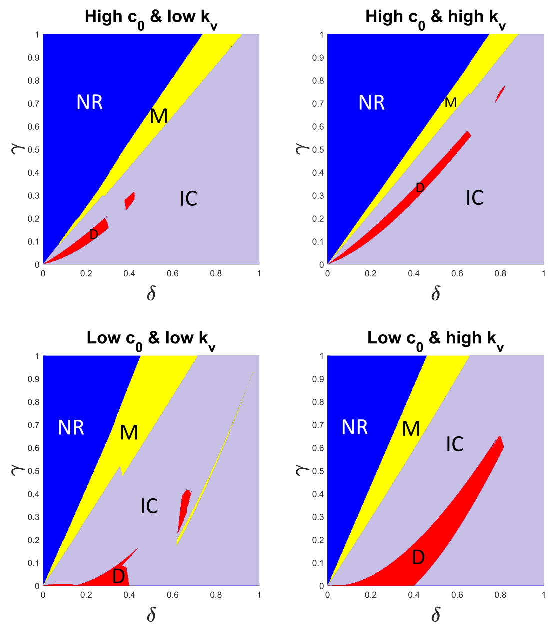

Figure 1.5: The superiority of the monopoly and duopoly

In this part, we define the conditions where either a monopoly or duopoly is superior in the two performance measures, that is, having higher E and lower M at the same time with respect to the other competitive setting. In Figure 1.5, *NR*, *M*, *D*, and *IC* represent the regions where remanufacturing is not profitable for either firm, where monopoly is superior, where duopoly is superior, and where the result is inconclusive (neither monopoly nor duopoly is superior), respectively.

When remanufacturing becomes profitable for the IR, with an increase in δ or a decrease in γ, society's economic gain from the innovative market E is lower and the raw material usage M is higher in the competitive setting. When the remanufacturing resource constraint becomes binding, with an increase in δ or a decrease in γ, we can observe that competition is superior in both the environmental and economic performance measures. In order to make conclusions regarding the region *IC*, we need further information regarding society's priority between the economy and the environment.

When the cost of adding innovative features k_v increases, the region where a monopoly is superior M shrinks, and the region where a duopoly is superior D enlarges. When the base manufacturing cost c_0 increases, both M and D shrink.

1.6 Extensions

1.6.1 OEM sells innovation information to IR

Agrawal et al. (2015) showed that the very availability of OEM-remanufactured products may negatively affect the perceived value of its new products. Let us suppose that this is the case, so that the OEM prefers not to enter the remanufacturing market. Further, let us assume that the OEM's innovative advancement does not spill over at all to the IR. An up-to-date software is needed to use innovative features of products. The OEM can use the software of the product to fully appropriate the innovative features. Consequently, the IR cannot remanufacture end-of-use products with innovative features, unless the OEM agrees to transfer the innovative information to the IR. This arrangement only covers innovation transfer from the OEM to the IR, that is, they still decide on their production quantities and level of innovation investment independently to maximize their own profits.

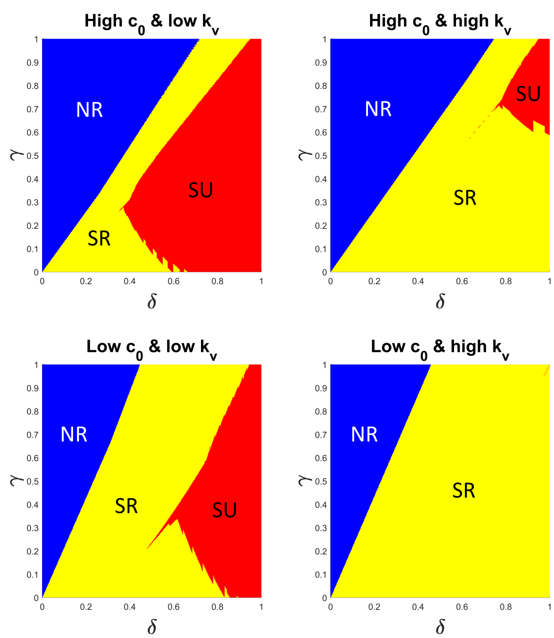

Figure 1.6: Innovation-sharing agreement between the OEM and IR

In this section, we want to answer the following two research questions: (i) Under what conditions are the OEM and IR better off with the information transfer? (ii) When they agree on an information transfer, how are the equilibrium innovation level, the consumer surplus, and the material usage affected by this agreement? Note that we do not account for the sharing mechanism of the additional profit. Our focus is to investigate the conditions where this agreement creates additional value to be shared.

To answer these questions, we characterize and compare the equilibria in two setups, having in common that the OEM does not remanufacture nor upgrade: (i) the OEM does not transfer the innovative information to the IR; and (ii) both parties agree on an information transfer. In (i), the IR can only remanufacture, while in (ii) it can upgrade.

To evaluate whether information sharing is profitable, we compare the sum of equilibrium profits, $\pi_T = \pi_O + \pi_I$, in both settings. Figure 1.6 summarizes the conditions where the total profit is larger with information sharing. *NR*, *SR*, and *SU* define the regions where remanufacturing is not profitable, where the information-sharing agreement is not profitable, and where information sharing is profitable, respectively. The information transfer agreement is profitable when the relative WTP for the remanufactured products δ is high, but the effect of proportional remanufacturing cost γ is not straightforward. When γ is low, sticking to the cost advantage of remanufactured products is more profitable for the IR, hence the agreement does not create additional profit. When γ is high, δ should be sufficiently high to compensate for the additional cost of adding innovative features in remanufactured products since the cost advantage against new products is limited. The size of *SU* is increasing in c_0 and decreasing in k_v.

With the introduction of the agreement, the equilibrium innovation level always decreases. Even though the firms benefit from the agreement in some conditions, the innovation information-sharing agreement is almost never beneficial for consumers. Consumer surplus almost always decreases with the agreement. The decrease in the new-product quantity q_{On} dominates the increase in upgrading quantity q_{Iu} (compared to the remanufacturing quantity q_{Ir} without the agreement) and the material usage M always decreases with the agreement.

1.6.2 Preemptive recycling

As explained in Section 1.6.1, the OEM may choose not to remanufacture end-of-use products for the reasons that fall outside the scope of our work. However, when the OEM does not remanufacture those end-of-use products, an IR can always use them for remanufacturing or upgrading. In Figure 1.7, the OEM's profit loss when end-of-use products are remanufactured or upgraded by the IR can be seen. We can also name that loss as the amount that the OEM is willing to spend on costly recycling (or landfilling) to deter the entry of an IR onto the market with remanufactured or upgraded products. In our study, we assume that the OEM pays a fixed recycling cost to deter this entry, which will be called the maximum deterrence cost for brevity, and we analyze how the fixed cost that the OEM is willing to pay changes with the relative WTP for remanufactured products δ and the ratio of remanufacturing cost to the manufacturing cost γ. For a more detailed analysis of preemptive strategies against the IR, see Ferguson and Toktay (2006).

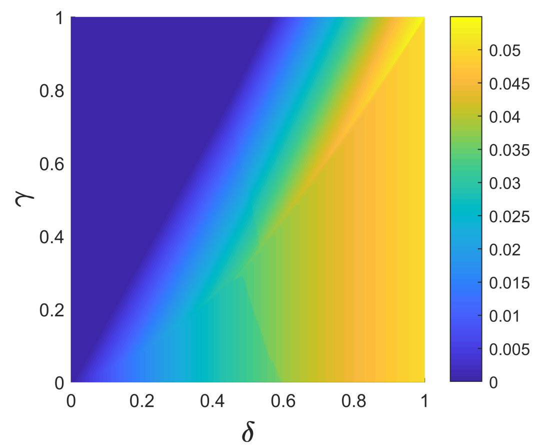

Figure 1.7: Amount that the OEM is willing to spend on preemptive recycling

The maximum deterrence cost is higher when the IR upgrades compared to when it remanufactures, because of the higher WTP for upgraded products that make them better substitutes to the OEM's new products. When the remanufacturing resource constraint is not binding, we can observe that with an improvement in the IR's market position, i.e., with an increase in δ, and with an increase in the cost advantage of the remanufactured products (with a decrease in γ), that the maximum deterrence cost increases. When the remanufacturing resource constraint becomes binding with changes in δ or γ, the OEM can manipulate the remanufacturing (or upgrading) quantity by changing the new product quantity. In that case, we see a sudden decrease in the maximum deterrence cost. With further increases in δ, the maximum deterrence cost keeps increasing, whereas it is not affected by the change in γ since the remanufacturing (or upgrading) quantity is determined by the OEM via remanufacturing supply, not by the IR, and that quantity is independent of γ when the constraint is binding.

1.7 Conclusion

In this paper, we developed managerial insights for OEMs considering introducing remanufactured products, and for IRs looking to enter the market. Also, we assessed the implications of the various remanufacturing strategies on consumers and the environment. The two main strategic decisions regarding remanufacturing for the OEM and the IR that we investigate are whether to introduce remanufactured products and whether to include innovative features developed by the OEM for new products, into the remanufactured products while explicitly considering profit-maximizing innovation investment levels for the OEM. In order to define the conditions under which remanufacturing strategies are selected by the OEM and the IR, and how the equilibrium innovation level, raw material usage, and consumer surplus change, we focus on the customer perception of the remanufactured product; the cost of manufacturing new products and its relationship to the cost of remanufacturing; and the cost of innovation investment and the cost to include those innovative features in the products. Our work differs from the existing literature by investigating the competition and remanufacturing strategies of an OEM and an IR while innovation is taken as a decision variable and considering the option to include innovative features in remanufactured products.

We showed that the consumer perception toward remanufactured products and the cost advantage of remanufacturing are the most important factors for both the OEM and the

IR to introduce remanufactured products. While the decision to introduce remanufactured products for the OEM is robust to changes in other problem parameters, the decision of the IR is significantly affected by changes in the base manufacturing cost: the IR is more prone to enter the market with lower base manufacturing costs. Since the OEM considers the decrease in demand for new products arising from the introduction of remanufactured products, it expects higher valuations for the remanufactured products and a higher remanufacturing cost advantage compared to the IR.

The decision to include innovative features in the remanufactured products is dependent not only on the relative valuation for remanufactured products and the cost advantage of remanufacturing but also on the base manufacturing cost and the cost of adding innovative features. As expected, the cost of adding innovative features is a very important factor to determine whether to include innovative features to the remanufactured products. With a lower k_v, both the OEM and the IR prefer upgrading to remanufacturing. With a higher relative valuation for remanufactured products or with a higher base manufacturing cost, both players choose to include innovative features in the remanufactured products. Like the decision of whether to remanufacture, the OEM is not as aggressive as the IR to include innovative features in remanufactured products, due to demand-decreasing effects on the new products.

As expected, the total profit in of the monopoly setting is higher than in the duopoly setting. However, unexpectedly, competition is not always beneficial the consumers. Even though the common expectation is true when the remanufactured constraint is non-binding, we showed that the consumer surplus almost always decreases with competition when the constraint is binding. Competition is harmful to the environment if the constraint is non-binding but is beneficial if the constraint is binding. Contrary to common belief, remanufacturing end-of-use products is not always beneficial for the environment. Although the remanufactured products use less raw material compared to new products, the market expansion effect can dominate this advantage of remanufacturing. This effect is more severe in the duopoly setting when the remanufacturing constraint is non-binding.

There are some limitations of our work that can be addressed in future works. We considered a steady-state single-period model to analyze the problem and answer our research questions, whereas a multi-period model can better represent the life-cycle effect of an OEM's innovative product and the accumulation of end-of-use products as a supply for remanufacturing. Furthermore, alternative cost and demand functions can be investigated. Firstly, we assumed that the cost to produce goods and the cost of adding innovative features are symmetric for the OEM and IR. This assumption can be relaxed to assess the effects of production advancements by the two firms. Secondly, we used a demand function that is linear in prices, which is an outcome of assuming that customer willingness-to-pay is distributed uniformly and that relative valuation for the remanufactured products compared to new ones is constant for all customers. As shown in Debo et al. (2005) and Jin et al. (2016), these assumptions have an important impact on the results. Consequently, it is worth relaxing these assumptions by adopting different demand functions where the customers' willingness to pay for remanufactured products depends on the willingness to pay for new products in a nonlinear fashion, and customers' willingness to pay is not uniform.[4] In addition to the relaxation of the above-mentioned assumptions, an innovative market where both the OEM and the IR remanufacture at the same time can be considered in order to investigate the effects of competition in remanufacturing and the limited amount of end-of-use products.

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Chapter 2

Strategic Pricing and Investment in Environmental Quality by an Incumbent Facing a Greenwasher Entrant

Abstract

We examine how greenwashing affects the strategies and outcomes of companies and consumers. We develop a two-stage game, where a monopolist sets price and invests in environmental quality in the first stage, and competes with a new entrant in the second stage. The incumbent company is genuinely environmentally friendly, while the new entrant may use deceptive green marketing. We assume that only inexperienced consumers can be influenced by greenwashing, and consider two important dynamic factors, i.e., a change in competitive structure and a learning effect in the market. We investigate the conditions under which greenwashing is profitable for the new entrant, the ways in which the incumbent company responds to it, and the impact of greenwashing on the environment and consumers. We find that greenwashing can be mutually beneficial for both firms

thanks to higher market potential and encouraged by the incumbent firm with its first-period actions. Customers always suffer from greenwashing, in rare cases greenwashing can be beneficial to enhance environmental quality.

2.1 Introduction

A vital sustainability-related question today is - Are green products really green? While the burgeoning interest of firms in green product lines stems from environmental regulations, government incentives, and gaining a competitive advantage, the underlying vice of greenwashing practices casts doubt on products actual green qualities. Greenwashing is the act of positively projecting a firm's environmental performance when it is not truly up to the mark. Often, competitive pressures, low environmental performance, hyperbolic discounting, and other organizational factors result in such greenwashing (Delmas and Burbano, 2011; Truong and Pinkse, 2019; Blome et al., 2017).

Volkswagen (VW) was found to have engaged in greenwashing. The Federal Trade Commission (FTC) accused VW of falsely claiming that its diesel cars were "low emission" and "environmentally friendly," when in fact they were emitting more pollutants than advertised. VW agreed to pay $96.5 million in penalties to settle the case (Sheppardson, 2016). In 2020, Amazon was accused of greenwashing by claiming that it was committed to reducing its carbon footprint and using renewable energy, while continuing to provide cloud computing services to fossil fuel companies. Amazon employees and environmental groups criticized the company for not doing enough to address its environmental impact (Dolsak and Prakash, 2016). In 2019, fashion brand H&M was criticized for greenwashing after it launched a sustainable clothing collection. Critics argued that the collection was not as sustainable as advertised and that H&M was still producing a huge quantity of fast-fashion garments that contributed to environmental damage.

The Guardian newspaper revealed that Coca-Cola, Nestlé, and PepsiCo were among the companies selling bottled water in plastic bottles they claimed were environmentally friendly, when in fact the production of plastic bottles contributes to plastic pollution

(Laville, 2022). These companies were accused of greenwashing and of not doing enough to reduce their environmental impact. Companies greenwash to capitalize on the growing demand for environmentally friendly products without actually changing their practices. Quality, on the other hand, refers to the degree to which a product or service meets the expectations of its users and meets certain standards.

From the above examples, we can see that greenwashing is prominent in many industries like fashion, automotive, consumer products, and even e-retail. In the context of greenwashing, quality is often compromised in order to make environmental claims that are not supported by evidence. For example, a company may claim that its products are made from recycled materials, when in reality only a small portion of the product is made from recycled materials. Consumers should be aware of greenwashing and take steps to ensure that they are purchasing products that are truly environmentally friendly. This can be done by researching the claims made by companies and seeking out independent certification and labeling programs, such as the Forest Stewardship Council and the Global Organic Textile Standard.

In this paper, we analyze the effect of greenwashing on firms' strategies and outcomes, and on consumers. We consider a two-stage game where a monopolist makes pricing and environmental-quality decisions in the first stage, and competes with an entrant in the second stage. The incumbent is a good citizen and does not overrate the environmental quality of its product, while the entrant may be tempted by greenwashing. We assume that only inexperienced consumers, that is, consumers who did not purchase the product in the first period, can be lured by greenwashing. Consequently, our model captures two important dynamic features, namely, the change in the competitive structure and the presence of a "learning" effect in the market. Our objective is to investigate the following research questions:

RQ1: In the first period, what are the optimal quality and pricing policies of the green firm?

RQ2: In the second period, what are the equilibrium pricing decisions of the green incumbent and the greenwashing entrant?

RQ3: What is the impact of greenwashing on the incumbent's first-period decisions?

RQ4: Are there circumstances under which greenwashing is profit-improving for both firms?

RQ5: What is the impact of greenwashing on consumers?

RQ6: How do the equilibrium results change if the incumbent ignores greenwashing?

Based on the above research questions, our major findings can be summarized as follows: Even though the incumbent is a green firm, it can benefit from the greenwashing activities of its competitor via a price increase. So, in order to provide a hospitable environment for greenwashing, the incumbent adjusts its first-period actions, namely, it always increases the price and usually decreases the environmental quality investment to decrease the rate of experienced customers. In some cases, the incumbent channels the entrant to greenwash by using its first-period actions, and the entrant's profit decreases with greenwashing. If the rate of experienced customers is low and/or greenwashing is not costly, then both firms can benefit from greenwashing thanks to inflated prices. Moreover, the inflated prices bring the opportunity for both firms to invest more in environmental quality to enhance demand. Shortly, greenwashing can, in turn, provide better environmental performance. Customers are always worse off as a result of greenwashing since they are tricked to buy products; otherwise, they do not, despite the possibility to have better environmental performance.

When the incumbent is unaware of the entrant's greenwashing possibility at the first period, the likelihood of greenwashing reduces due to the absence of the aforementioned greenwashing encouraging actions of the incumbent. The incumbent's overlooking the entrant's greenwashing activities is always beneficial for the environment and the customers.

The rest of the paper is organized as follows. In Section 2.2, we conduct a comprehensive literature review. We present the model in Section 2.3, and discuss the analytically derived optimal policies in Section 2.4. Section 2.5 complements our analytical findings with numerical simulations to draw insightful results. We investigate the effects of overlooked greenwashing in Section 2.6. Finally, we conclude in Section 2.7 by summarizing our contribution and giving directions for future research.

2.2 Literature Review

Greenwashing has drawn a lot of attention in recent years. A large number of empirical articles and a few with mathematical methods have investigated various aspects of greenwashing; however, many important topics remain to be studied in this area (Tang, 2018). We address greenwashing, quality lag effects, and pricing together, which, to the best of our knowledge, have scarcely been studied even separately. These topics encompass the relationship between greenwashing and marketing variables like brand image, corporate communications, corporate social responsibility (CSR), public policies, environmental issues, finance and accounting, and ethics (Yang et al., 2020). Our paper is at the intersection of greenwashing, quality, and price decisions.

2.2.1 Greenwashing and price

Several articles related to our study have analyzed pricing decisions. As Wu et al. (2020) posited, direct price competition between firms, when one is a possible greenwasher and the other is a true green firm is of sufficient interest. They showed that information transparency has a big role to play where greenwashing occurs. Ben Youssef and Abderrazak (2009) found that under incomplete information, competing firms may increase price and reduce environmental commitments, leading to greenwashing. Shleifer (2004) found that unethical behavior (greenwashing in the context of this paper) reduces costs (in our case, green innovation or quality costs), and competition drives down prices. We investigate this in a setting where one firm may be unethical and the other is not.

Huang et al. (2020) found that the entrant firm's greenwashing behavior softens price competition and benefits the incumbent through a larger market share. Awasthy et al. (2022) showed that when negative spillover of greenwashing happens to a competing firm, the firm increases its greening efforts and prices. If the negative spillover is low, a competing firm can still invest in positive green efforts. While we do not use the term "spillover" directly, we do consider the lag effect of quality, which can be looked upon as temporal spillover of greening investments to self, rather than spillover to the competitor.

Using a two-period game, Zong et al. (2022) found that greenwashing can be profitable for a manufacturer, while it is not beneficial for a supply chain as a whole. According to the authors, greenwashing, or misreporting as they term the practice, has very little effect on price in the entire supply chain. We do not consider a supply chain but focus on the competition between two horizontal members of a chain and consumer experience. In another game theoretic study, Zhang and Yang (2022) found that greenwashers may reduce price and increase quality in the presence of true greenfirms. This will ensure a growing market demand for greenwashing companies.

2.2.2 Greenwashing and green quality innovation

A large part of the literature on green quality and price competition has focused on competition between green products or green and traditional products,; see, e.g., Mukherjee and Carvalho (2021); Yang and Xiao (2017); Yenipazarli and Vakharia (2015); Zhang et al. (2020). Another body of the literature has focused on competition between greenwashing and true green firms or between purely greenwashing firms, for example, Baksi et al. (2017); Lambertini et al. (2020); Xiao and Choi (2019); Lee et al. (2018); Huang et al. (2020). Ruiz-Blanco et al. (2021) found that environmental or green practices enhance product quality in emerging markets.

Lee et al. (2018) showed that in a supply chain, under competition, regulating greenwashing may be detrimental to firms' CSR efforts because of high costs. In fact, allowing greenwashing may incentivize some firms to invest more in true green quality.

In their work, Baksi et al. (2017) interestingly found that quality overestimation by consumers, which is analogous to consumers not being able to detect greenwashing, increases profit for the firm producing lower-quality goods. However, the firm raises its product's quality. The high-quality firm (green firm in our case) improves its product quality at the cost of a lower profit. Huang et al. (2020) obtained that when an incumbent green firm's greenness level and an entrant's degree of greenwashing are both relatively low, the entrant's greenwashing may be beneficial for the incumbent. This is because a trade-off exists between price and quality for both firms, and the green firm may allow the greenwashing for her own benefit at equilibrium.

2.2.3 Research gaps and our contribution to the literature

The above synthesis of the literature shows that many studies delve into the complex interplay between environmental sustainability, consumer behavior, and firm decision-making while facing or practicing greenwashing. Moreover, the literature explores how pricing mechanisms can influence consumers' willingness to pay for environmentally friendly products, with studies revealing that moderate price premiums are often accepted for greener options. Additionally, the role of green innovation emerges as a critical factor in promoting sustainable development. Scholars highlighted the importance of fostering eco-innovative practices within businesses to achieve genuine environmental progress while meeting consumer demands for ethically responsible products and services (Zheng et al., 2021; Zheng and Li, 2023). Through the examination of these interconnected topics, the literature provides valuable insights for creating a more sustainable and environmentally conscious marketplace.

The question remains whether consumers are willing to pay for green firms, as perceived by them through experience. Hao et al. (2022) showed that investments in green innovation have a positive lag effect on enterprise value after several years. Our analysis shows that the literature on greenwashing has rarely considered the lag effect of green innovation or green quality investments when an incumbent anticipates the market entry of a possible greenwasher. In the context of the above literature (Hao et al., 2022; Chen et al., 2022), we investigate a market where experienced consumers may detect greenwashing and will not overvalue the greenness of greenwashing entrant's products. Consequently, the green incumbent uses only price as a weapon to combat possible greenwashing, while relying on the lag effect of its quality investments in the monopoly regime. Our paper is close to that of Huang et al. (2020) in terms of concept; however, there are some important differences, as we use a model that considers the exposure probability of greenwashing. Secondly, we consider the lagged effect of quality, which incorporates consumer learning in a straightforward form.

To summarize, there are notable gaps that pertain to the lag effect of green quality and product pricing. While existing research has shed light on the deceptive nature of greenwashing and its implications for consumer behavior and on optimal decision-making in the face of greenwashing, there remains a limited understanding of the long-term effects of green product quality. The lag effect refers to the time delay between the perception of a product's environmental credentials and the realization of its actual impact on the environment. Further exploration is needed to ascertain how consumers' trust in green claims evolves over time and whether the price and green quality of a product's eco-friendly attributes affect their purchasing decisions. Moreover, the literature also lacks comprehensive investigations into the dynamic relationship between pricing and consumer acceptance of green products. Understanding the optimal price level that strikes a balance between affordability and environmental consciousness is crucial for incentivizing sustainable consumption on a wider scale. In our paper we precisely address these gaps in the literature. Table 2.1 positions our paper with respect to the greenwashing literature.

Table 2.1: Contribution Table

Paper	**Unit of Analysis**	**Dec. Var. or Ind. and Dep. Variables**	**Type of Research**	**Focus of study**	**Lead.**	**Multi Period Model?**
Hao et al. (2022)	firms	green Innovation (GI), Enterprise value (EV)	empirical	lingering effect of EV on GI	NA	NA
Chen et al. (2022)	firms	green Innovation, Enterprise reputation	empirical	lag effect of GI on firm reputation	NA	NA
Huang et al. (2020)	manufacturers	pricing	modeling	customer behaviors, greenwashing, government str.	Yes	Yes
Baksi et al. (2017)	manufacturer	price, quality, quantity	modeling	competition, product differentiation, consumer's quality over estimation	No	No
Zheng et al. (2021)	manufacturer	sustainability levels	modeling	willingness-to-cede (WTC) behaviour in competitive supply chains	Yes	No
Zheng and Li (2023)	manufacturer, supplier	price, innovation	modeling	non-cooperation, and cooperation, price and innovation competition	Yes	No
Blome et al. (2017)	firms	greenwashing, ethical leadership, green supplier championing, rewarding, etc.	empirical	effects of supply chain leadership & ethical incentives on suppliers' greenwashing	Yes	No
Lee et al. (2018)	firms	env. quality, price of product	modeling	effect of greenwashing regulation	No	No
Ruiz-Blanco et al. (2021)	firms	greenwashing, different types of industries, sustainability report	empirical	determinants of greenwashing	No	No

Shen et al. (2020)	manufacturer, retailer, supplier	prices, sustainability overstatement	modeling	effect of deferred payment and inspection on sustainability	Yes	No
Our paper	manufacturers	price, quality	modeling	greenwashing, competition, lagged effect of quality, consumer experience	Yes	Yes

2.3 Model

We consider a two-stage model where an incumbent is a monopolist in the market in the first stage, and is joined by an entrant in the second stage. The incumbent invests in environmental quality in the first period and does not greenwash. The entrant also invests in environmental quality, and greenwashes if this strategy is profitable. However, only inexperienced consumers might be lured by a false statement made by the entrant about environmental quality. An experienced consumer is one who had bought the incumbent's product in the first period.

Denote by q_1 the incumbent's investment in environmental quality (EQ) in the first period, and by p_1 its price. The demand in that period is given by

$$D_1 = 1 + \gamma_1 q_1 - p_1, \tag{2.1}$$

where γ_1 is a parameter measuring the impact of EQ on the incumbent's demand, with $0 < \gamma_1 < 1$. The upper bound on γ_1 implies that the direct impact of price on demand is higher in absolute value than the effect of the EQ. The linear specification in (2.1) is common in economics, operations management, and marketing, as it can be derived from consumers' maximization of a quadratic utility function. The interpretation of D_1 is as follows: the intrinsic market potential is (normalized to) one, and, by investing in EQ, the incumbent can enlarge it to $1 + \gamma_1 q_1$ by attracting consumers who are looking for environmentally friendly products (Awasthy et al., 2022; Zong et al., 2022).

Denote by D_i and D_e the incumbent's and entrant's second-period demand, respectively, and by p_i and p_e their price. The second-period intrinsic market potential is also normalized to one, with the incumbent's and entrant's share being given by $\frac{1}{1+\alpha}$ and $\frac{\alpha}{1+\alpha}$, respectively, where $\alpha \in (0,1)$ is a given parameter. The incumbent's demand is specified as follows:

$$D_i = \frac{1}{1+\alpha} + \gamma_1 q_1 - p_i + \beta p_e, \tag{2.2}$$

where $\beta \in (0,1)$ is the cross-price effect. The interpretation is as before, with the addition of the competitor's price. Note that we have implicitly assumed that the incumbent invests in EQ only once during the game, which is intuitively appealing, as such improvements have a lasting effect, as in, e.g., switching to recyclable packaging, using a low carbon footprint input, etc.

The entrant makes two investments to boost its market potential, one in EQ, denoted by q_e, and one in greenwashing activities, denoted by g_e. The impact on the entrant's demand of these investments is measured by the term $\gamma_e^k\left(q_e + (1-D_1)^+ g_e\right)$, where $\gamma_e^k \in (0,1)$ and $k \in \{g,n\}$, with g corresponding to the case where the entrant greenwashes and n to the case where it does not, that is, $g_e = 0$ (Shen et al., 2020). As stated above, greenwashing can only act on consumers with no previous experience with the product, which is measured by $(1-D_1)^+$ (Huang et al., 2020). Despite having been informed of greenwashing, experienced customers can still purchase the entrant's product if the combination of the entrant's price and environmental quality attracts them more than the incumbent's. Non-governmental organizations (NGOs) examine the firms with environmental claims, and they expose the greenwashing activities of the firms. Since the actions of NGOs are out-of-scope for our research objectives, we assume that they can detect greenwashing firms with an exogenous success rate r. The value of γ_e^k depends on the probability r of the entrant getting caught if it chooses to greenwash. Let γ_e^l and γ_e^h be parameters corresponding to a low- and a high-quality impact on demand. If the entrant greenwashes, then the expected value of γ_e is given by $\gamma_e^g = \gamma_e^l r + \gamma_e^h(1-r)$, and the impact corresponds to $\gamma_e^n = \gamma_e^h$, when the entrant does not greenwash. Consequently, the entrant's demand is as follows:

$$D_e = \frac{\alpha}{1+\alpha} - p_e + \beta p_i + \gamma_e^k \left(q_e + (1-D_1)^+ g_e\right). \tag{2.3}$$

Note that the entrant's demand depends on the incumbent's first-period decisions q_1 and p_1, whereas the incumbent's demand D_i depends directly only on q_1. However, we expect p_1 to play a role in the second-stage outcomes due to competition.

We assume that the investment costs in EQ and in greenwashing are convex increasing and given by the following quadratic functions:

$$c(q_1) = \frac{1}{2}kq_1^2, \quad d(q_e) = \frac{1}{2}mq_e^2, \quad f(g_e) = \frac{1}{2}cg_e^2, \tag{2.4}$$

where k, m, and c are positive parameters. Such quadratic costs in the context of green quality efforts or greenwashing have been used in the literature (Mukherjee and Carvalho, 2021; De Giovanni and Zaccour, 2023). To keep the model as parsimonious as possible and focus on the most important parameters in terms of our research questions, we set $k = m = 1$. We believe that this normalization does not qualitatively affect our results. Further, we assume that $c \leq 1$, which reflects the idea that the cost of greenwashing is at most as high as investing in quality. Note that the corresponding variables, that is, q_1, q_e,and g_e, are scaled with different γ parameters in the demand functions.

The second-period optimization problems of the incumbent and the entrant are given by

$$\max_{p_i} \pi_i(p_i) = \left(\frac{1}{1+\alpha} - p_i + \beta p_e + \gamma_1 q_1\right) p_i, \tag{2.5}$$

$$\max_{p_e, q_e, g_e} \pi_e(p_e, q_e, g_e) = \left(\frac{\alpha}{1+\alpha} - p_e + \beta p_i + \gamma_e \left(q_e + [p_1 - \gamma_1 q_1]^+ g_e\right)\right) p_e - \frac{1}{2}(q_e^2 + cg_e^2), \tag{2.6}$$

and the incumbent's first-period (overall optimization) problem by

$$\max_{p_1, q_1} \pi_1(p_1, q_1) = (1 + \gamma_1 q_1 - p_1) p_1 - \frac{1}{2}q_1^2 + \left(\frac{1}{1+\alpha} - p_i^* + \beta p_e^* + \gamma_1 q_1\right) p_i^*, \tag{2.7}$$

where p_i^* and p_e^* are the second-stage equilibrium prices.

To wrap up, we have defined a perfect information two-period noncooperative game with two players (incumbent and entrant). In the first period, the incumbent chooses the price and the investment in the EQ of the product anticipating the reactions of the entrant in the second period and foreseeing the possibility of greenwashing. In the second stage, the incumbent decides its price, and the entrant decides the price and the investments in EQ and in greenwashing activities. The solution concept of the game is the subgame-perfect Nash equilibrium. Table 1 summarizes the notation used throughout the paper.

Table 2.2: Notation

	Indices
a	$= \begin{cases} 1, \text{Index of incumbent's decisions in the first period,} \\ i, \text{Index of incumbent's decisions in the second period,} \\ e, \text{Index of entrant's decisions in the second period.} \end{cases}$
	Decision and state variables
p_a	Price, $a = 1, i, e$
q_a	Environmental quality level, $a = 1, e$
g_e	Greenwashing level
D_a	Demand, $a = 1, i, e$
	Parameters
α	Market potential sharing
β	Cross-price sensitivity
γ_a	Quality sensitivity, $a = 1, e$
c	Greenwashing cost coefficient
r	Probability of greenwashing activities getting exposed

2.4 Analytical Results

To determine a subgame-perfect Nash equilibrium, we first solve for the second-period equilibrium. Assuming an interior solution and $(1 - D_1) > 0$, the first-order equilibrium conditions are

$$\begin{aligned}
\frac{\partial \pi_i}{\partial p_i} &= \frac{1}{1+\alpha} - 2p_i + \beta p_e + \gamma_1 q_1 = 0, \\
\frac{\partial \pi_e}{\partial p_e} &= \frac{\alpha}{1+\alpha} - 2p_e + \beta p_i + \gamma_e \left(q_e + [p_1 - \gamma_1 q_1]\, g_e\right) = 0, \\
\frac{\partial \pi_e}{\partial q_e} &= \gamma_e p_e - q_e = 0, \\
\frac{\partial \pi_e}{\partial g_e} &= \gamma_e [p_1 - \gamma_1 q_1]\, p_e - c g_e = 0.
\end{aligned}$$

Two comments are in order about these conditions. First, the investment strategies in EQ and greenwashing are dictated by the familiar rule of marginal revenue equals marginal cost, that is, $\gamma_e p_e = q_e$ and $\gamma_e [p_1 - \gamma_1 q_1]^+ p_e = c g_e$ for EQ and greenwashing, respectively. Second, the investment levels do not depend on the current incumbent decision p_i, which implies strategic independence, whereas there is strategic complementarity between the two players' prices. Indeed, it is easy to see that if a player increases its price, the best response of the other player is to also increase its price.

Solving the equilibrium conditions yields the second-period decisions as functions of the incumbent's first-period decisions. To save on notation, let

$$X = \frac{(p_1 - \gamma_1 q_1)^2}{c} + 1 = \frac{(1 - D_1)^2}{c} + 1.$$

Simply, X is the summation of the environmental quality's and greenwashing's effectiveness coefficients, 1 and $\frac{(p_1-\gamma_1 q_1)^2}{c}$, respectively. As the rate of inexperienced customers $(1 - D_1)$ increases and the cost coefficient of greenwashing (c) decreases, the effectiveness of the greenwashing rises.

If the entrant does not greenwash, i.e., $g_e^n = 0$, then the second-period equilibrium is given by

$$p_i^n = \frac{\left(\frac{1}{1+\alpha} + \gamma_1 q_1\right)\left(2 - (\gamma_e^n)^2\right) + \frac{\alpha\beta}{1+\alpha}}{4 - \beta^2 - 2(\gamma_e^n)^2},$$

$$p_e^n = \frac{\frac{2\alpha+\beta}{1+\alpha} + \beta\gamma_1 q_1}{4 - \beta^2 - 2(\gamma_e^n)^2}, \quad q_e^n = \gamma_e^n p_e^n, \quad g_e^n = 0.$$

If the entrant greenwashes, i.e., $g_e > 0$, then the second-period equilibrium is given by

$$p_i^g = \frac{\left(\frac{1}{1+\alpha} + \gamma_1 q_1\right)\left(2 - (\gamma_e^g)^2 X\right) + \frac{\alpha\beta}{1+\alpha}}{4 - \beta^2 - 2(\gamma_e^g)^2 X},$$

$$p_e^g = \frac{\frac{2\alpha+\beta}{1+\alpha} + \beta\gamma_1 q_1}{4 - \beta^2 - 2(\gamma_e^g)^2 X}, \quad q_e^g = \gamma_e^g p_e^g, \quad g_e^g = \frac{\gamma_e^g}{c}(p_1 - \gamma_1 q_1) p_e^g.$$

Remark 1 *The results are obtained under the assumption of an interior solution. If the entrant does not greenwash, then clearly p_e^n, p_i^n, and q_e^n are positive because $4 - \beta^2 - 2(\gamma_e^n)^2$ and $2 - (\gamma_e^n)^2$ are positive. In the greenwashing scenario, the solution is interior if $4 - \beta^2 - 2(\gamma_e^g)^2 X > 0$. Indeed, under this inequality, p_e^g is positive, and consequently p_i^g, q_e^g, and g_e^g are also positive.*

The players' second-period profits when the entrant greenwashes are given by

$$\begin{aligned}
\pi_i^g &= \left(\frac{\left(\frac{1}{1+\alpha} + \gamma_1 q_1\right)\left(2 - (\gamma_e^g)^2 X\right) + \frac{\alpha\beta}{1+\alpha}}{4 - \beta^2 - 2(\gamma_e^g)^2 X}\right)^2, \\
\pi_e^g &= \frac{\left(\frac{2\alpha+\beta}{\alpha+1} + \beta\gamma_1 q_1\right)^2 \left(2 - (\gamma_e^g)^2 X\right)}{2\left(4 - \beta^2 - 2(\gamma_e^g)^2 X\right)^2},
\end{aligned}$$

and, when the entrant does not greenwash, by

$$\pi_i^n = \left(\frac{\left(\frac{1}{1+\alpha} + \gamma_1 q_1\right)\left(2 - (\gamma_e^n)^2\right) + \frac{\alpha\beta}{1+\alpha}}{4 - \beta^2 - 2(\gamma_e^n)^2}\right)^2,$$

$$\pi_e^n = \frac{\left(\frac{2\alpha+\beta}{\alpha+1} + \beta\gamma_1 q_1\right)^2 \left(2 - (\gamma_e^n)^2\right)}{2\left(4 - \beta^2 - 2(\gamma_e^n)^2\right)^2}.$$

Proposition 8 *The impacts of the first-period decisions p_1 and q_1 on second-period decisions and outcomes are as follows:*

1. *If the entrant does not greenwash,*

   a) *p_i^n and p_e^n are independent of p_1, and increasing in q_1.*

   b) *The second-period profits are increasing in q_1 and independent of p_1.*

2. *If the entrant greenwashes,*

   a) *p_i^g and p_e^g are increasing in p_1.*

   b) *The effects of q_1 on second-period decisions are as follows:*

      i. *p_e^g and q_e^g increase with q_1 if*

$$\frac{\frac{2\alpha+\beta}{1+\alpha}+\beta\gamma_1 q_1}{4-\beta^2-2(\gamma_e^g)^2 X}<\frac{\beta c}{4(\gamma_e^g)^2(p_1-\gamma_1 q_1)}.$$

      ii. *p_i^g increases with q_1 if*

$$\frac{\frac{2\alpha+\beta}{1+\alpha}+\beta\gamma_1 q_1}{4-\beta^2-2(\gamma_e^g)^2 X}<\frac{c(2-\gamma_e^g)^2 X}{2\beta(\gamma_e^g)^2(p_1-\gamma_1 q_1)}.$$

      iii. *g_e^g increases with q_1 if*

$$\frac{\frac{2\alpha+\beta}{1+\alpha}+\beta\gamma_1 q_1}{4-\beta^2-2(\gamma_e^g)^2 X}<\frac{\beta(p_1-\gamma_1 q_1)}{4-\beta^2-2(\gamma_e^g)^2\left(1-\frac{(p_1-\gamma_1 q_1)^2}{c}\right)}.$$

When the entrant does not greenwash, the independence of p_i^n and p_e^n with respect to p_1 follows from the absence of p_1 from both players' second-period optimization problems. The absence of experience effect on the purchasing decision of the customers when the entrant does not greenwash makes p_1 irrelevant for the second-period actions of the incumbent and the entrant. As q_1 shifts up its market potential, the incumbent can ask for a higher price in the second period. By strategic complementarity, the entrant also increases its price with a larger q_1. When the incumbent greenwashes, the change in the entrant's price can be explained as follows: A larger p_1 leads to larger $1-D_1$, which is the target base for the entrant's greenwashing, and therefore, the larger is its price p_e^g. Again, strategic complementarity leads to the result that p_i^g is increasing in p_1.

The impact of q_1 on second-period decisions is ambiguous, as it depends on all parameter values. Even the right-hand sides in the three inequalities cannot be compared without additional assumptions on the parameters. When the entrant does not greenwash, both players benefit from the EQ investment made by the incumbent in the first period, because it enlarges the market potential and leads to higher prices. Unfortunately, we cannot make any specific statements regarding the impact of q_1 when the entrant greenwashes. As alluded to before, in the absence of greenwashing, p_1 does not enter the second-period profit functions, hence, the result that p_1 has no impact on the profits.

Remark 2 *From Proposition 8, we can see that p_i^g can decrease and g_e^g can increase with the incumbent's environmental-quality investment. However, when we check the feasibility of these two cases numerically, we see that they never show up when we keep the parameters in the $[0,1]$ interval, which is a reasonable assumption for our model. Only in the limit case, where $c = 1$ and γ_1 is unreasonably high, p_i^g decreases with the incumbent's environmental quality q_1. Parallel changes between greenwashing and q_1 are never observed, even with extreme parameter values.*

Proposition 9 *If $\frac{\gamma_e^n}{\gamma_e^g} < \sqrt{X}$, then the second-period prices are higher when the entrant greenwashes than when it does not, i.e., $p_e^g > p_e^n$ and $p_i^g > p_i^n$.*

Recalling that $X = \frac{(1-D_1)^2}{c} + 1$,with $c \leq 1$, the above result states that if γ_e^g is large enough, i.e., the probability of detecting greenwashing is low enough, then greenwashing will inflate the second-period prices. The inequality in the statement of the proposition is easier to satisfy when the cost parameter of greenwashing c is low, or when the potential target base for greenwashing $(1-D_1)$ is high. The risk of exposed greenwashing, which reduces the effectiveness of the environmental image, $\gamma_e^g < \gamma_e^n$, can be compensated for, and the entrant's market potential increases, which allows the entrant to charge higher prices. As explained, since the incumbent's actions are affected by the entrant's environmental quality and greenwashing decisions through the entrant's price, whenever the entrant's price increases as a result of greenwashing, so does the incumbent's price.

Proposition 10 *The entrant's environmental-quality investment is higher in the greenwashing setting if*

$$\frac{(1-D_1)^2}{c} > \frac{\left(\gamma_e^n - \gamma_e^g\right)\left(2\gamma_e^g\gamma_e^n + 4 - \beta^2\right)}{2\gamma_e^n(\gamma_e^g)^2}.$$

The above proposition states that the size of the target market for greenwashing must be larger than a threshold in order for the entrant's EQ investment to be larger in the greenwashing scenario. It is readily seen that the inequality is easier to satisfy if the cost of greenwashing c is low, or if γ_e^g is close enough to γ_e^n. The condition in the proposition is easier to interpret when rewritten equivalently as

$$\frac{\gamma_e^g}{\gamma_e^n} > \frac{p_e^n}{p_e^g}.$$

Even though the expected quality sensitivity of the customers is lower in the greenwashing setting, that decrease can be compensated for with the increasing effect of greenwashing on the entrant's price. As a result, if the expected quality-sensitivity decrease is not too high, the entrant's environmental quality can increase with greenwashing.

Proposition 11 *Impact of greenwashing on the profits of the incumbent and entrant.*

1. *The entrant benefits from greenwashing if*

$$\left(\frac{p_e^g}{p_e^n}\right)^2 > \frac{2-(\gamma_e^n)^2}{2-(\gamma_e^g)^2 X}. \tag{2.8}$$

2. *If $p_e^g > p_e^n$, then the incumbent's second-period profit is larger when the entrant greenwashes than when it does not.*

Proposition 11 shows that, under some conditions, greenwashing leads to higher profits for both players in the second period. While the entrant can benefit from greenwashing by replacing costly environmental quality investment with cheaper greenwashing or by increasing the perceived value of the product and charging higher prices, the incumbent can only benefit indirectly from the entrant's greenwashing activities with the latter case. That is why the entrant's profit can increase even with a price drop with greenwashing. If the entrant charges more for its product as a result of greenwashing, then the incumbent too can charge higher prices thanks to the raised price of its competitor, which in turn makes the incumbent's profit increase.

Equation 2.8 in Proposition 11 can be rearranged as

$$K^n\left(2-\frac{\beta^2}{K^n}\right)^2 > K^g\left(2-\frac{\beta^2}{K^g}\right)^2, \tag{2.9}$$

where $K^n = 2-(\gamma_e^h)^2$ and $K^g = 2-(r\gamma_e^l+(1-r)\gamma_e^h)^2\left(1+\frac{(p_1-\gamma_1 q_1)^2}{c}\right)$. Note that $K^n > K^g$ does not guarantee the profitability of greenwashing for the entrant, but we can easily observe that as K^n increases and K^g decreases, the inequality in (2.9) becomes more likely to hold. This enables us to make comments about the impact of the parameters on the entrant's greenwashing strategy. The cost and exposure risk of greenwashing are two factors that can make the entrant avoid greenwashing, and these two parameters increase with an increase in c and r, respectively. We can see that a higher c or r increases K^g and makes greenwashing less profitable. As γ^l increases, the loss due to exposure gets lower, and the entrant becomes more eager to greenwash. With a higher proportion of uninformed customers $(p_1-\gamma_1 q_1)$, the impact of greenwashing rises and K^g decreases, so an increase in p_1 and a decrease in γ_1 or q_1 make the entrant more likely to greenwash.

Table 2.3: Effects of the parameters on the second-period equilibrium outcome

	Greenwashing				**Not GW**		
	p_i^g	p_e^g	q_e^g	g_e^g	p_i^n	p_e^n	q_e^n
γ_1	?	?	?	?	+	+	+
β	+	+	+	+	+	+	+
α	−	+	+	+	−	+	+
γ_e^g/γ_e^n	+	+	+	+	+	+	+
c	−	−	−	−			

As shown previously, the entrant's environmental-quality investment and greenwashing activities are proportional to its price ($q_e^g = \gamma_e^g p_e^g$ and $g_e^g = \frac{\gamma_e^g}{c}(p_1-\gamma_1 q_1)p_e^g$). As a result of these linear relationships, from Table 2.3, we can observe that the changes in the environmental quality and greenwashing follow the trend of the entrant's price.

The effects of γ_1 on the equilibrium decisions in the second period when the entrant greenwashes depend on the same conditions as the effects of q_1 on the second-period decisions, as presented in Proposition 8, since γ_1 and q_1 always exist together in $\gamma_1 q_1$ form.

When the entrant does not greenwash, both firms' price and the entrant's quality investment increase with γ_1 as they increase with q_1. The demand of the incumbent increases with the customer sensitivity to environmental quality, thus the incumbent can charge more for its product and this price increase allows the entrant to raise its price.

As the competitor's price increases, the consumer's reference price for the focal product increases with it. That impact increases as the cross-price sensitivity β increases. As a result, as can be seen from Table 2.3, a higher β allows both firms to increase their price together in both greenwashing settings.

The entrant's market share increases with α, and this also mean a shift in the demand curve; so an increase in α raises the willingness-to-pay (WTP) of the customers for the entrant's product. As a result of this, the entrant can charge a higher price for its product. Conversely, the incumbent's demand and the customers' WTP decrease with α so that the price that the incumbent can charge decreases.

γ_e^g and γ_e^n are composed of γ_e^h, γ_e^l, and r; hence by understanding the impact of γ_e^g and γ_e^n, we can understand the impact of γ_e^h, γ_e^l, and r. γ_e^h, γ_e^l, and r constitute $\gamma_e^g = \gamma_e^l r + \gamma_e^h(1-r)$ and $\gamma_e^n = \gamma_e^h$. As a result, an increase in γ_e^h and γ_e^l or a decrease in r has the same effect on the equilibrium outcome. Therefore, when we investigate the impact of γ_e^g and γ_e^n, we can figure out the impact of the constituents. With an increase in γ_e^g or γ_e^n, consumers' sensitivity to the entrant's environmental quality and greenwashing increases, and the entrant becomes more motivated to invest in those. With an increased valuation for its product, the entrant can charge more for its product and the incumbent can benefit from its competitor's raised price by increasing its own price.

Proposition 12 *The incumbent's first-period price is higher in the greenwashing setting. The price and quality vary as follows, with market-potential sharing α and quality sensitivity γ_1:*

$$\frac{\partial q_1^n}{\partial \alpha} > 0, \quad \frac{\partial p_1^n}{\partial \alpha} < 0, \quad \frac{\partial q_1^n}{\partial \gamma_1} > 0, \quad \frac{\partial p_1^n}{\partial \gamma_1} > 0.$$

To avoid repetition, we shall comment on this proposition in the next section.

Turning to the incumbent's overall optimization problem, we were able to analytically solve the case when the entrant does not greenwash, but not when it does. In this latter case, one faces a highly nonlinear problem that does not admit an analytical solution. In the absence of greenwashing, the equilibrium first-period decisions are as follows:

$$p_1^n = \frac{(1+\alpha)(4-\beta^2-2(\gamma_e^n)^2)^2 - 2\alpha\gamma_1^2(2-(\gamma_e^n)^2)(2-\beta-(\gamma_e^n)^2))}{(1+\alpha)\left(\left(2-\gamma_1^2\right)(4-\beta^2-2(\gamma_e^n)^2)^2 - 4\gamma_1^2(2-(\gamma_e^n)^2)\right)}.$$

$$q_1^n = \frac{\gamma_1\left((1+\alpha)(4-\beta^2-2(\gamma_e^n)^2)^2 - 4(2-(\gamma_e^n)^2)(2+\alpha\beta-(\gamma_e^n)^2))\right)}{(1+\alpha)\left(\left(2-\gamma_1^2\right)(4-\beta^2-2(\gamma_e^n)^2)^2 - 4\gamma_1^2(2-(\gamma_e^n)^2)\right)}.$$

In the greenwashing case, the first-period problem is highly nonlinear in q_1 and p_1, and an analytical solution is out of reach. Consequently, we shall proceed numerically.

2.5 Numerical Analysis

To find the optimum values, we search the two-dimensional space, $(q_1, p_1) \in [0,1] \times [0,1]$, by discretizing values of q_1 and p_1 with a 10^{-4} step size. To understand the effects of the parameters on the equilibrium outcome (see Table 2.4), we first find the optimum values of q_1 and p_1 for varying values of one parameter with a discretized step size of 10^{-3} while keeping other parameters at their base levels ($\alpha = 0.8$, $\beta = 0.5$, $\gamma_1 = 0.4$, $\gamma_e^h = 0.4$, $\gamma_e^l = 0$, $c = 0.3$ and $r = 0.2$). Next, to check whether or not the effects of parameters are robust to the changes in the levels of the other parameters, we repeat this for higher and lower values of these other parameters. If the effect of a parameter on an outcome is influenced by other parameters, a question mark is added to a cell to show that the effect is not monotone.

As γ_1 increases, the demand-enhancing investment in environmental quality rises; hence the positive effect of γ_1 on q_1 in both greenwashing cases is expected. With an increase in market potential with γ_1 and q_1, the incumbent gets the chance to increase its profit margin by increasing its price, and consequently, the incumbent's profit increases with γ_1. Furthermore, an increase in γ_1 and q_1 means higher consumer utility; thus we see an increase in consumer surplus. As discussed in Section 2.4, a higher β allows both

Table 2.4: Effects of the parameters on the first-period outcome

	GW				Not GW			
	q_1^g	p_1^g	π_1^g	CS^g	q_1^n	p_1^n	π_1^n	CS^n
γ_1	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$+$
α	$-$	$-$	$-$	$-$	$-$	$-$	$-$	$-$
β	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$+$
γ_e^g/γ_e^n	$+?$	$+$	$+$	$-$	$+$	$+$	$+$	$+$
c	$+$	$-$	$-$	$+$				

firms to increase their second-period prices, so an increase in β has the same effect on the results as an increase in γ_1.

With a higher α, the incumbent's second-period market share shrinks and its motivation to invest in environmental quality decreases. As a result, the price it can charge also goes down. The increase in the entrant's environmental quality with α cannot compensate for the decrease in the incumbent's environmental quality, even without the negative consumer surplus caused by increased greenwashing activities; thus CS decreases with α in both greenwashing cases.

Even though the incumbent is an environmentally honest firm, it benefits from the greenwashing activities of the entrant too. Higher greenwashing as a result of the low greenwashing cost c lets the incumbent increase its prices, and this impact diminishes as c rises. The market potential of the incumbent shrinks with an increase in c, and the incumbent invests more in environmental quality to increase demand. Consumers are better off with a higher c since it increases the environmental quality of the incumbent and decreases the greenwashing level.

As stated in Section 2.4, a higher γ_e^g/γ_e^n means higher environmental quality and greenwashing, and consequently, higher prices for both firms. With an increased profit margin thanks to a higher γ_e^g/γ_e^n, the incumbent can invest more in the environmental quality, and this enhanced quality creates the opportunity to raise the price in the first period. The only exception to this is when the cost of greenwashing activities c is low. In that case, the incumbent free rides on the boosted prices of the entrant as a result of high greenwashing levels. Even though the consumer utility increases with γ_e^g in the greenwashing case, its indirect negative effects on consumer surplus cannot be compensated for by the direct positive effect. Improved environmental qualities of the two firms cannot create enough positive impact on the consumer surplus to overcome losses due to greenwashing, whereas when the entrant does not greenwash, the impact of an increase in γ_e^n is always positive.

In Figure 2.1, we can see the market conditions that make greenwashing profitable for the entrant, namely, the levels of the entrant's market share α and the cross-price sensitivity β. In Section 2.4, we see that α and β have a positive impact on the entrant's greenwashing level g_e^g as a result of the entrant's price increase. Despite having the same impact on the level of greenwashing, their impacts on whether or not to greenwash are not the same. From Figure 2.1, we can observe that the entrant is more likely to greenwash with a higher market share α. The cross-price sensitivity's effect on the entrant's price is higher than the market share's effect, with a higher cross-price sensitivity, and the entrant has more to risk from exposed greenwashing if β is high. That is why the entrant is less keen to greenwash with a high β.

As shown analytically in Proposition 12, the incumbent's first-period price is higher under the greenwashing scenario. We can validate this and observe the reduction in the incumbent's environmental-quality investment with greenwashing, by checking Figure 2.1. The incumbent decreases the number of informed customers by increasing its first-period price and decreasing its investment in environmental quality in order to let the entrant exploit greenwashing more, which helps the entrant raise its price and shifts up the reference price for the incumbent's product. Consequently, we can see that the incumbent's profit is higher under the greenwashing setting.

The entrant can benefit from greenwashing in two ways, either by increasing the perceived environmental-quality with a high level of greenwashing or by cutting the cost by switching from true environmental quality investments to greenwashing. In Figure 2.1, we see an example of the former, but, Proposition 8 shows us that the decrease in environmental-quality investment can dominate and the entrant's price can decrease. We observe a sharp decrease in the entrant's environmental-quality level, but greenwashing is

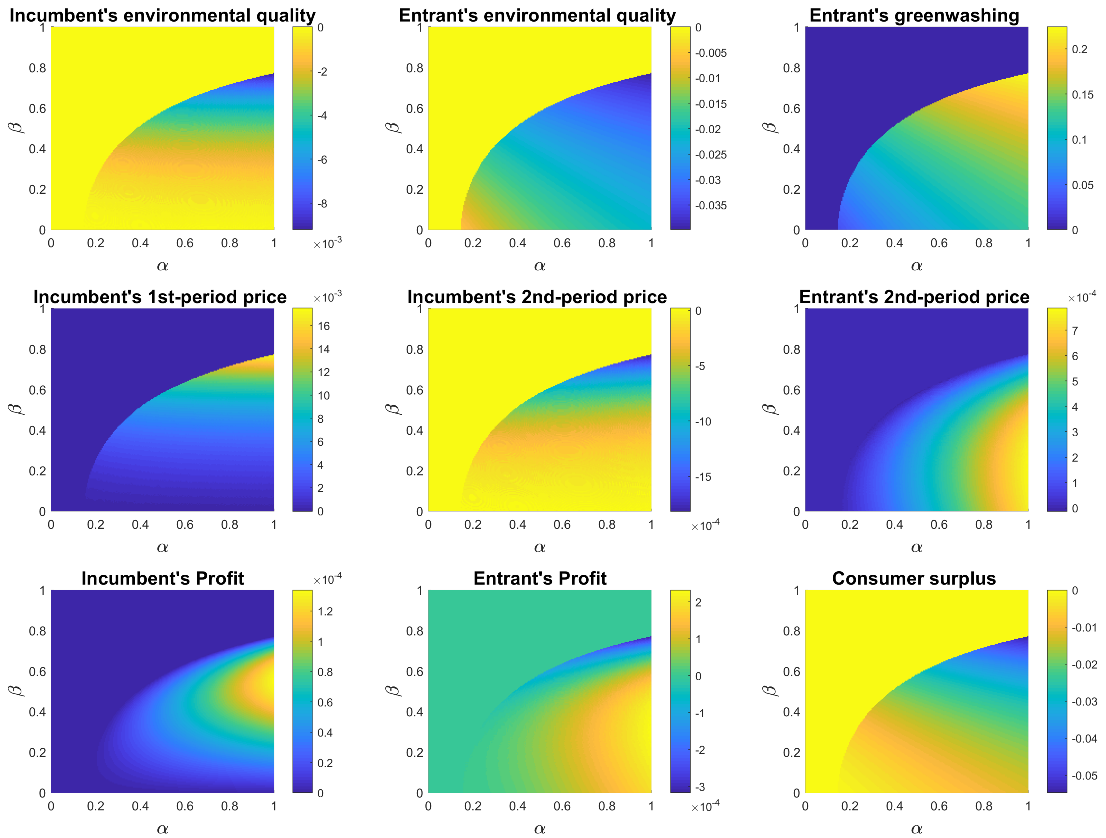

Figure 2.1: The effects of greenwashing on the equilibrium outcome

high enough to compensate for that decrease, and the price increases with greenwashing.

Since the exposed greenwashing activities diminish the demand-enhancing effect of true environmental-quality improvements together with the effect of greenwashing activities ($\gamma_e^g < \gamma_e^n$), the entrant stays away from greenwashing when the benefits of greenwashing are not sufficiently high. We do not see an incremental increase in the greenwashing level when it becomes profitable for the entrant, since the greenwashing level should be high enough to compensate for the decrease in demand enhancing the effect of environmental quality.

By definition, greenwashing activities are present to trick the customers into purchase the product when they otherwise wouldn't. Hence, with an increase in greenwashing, the consumer surplus goes down. With the help of a reduction in prices or improved environmental quality, the negative impacts of greenwashing can be avoided. However, by checking Figure 2.1, we see that with the introduction of greenwashing, the environmental-quality levels of both firms decrease, and only the incumbent's second-period price decreases. Consequently, we see a reduction in consumer surplus.

As shown in Figure 2.1, a very counterintuitive result is the entrant's loss of profit under greenwashing. Since the entrant is the one who decides whether to greenwash or not, we expect the entrant not to greenwash if it causes a profit loss. However, as explained, in our case, the incumbent can benefit from its competitor greenwashing, even though the incumbent is a green firm. That is why the incumbent sets its first-period decisions to incentivize the entrant towards greenwashing, by increasing its first-period price and decreasing its environmental-quality investment. After the incumbent makes these decisions, the entrant chooses its own actions to maximize its profit in the manipulated environment, but it ends up losing profit by greenwashing. In such case, the entrant can be better off committing not to greenwash from the beginning.

2.6 Overlooking Greenwashing

So far, we have assumed that the incumbent is aware that the entrant can greenwash and that it adjusts its actions in the first period in anticipation of the entrant's greenwashing strategy. In this section, we analyze the impact of the incumbent overlooking greenwashing. In other words, the incumbent determines its first-period price and environmental quality without realizing that the entrant can promote its products by greenwashing. Since the incumbent overlooks the entrant's greenwashing, the first-period price and environmental-quality level are equal to p_1^n and q_1^n in the base model. The incumbent realizes the entrant's potential to greenwash before setting its second-period price and determines it with full information.

Since we cannot get analytical results for the base scenario, we investigate the effects of overlooking the entrant's greenwashing numerically. Figures 2.2 and 2.3 give us the changes in the entrant's greenwashing strategy and the outcome as a result of overlooking, respectively.

The change in the entrant's greenwashing strategy can be represented by the three regions in Figure 2.2; *NN*: the region where the entrant sticks to not greenwashing when the incumbent is overlooking; *GG*: the region where the entrant greenwashes regardless of the incumbent's awareness; and *GN*: the region where the entrant greenwashes if the incumbent is aware of the entrant's greenwashing, but does not otherwise.

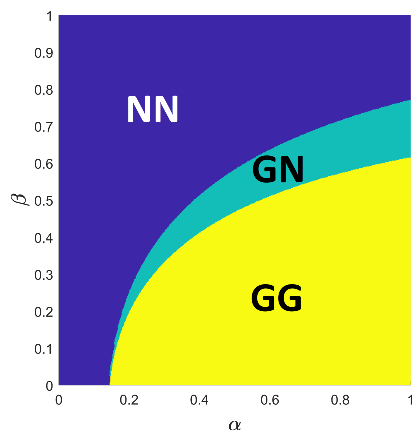

Figure 2.2: The change in the entrant's greenwashing strategy when greenwashing is overlooked

From Figure 2.2, we can observe that the conditions that make greenwashing profitable become more strict. When the incumbent is aware of the entrant's greenwashing potential, it creates a better environment for the entrant to greenwash and increases its price, so that the incumbent can increase its own second-period price and its profit increases, as discussed in Section 2.5. As can be seen, there is no region where the entrant switches to greenwashing when the incumbent overlooks it. We can conclude that greenwashing is more likely to occur in this market if the incumbent is aware of it.

In *NN*, the outcome is not affected by the incumbent's awareness of the entrant's greenwashing activities. The incumbent makes its first-period decisions assuming the entrant does not greenwash, and the entrant acts in line with the incumbent's first-period assumptions.

As mentioned in Section 2.5, the incumbent also benefits from the entrant's greenwashing and creates a better environment to promote the entrant's greenwashing by de-

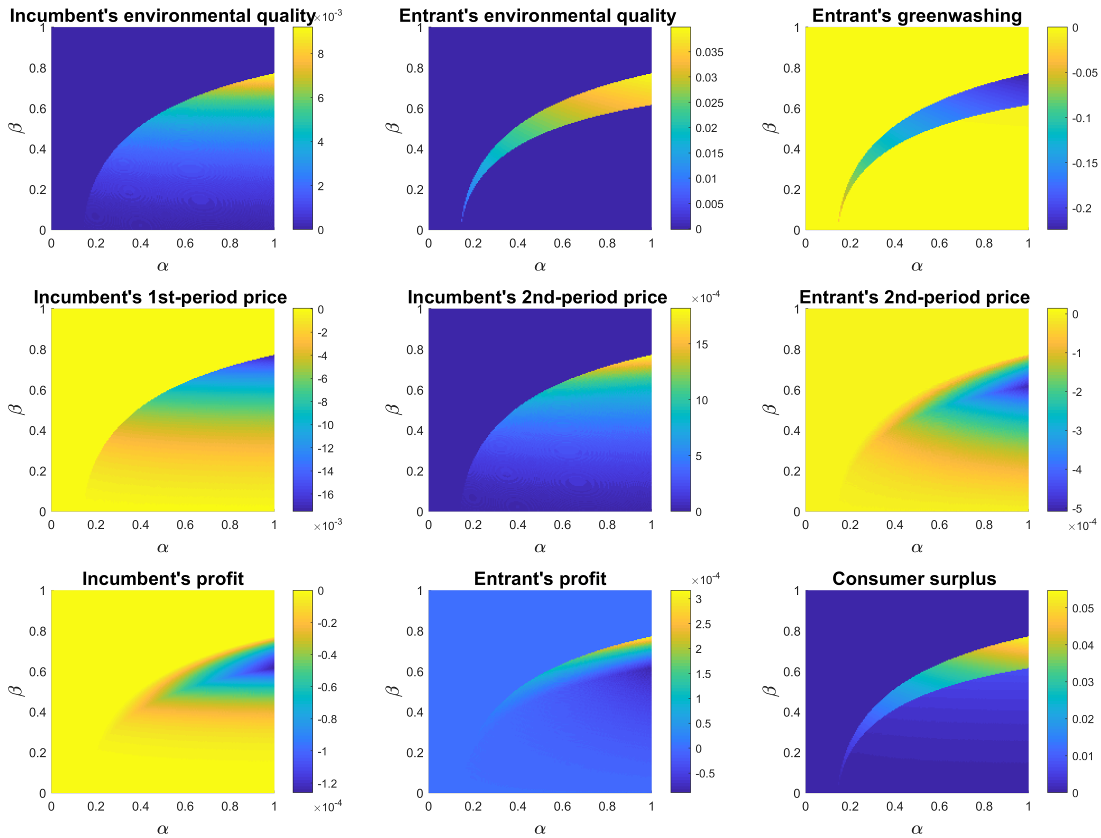

Figure 2.3: The effects of overlooking the entrant's greenwashing activities

creasing its environmental quality and increasing its first-period price. That's why we see an improvement in the incumbent's environmental quality and a price cut. Both these changes resulting from overlooking greenwashing benefit customers. The result in terms of the profit of the incumbent in *GN* and *GG* is not suprising, as the lack of information causes a profit loss for the incumbent.

When we compare *GG* and *GN*, we can observe from Figure 2.3 that the impact of overlooking on the equilibrium outcome is more significant when the entrant's greenwashing strategy alters with overlooking (*GN*). As discussed in Section 2.5, the entrant makes a sudden switch from investing in environmental quality to greenwashing when greenwashing becomes profitable. Since the region where greenwashing is profitable shrinks when the incumbent overlooks it, in *GN*, we can see a significant increase in the entrant's environmental-quality investments and a significant decrease in greenwashing. Since the consumers have higher utility with better environmental quality and are not tricked by greenwashing, we see a positive jump in the consumer surplus in *GN*. Since the decrease in greenwashing is higher than the increase in environmental quality, the entrant's price decreases. Despite a decrease in the price, the entrant's profit increases when greenwashing is overlooked in *GN* since the incumbent was enticing the entrant to greenwash, as discussed in Section 2.5. In determining the incumbent's second-period price, the decrease in the entrant's price pulls down, and the increase in the incumbent's environmental quality pulls up, the incumbent's second-period price. The latter dominates the former and we observe an increase in the incumbent's second-period price.

The signs of the changes in the equilibrium outcome with the incumbent's overlooking in *GG* are the same with *GN*. However, the levels of the changes in *GG* are significantly lower compared to *GN*. The only difference between the two regions is in the profit of the entrant. As mentioned, the incumbent creates a better environment for the entrant's greenwashing activities if it is aware of greenwashing, and therefore, the entrant's profit is lower without this implicit agreement.

2.7 Conclusion

In this article, using a two-period game, we investigated the price and quality competition between a green firm and a possible greenwasher. We assumed that consumers become experienced through the quality of the incumbent green firm in the first period and can differentiate between greenwashing and true green quality in the second period. The quality efforts of the green firm has a lingering effect in the second period when the potential greenwasher enters the market. The firms' decisions depend on a number of parameters in our model, as illustrated in the previous sections. To conclude, we highlight our theoretical contributions, the managerial implications of the study, and avenues for future research in this context.

Theoretical contribution: We propose a rich model that articulates the lag effect of prior quality investments by the incumbent, farsighted decision-making with anticipation of possible greenwashing, and quality and price competition in the presence of experienced consumers. Our work differs from existing literature, which considers the environmental quality level is exogenous and the greenwashing firm determines to mimic that environmental quality level, by letting both firms determine their environmental quality investment levels and the false green advertisement level of the entrant.Despite considering different dimensions, the model gives us several analytical findings complemented by insights from our numerical simulations. We provide the second-period decisions in closed form, but the presence of high levels of non-linearity makes it impossible to determine the first-period decisions analytically. Nevertheless, we were able to show that the incumbent's first-period prices are higher in the greenwashing setting. We analytically derive the first-period decisions of the incumbent in the absence of greenwashing. The theoretical findings are complemented by the numerical results that produce several qualitative insights.

Managerial Findings: Our findings show that the management of an incumbent firm should focus on the signals about an entrant's nature (greenwasher or not). This is extremely important because the incumbent's price and quality decisions in both periods should be adjusted accordingly for an equilibrium profit. If the incumbent knows of the greenwashing possibility of the entrant, it adjusts its first-period decisions to promote the entrant's greenwashing. Second, the management of the incumbent firm should charge higher prices for its product if it thinks that the entrant will greenwash. In fact, as we have shown, the incumbent indirectly benefits from greenwashing by increasing price in a competitive environment. Third, an entrant firm will be inclined to greenwash more if its market potential is higher. Consequently, to nullify the adverse effects of greenwashing, the incumbent should increase its environmental quality. Lastly, the entrant firm's management can quit greenwashing if the incumbent overlooks greenwashing.

As shown numerically, greenwashing is never beneficial for the customers as they are tricked to buy products with a negative surplus, the products they would not buy without greenwashing. The level of loss in consumer surplus as a result of greenwashing increases with the cross-price sensitivity and the market potential of the entrant. Even though it is possible that the incumbent's and the entrant's environmental quality levels can increase with greenwashing, it happens in very rare instances. The ignorance of the incumbent about the greenwashing possibility of the entrant benefits both the customers and the environment with a decrease in first-period price, likely increases in both firms' environmental quality, and a decrease in greenwashing level.

Future Research: In this paper we have considered only the entrant as a greenwasher, while this is not always the case. Considering the incumbent as a greenwasher while facing competition from the entrant is an interesting avenue for future research. One could also consider competition in both stages of the game. Extending the setup to a supply chain by, e.g., including a retailer and justifying the role of each player in the greenwashing context is another interesting avenue. Considering the horizontal differences in products can help understand the impact of customer perception.[1] Lastly, government intervention is not considered in our model, but it is clearly worth considering in future research.

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Chapter 3

Supplier Environmental Development with Greenwashing Activities of the Retailer

Abstract

We investigate the strategic interaction between a retailer, a manufacturer, and a supplier in a three-echelon supply chain with a game-theoretical model in the presence of supplier development and greenwashing. The retailer and manufacturer are environmentally sustainable and want to improve the environmental image of products with the improvement in the supplier's environmental quality to enhance demand by benefiting from the environmental consciousness of the consumers. To achieve that, the manufacturer offers to share the investment cost of the supplier and the retailer advertises the product's environmental quality. When the advertised quality exceeds the true quality, this excess is called greenwashing. If greenwashing is exposed, consumers punish the supply chain by not buying the product.

3.1 Introduction

With the accumulation of memories related to environmental disasters (`https://www.cfr.org/timeline/ecological-disasters`) and the impact of global warming being perceivable in daily life, environmental consciousness has risen and its impact on purchasing behavior of the customers is evident. According to the joint report of McKinsey and NielsenIQ (2023), customers state that they value the product's sustainability while purchasing and they found that there is a positive correlation between demand growth and environmental claims.

While firms in developed countries quit their environmental misconducts and improved their environmental performance as a result of the market pressure and government regulations, their overseas suppliers might still lack high environmental quality. With the efforts of non-governmental organizations (NGOs) to inform customers, global firms are held responsible for their supplier's environmental performance. Nestlé has been targeted by Greenpeace for its second-tier supplier's environmental misconduct, deforesting to increase palm-oil production, and forced by customers to change its supplier (The Economist, 2010). Nike and Adidas have been aimed to act for taking responsibility for their supplier's toxic wastes (Birch, 2012).

A buying firm that expects high environmental performance from its all supply-chain partners should either search for environmentally responsible partners or support its existing partners improve their environmental performance. When high-performing alternative suppliers exist, the buying firm can easily switch its supplier for environmental performance improvement, however, when there is not a better alternative, the buying firm should support financially or be an intermediary for environmental performance improvement of suppliers. Coffee and Farmer Equity (C.A.F.E.) practices of Starbucks is a well-known example of a buying firm taking responsibility to achieve high environmental/social quality of its suppliers (Chen and Lee, 2017).

Even though the environmental performance of the supplier improves with the fear of losing business or the support from its downstream partners, the resulting environmental quality might not match the buying firm's expectations to differentiate itself in the market to enhance the demand. Since the validity of the claimed environmental performance of a supplier is very hard to track by customers, a buying firm, in that case, can overstate the environmental quality of the product (environmental performance of the supply chain while producing the product) by using false or vague terms, that is, to greenwash.

Greenwashing activities can be in various forms: Nature-based imagery, environmental buzzwords, official-looking labels, etc. BlueTriton (formerly known as Nestlé Waters) faced a lawsuit for its attempt to advertise its bottled water as sustainable while bottled water is one of the largest sources of plastic waste and defended themselves by accepting their claims are "vague and hyperbolic" (Lindwall, 2023). In other cases, firms can develop devices to trick the measurement devices: The Environmental Protection Agency (EPA) found that Volkswagen was using a device to pass the emissions test for its "clean diesel" cars which had been advertised as "Green has never felt so right" (Hotten, 2015).

It is evident that customers seek products whose entire production process complies with high environmental standards, and the retailers (the buying firms that directly interact with the customers) try to improve their suppliers' environmental performance to enhance their sales, whereas, retailers can still greenwash their product when it is profitable for them. In order to understand the collaboration effort between supply chain partners, environmental quality investment behavior of suppliers, and greenwashing strategy of retailers (buying firms), we develop a sequential move game considering a three-echelon supply chain existing of a retailer, a manufacturer, and a supplier where the retailer and the manufacturer are environmentally responsible in their operations and the supplier is required to improve its environmental performance. The retailer or the manufacturer shares the environmental quality improvement cost of the supplier in two different settings. The retailer advertises the product's environmental quality to enhance demand. In order to understand the interactions between the retailer's greenwashing strategy, the supplier's environmental quality investment, and the manufacturer's (or the retailer's) cost sharing, we pose the following research questions:

1. Under what conditions is it profitable for the retailer to greenwash?

2. Under what conditions does the manufacturer or the retailer share the environmental quality investment cost of the supplier? How does the rate of support change when the retailer greenwashes?

3. What are the effects of greenwashing on the firms' profits, consumer surplus, and environment?

4. What are the effects of the identity of supporter (the manufacturer or the retailer) on the equilibrium outcomes and the retailer's greenwashing strategy?

Even though we approach the problem profit maximization perspective of the supply chain members, our results are also beneficial to understand the effects of greenwashing and the identity of the cost-sharing firm on the environment and consumers.

We find that the retailer's greenwashing strategy is dependent on the environmental quality level of the supplier; if it is lower than a threshold quality level, the retailer greenwashes; otherwise, the retailer does not. The level of greenwashing decreases and the environmental quality level increases with the rate of cost-sharing. The manufacturer's rate of cost-sharing is higher than the retailer's, hence both the likelihood and the level of greenwashing are higher when the retailer shares the supplier's investment cost. In addition to its detrimental effect on consumers, the supplier's environmental quality investment decreases if the retailer greenwashes although the rate of support is almost always higher in that case. Even though greenwashing is the retailer's decision, it is not always beneficial for the retailer especially when the manufacturer supports the supplier due to the reduced environmental quality level of the supplier.

The remainder of the paper is organized as follows. In Section 3.2, we review the relevant literature, and in Section 3.3, we introduce the model formulation. We present our analytical findings regarding the retailer's and the supplier's responses and the equilibrium outcome in Section 3.4, and numerical findings in Section 3.5. In Section 3.6, we discuss our insights and conclude the study.

3.2 Literature Review

In this section, we discuss the two streams of literature that are related to our work; responsible sourcing and greenwashing.

There have been several articles that focused on different mechanisms to motivate the supplier for investing in environmental/social quality (achieving high environmental/social standards) with different supply chain structures. Cho et al. (2019), Kalkanci and Plambeck (2020) and Kraft et al. (2020) investigated under what conditions it is better for the buying firm to reveal its suppliers and its effect on the environmental compliance efforts of the suppliers. Chen et al. (2019) analyzed the impact of revealing supplier identity considering NGO's auditing decision endogenously. There is an abundance of articles that investigated the efficiency of auditing for achieving high environmental/social quality (Chen and Lee, 2017; Chen et al., 2020; Plambeck and Taylor, 2016; Caro et al., 2018; Fang and Cho, 2020; Lu and Tomlin, 2022). Lu and Tomlin (2022) examined a buyer's auditing strategies in the presence of a self-reporting supplier. Plambeck and Taylor (2016) analyzed a supply chain where the supplier responds to the buyer's auditing efforts by hiding the non-compliant actions. Caro et al. (2018) and Fang and Cho (2020) investigated different auditing schemes of competing firms for a common supplier; individual auditing, audit sharing, and joint auditing. While Murali et al. (2019) compared the effectiveness of certification and government regulations, Chen and Lee (2017) evaluated certification and auditing. Chen et al. (2020) examined auditing strategies in a multi-supplier multi-buyer market.

The articles that are referred to above considered a buyer who uses sticks (requiring certification to continue the supply agreement, penalty or cancellation of supply agreement if the supplier fails the audit, revealing identity to force the supplier for environmental quality investment), there are also articles that examined the effectiveness of carrots (cost-sharing, wholesale price premiums dependent on environmental quality, revenue-sharing). Ni et al. (2010) analyzed the efficiency of wholesale price contract for environmental quality investment under different power structures, the supplier or the downstream firm determines the wholesale price premium and found that the corporate social responsibility level is higher when the supplier determines the wholesale price premium. Ghosh and Shah (2012) investigated the green quality investments of the manufacturer in a two-firm supply chain and used Nash bargaining solution for the manufacturer and the retailer to cooperatively determine the optimal greening level. Ghosh and Shah (2015) extended their prior study by investigating a cost-sharing contract and indicated its benefits on the firms' profits and on the environment. Yang and Chen (2018) investigated revenue-sharing and cost-sharing contracts to improve environmental performance (carbon abatement). Karaer et al. (2017) considered wholesale price premium and environmental quality investment cost sharing to improve supplier environmental performance and investigated the conditions to implement one or both to maximize environmental quality. In addition to the articles that examined the interaction between the retailer (or the buyer) and the manufacturer (or the supplier) in a two-echelon supply chain, there are also articles that considered multi-echelon supply chains (Karaer et al., 2020; Qiao et al., 2021; Huang et al., 2022). Karaer et al. (2020) investigated a three-echelon supply chain where the buyer shares the environmental quality investment cost of the suppliers while considering additive and minimum quality scenarios. Qiao et al. (2021) analyzed revenue-sharing and cost-sharing contracts in a three-echelon supply chain. Huang et al. (2022) examined who should support the upstream supplier, the buyer or the tier-1 supplier, in a three-echelon supply chain when the tier-2 supplier is the only firm in the supply chain that lacks environmental quality.

With the increased attention on the social and environmental sustainability of the customers, non-governmental organizations, and regulatory authorities, several articles that investigate different aspects of greenwashing have been published in recent years. When there are both observable and unobservable aspects of a product's sustainability, firms can invest in the observable aspects to generate profit while neglecting unobservable ones, Wu et al. (2020) investigated a market with socially responsible firm and a solely profit maximizer firm and found that the socially responsible firm can increase its sustainability efforts to distinguish itself from the greenwasher firm. Huang et al. (2020) considered a market where an incumbent green firm competes with a greenwashing entrant firm, which imitates the exogenous green quality of the green firm. Cetin et al. (2023) extended Huang et al. (2020) by investigating the green quality investment decision of the incumbent and the entrant, and greenwashing level of the entrant and found that the incumbent green firm also benefits from the entrant's greenwashing activities. Wang et al. (2022) investigated the impact of regulatory interference with a false-claim ban on a firm's greenwashing strategy in the presence of imperfect information about the true green quality and found that a false-claim penalty is necessary to avoid intentional greenwashing and beneficial to decrease the likelihood of unintentional greenwashing. Lee et al. (2018) focused on a different aspect greenwashing ban by investigating under what conditions a greenwashing ban is beneficial to achieve high environmental quality. Sun and Zhang (2019) analyzed the impacts of the government's subsidy and penalty in a competitive market with an evolutionary game model. Shen et al. (2020) considered a supply chain in which the manufacturer can overstate the environmental quality of the product to enhance demand and investigated the effectiveness of inspection and deferred payment mechanism.

As summarized, several articles have been published on responsible sourcing and greenwashing, whereas our work is the first one to investigate the impact of the environmental quality investment of the supplier on the retailer's greenwashing strategy, the impact of greenwashing of the retailer on the supplier's environmental quality investment and the impact of cost-sharing by the retailer or manufacturer to these relationships.

3.3 Model

We consider a three-echelon supply chain with a retailer, a manufacturer, and a supplier. The supplier produces the parts with unit cost c_s and transfers them to the manufacturer with wholesale price w_s. The manufacturer further processes the product with unit cost c_m and delivers them to the retailer with the wholesale price w_m. The retailer sells the product to the final consumers for retail price w_r incurring the unit cost c_r. The contracts determining the wholesale prices between the retailer and the manufacturer and between the manufacturer and supplier have been already established and are out of our research scope. The retail price is market-driven and the retailer cannot change it. As a result, the profit margins of the firms are exogenous and out of the scope of our problem, which are as follows;

$$p_r = w_r - c_r - w_m,$$
$$p_m = w_m - c_m - w_s,$$
$$p_s = w_s - c_s.$$

The consumers value the products with higher environmental quality more, hence the demand increases with the environmental image of the products a and decreases with the retail price w_r, $Q(w_r, a) = \alpha - \beta w_r + \delta a$ (Ni et al., 2010; Yang and Chen, 2018). Since the retail price is exogenous, the demand function is reduced to the function of the environmental image of the products only, $Q(a) = \theta + \delta a$ where $\theta = \alpha - \beta w_r$.

The retailer and the manufacturer are located in a country where environmental regulations are strict, so we assume that they are environmentally responsible. The retailer wants to distinguish its products from other products in the market by improving the environmental image. The retailer can achieve its goal with the improvement of the environmental quality of the supply chain beyond the manufacturer. The supplier should make an investment to assess the problems related to environmental quality in the production process and improve them. The investment cost of environmental quality improvement increases quadratically with the level of environmental quality q, yq^2 (Karaer et al., 2017; Yang and Chen, 2018). In order to reduce the financial burden on the supplier and to motivate further improvements in the environmental quality, either one of downstream firms (the retailer or the manufacturer) offers to share the investment cost of the supplier with γ fraction. We evaluate the settings where the retailer delegates the manufacturer to support the supplier for environmental improvement and where the retailer directly interacts with and supports the supplier.

Even though the demand increases with the environmental image of the product a, the environmental quality of the supply chain cannot be observed by the consumers. The retailer advertises the environmental quality of the products with an advertisement campaign to create an environmental image. Convincing the consumers about the environmental quality of the product, in other words, improving the environmental image, gets harder with a higher level of environmental image a, hence the advertisement cost increases quadratically with the level of environmental image a, ta^2 (Shen et al., 2020; Cetin et al., 2023).

Since the retailer's investment on advertisement to build up the environmental image of the product is not limited with the environmental quality of the supply chain, the retailer can overstate the environmental quality to maximize its profit, that is to greenwash. Depending on the cost of advertising, the retailer can also understate the environmental quality to maximize her profit. Even though we will not consider the NGO (or the government agencies) as a player, its inspection effort to detect the greenwashing activities of the firms will affect our problem. We assume that the probability of the NGO detecting the green-washing activities increases with the green-washing level, $[a-q]^+$, and the NGO's exogenous inspection effort level k[1] (Huang et al., 2020). When the NGO detects greenwashing, it reveals its findings to the consumers. As a result, the retailer loses her credibility and the demand becomes 0. The inspection effort of the NGO is the main factor for the retailer to deter green-washing activities. We omit the out-of-pocket penalty mechanism in our work.

When the manufacturer is the one supporting the supplier, the resulting profit functions of the retailer, the manufacturer and the supplier are as follows:

[1] k can also be explained as the combination of two factors, n: exposition probability and m: the rate of customers who stops buying the product if greenwashing is exposed. The qualitative results don't change in either way. The loss in demand is either k or $m * n$, but the implication is the same.

$$\pi_r(a) = (\theta + \delta a)(1 - k[a-q]^+)p_r - ta^2,$$
$$\text{subject to}: a \geq 0$$
$$\pi_m(\gamma) = (\theta + \delta a)(1 - k[a-q]^+)p_m - \gamma y q^2,$$
$$\text{subject to}: 0 \leq \gamma \leq 1$$
$$\pi_s(q) = (\theta + \delta a)(1 - k[a-q]^+)p_s - y(1-\gamma)q^2.$$
$$\text{subject to}: q \geq 0$$

The sequence of events is as follows:

1. The manufacturer (or the retailer) offers to share the environmental quality improvement cost with the supplier at fraction γ.

2. After observing γ, the supplier determines its environmental quality level q.

3. The retailer determines its advertisement level a for the product's environmental quality and creates the environmental image of the product.

Table 3.1: Notation

	Parameters
θ	Base demand
δ	Consumers' sustainable quality sensitivity
p_i	Profit margin of firm i
t	Retailer's advertisement cost coefficient
y	Supplier's investment cost factor to build up environmental quality
k	Rate of increase in exposure probability with greenwashing level
	Decision and state variables
a	Environmental advertisement level of the retailer
q	Environmental quality level of the supplier
γ	Fraction of the supplier's investment cost that a downstream player shares
	Indices
i	The firms, r: retailer, m: manufacturer, s: supplier
j	The settings, *Del*: delegation, *DS*: direct-support
l	The cases, N: non-greenwashing, G: greenwashing, C: non-greenwashing with constrained environmental image

When the retailer directly supports the supplier, the manufacturer becomes a passive player and the problem is reduced to a two-player game. While everything else stays the same in the game design, at the first step, the retailer is the one who decides the fraction of the environmental investment cost to share γ.

3.4 Analytical Results

3.4.1 Delegation

In this setting, the retailer delegates the manufacturer to support the supplier. While the manufacturer supports the supplier, the retailer focuses its efforts for advertising the supply chain's environmental quality.

When the advertised environmental image a is less than the true greenwashing level q, there is no overstatement of the environmental quality. So, there is not any activity to be exposed and the profit function is updated as π_r^N.

$$\pi_r(a) = \begin{cases} \pi_r^G = (\theta + \delta a)(1 - k(a-q))p_r - ta^2, & if\ a > q, \\ \pi_r^N = (\theta + \delta a)p_r - ta^2, & if\ a \leq q. \end{cases}$$

Proposition 13 *The retailer's best response a to the supplier's environmental quality investment level q can be characterized as follows:*

$$a^*(q) = \begin{cases} a^G(q) = \dfrac{p_r(\delta - k\theta) + \delta k p_r q}{2(t + \delta k p_r)}, & q < \dfrac{p_r(\delta - k\theta)}{2t + \delta k p_r}, \\ a^N(q) = q, & \dfrac{p_r(\delta - k\theta)}{2t + \delta k p_r} \leq q < \dfrac{\delta p_r}{2t}, \\ a^C = \dfrac{\delta p_r}{2t}, & \dfrac{\delta p_r}{2t} < q. \end{cases}$$

As can be seen from Proposition 13, if q is too low, then the retailer overstates the environmental quality with greenwashing to attract consumers' valuation. If q is moderate, the retailer matches the advertisement efforts to q. However, if q is too high, the cost to advertise environmental quality of the product surpasses the demand benefits of it, then the retailer limits its advertisement level with $\frac{\delta p_r}{2t}$.

For the brevity of the expression, we represent the greenwashing threshold with $\overline{q}^G = \frac{p_r(\delta - k\theta)}{2t+\delta k p_r}$, and the advertisement threshold with $\overline{q}^C = \frac{p_r \delta}{2t}$. As customers value more the environmental quality of the product, as δ increases, both thresholds go up. The increases in the thresholds mean that the retailer is more eager to overstate the environmental quality, and more likely to match the environmental quality level of the product with advertisement even if it does not greenwash. The same effects on the thresholds is observed with an increase in the retailer's profit margin p_r and decrease in the cost of advertisement t, as the former improves the marginal revenue and the latter reduces the marginal cost of the retailer.

δ defines the rate of demand increase as the environmental image a increases and k is the rate of the exposition probability of the supply chain, hence $k\theta$ represents the increase in the expected demand loss as a result of greenwashing exposure with an increase in a. In order for the retailer to consider whether to greenwash and how much to greenwash, the necessary condition is for the demand increase rate δ to be higher than the expected demand loss due to the exposition of the greenwashing $k\theta$. $\delta - k\theta > 0$ is the fundamental assumption of our work, otherwise, the retailer does not have any motivation to exaggerate the environmental quality in any condition, which is a less interesting case that we disregard.

When we substitute the retailer's best response function into the profit function of the supplier, we get

$$\pi_s(q) = \begin{cases} \pi_s^G = \left(\theta + \delta a^G(q)\right)(1 - k(a^G(q) - q))p_s - y(1-\gamma)q^2, & q < \overline{q}^G, \\ \pi_s^N = (\theta + \delta q)\, p_s - y(1-\gamma)q^2, & \overline{q}^G \leq q < \overline{q}^C, \\ \pi_s^C = \left(\theta + \delta \dfrac{\delta p_r}{2t}\right) p_s - y(1-\gamma)q^2, & \overline{q}^C < q. \end{cases}$$

$\underline{\gamma}^N$ and $\overline{\gamma}^N$ define lower and upper bounds of the region where $q^N(\gamma)$ is an interior solution, respectively, and $\overline{\gamma}^G$ defines the regions where $q^G(\gamma)$ is an interior solution.

$$
\begin{aligned}
\underline{\gamma}^N &= 1 - \frac{p_s\delta(2t+\delta k p_r)}{2p_r y(\delta - k\theta)}, \\
\overline{\gamma}^N &= 1 - \frac{p_s t}{p_r y}, \\
\overline{\gamma}^G &= 1 - \frac{k p_s(2t+\delta k p_r)}{2y}\left(\frac{\delta}{t+\delta k p_r} + \frac{\theta}{p_r(\delta - k\theta)}\right).
\end{aligned}
$$

R^G, R^N, R^C, and R^L are the regions defining the supplier's best response to the manufacturer's rate of cost-sharing; R^G is the region where the supplier invests less than $\overline{q}^G$, R^N is the region where the supplier invests less than $\overline{q}^G$ and the retailer matches the advertised environmental quality to true environmental quality, R^C is the region where the retailer does not advertise as much as true environmental quality and R^L is the region where the supplier's environmental quality investment level causes the retailer to prefer unintended greenwashing strategy.

$$
\begin{aligned}
R^G = \Big\{ & \Big((\gamma < \overline{\gamma}^G) \cap (\gamma < \underline{\gamma}^N)\Big) \\
& \cup \Big((\gamma < \overline{\gamma}^G) \cap (\underline{\gamma}^N < \gamma < \overline{\gamma}^N) \cap \Big(\pi_s^N(q^N(\gamma)) < \pi_s^G(q^G(\gamma))\Big)\Big) \\
& \cup \Big((\gamma < \overline{\gamma}^G) \cap (\overline{\gamma}^N < \gamma) \cap \Big(\pi_s^N(\overline{q}^C) < \pi_s^G(q^G(\gamma))\Big)\Big) \Big\} \\
R^N = \Big\{ & \Big((\overline{\gamma}^G < \gamma) \cap (\underline{\gamma}^N < \gamma < \overline{\gamma}^N)\Big) \\
& \cup \Big((\gamma < \overline{\gamma}^G) \cap (\underline{\gamma}^N < \gamma < \overline{\gamma}^N) \cap \Big(\pi_s^N(q^N(\gamma)) > \pi_s^G(q^G(\gamma))\Big)\Big) \Big\} \\
R^C = \Big\{ & \Big((\overline{\gamma}^G < \gamma) \cap (\overline{\gamma}^N < \gamma)\Big) \\
& \cup \Big((\gamma < \overline{\gamma}^G) \cap (\overline{\gamma}^N < \gamma) \cap \Big(\pi_s^N(\overline{q}^C) > \pi_s^G(q^G(\gamma))\Big)\Big) \Big\} \\
R^L = \Big\{ & (\overline{\gamma}^G < \gamma) \cap (\gamma < \underline{\gamma}^N) \Big\}
\end{aligned}
$$

Proposition 14 *The supplier's best response q to the manufacturer's rate of cost-sharing γ can be characterized as follows:*

$$q^*(\gamma) = \begin{cases} q^G(\gamma) = \dfrac{kp_s(\delta p_r(\delta - k\theta)(2t + \delta kp_r) + 2\theta(t + \delta kp_r)^2)}{4y(1-\gamma)(t + \delta kp_r)^2 - \delta^2 k^2 p_r p_s(2t + \delta kp_r)}, & R^G \\ q^N(\gamma) = \dfrac{\delta p_s}{2y(1-\gamma)}, & R^N \\ q^C(\gamma) = \overline{q}^C, & R^C \\ q^L(\gamma) = \overline{q}^G, & R^L \end{cases}$$

$q^N(\gamma)$ and $q^G(\gamma)$ represents the optimal environmental quality investment levels of the supplier for a given rate of cost-sharing γ for the cases where the retailer does not greenwash and where the retailer greenwashes, respectively. The regions of the best response of the supplier are created with the boundaries that define whether $q^N(\gamma)$ and $q^G(\gamma)$ are interior. If only one of them is interior then we have a straightforward answer for the actions of the supplier. For example, if $\underline{\gamma}^N < \gamma < \overline{\gamma}^N$, the supplier's environmental quality investment expecting the retailer does not greenwash $q^N(\gamma)$ will be sufficient to prevent greenwashing, $q^N(\gamma) > \overline{q}^G$, and not too high to reach the retailer's advertisement threshold, $q^N(\gamma) < \overline{q}^C$. $(\overline{\gamma}^G < \gamma)$ means that the environmental quality investment level $q^G(\gamma)$ determined by the supplier to maximize its profit under the greenwashing case will make the buyer not to greenwash. Since it cannot make the supplier maximize its profit under the non-greenwashing case, the intersection of these two conditions, $\Big((\underline{\gamma}^N < \gamma < \overline{\gamma}^N) \cap (\overline{\gamma}^G < \gamma)\Big)$, guarantees the non-greenwashing case and the supplier sets its environmental quality investment to $q^N(\gamma)$. When both solutions are interior, the supplier can select the profit-maximizing greenwashing strategy. L solution is realized when neither $q^N(\gamma)$ nor $q^G(\gamma)$ are interior. Since $\overline{\gamma}^G$ is always larger than $\underline{\gamma}^N$, $(\overline{\gamma}^G < \gamma) \cap (\gamma < \underline{\gamma}^N) = \emptyset$ and we can eliminate L solution. In other words, at least one of $q^N(\gamma)$ and $q^G(\gamma)$ is always an interior solution, i.e. either $q^N(\gamma) > \overline{q}^G$ or $q^G(\gamma) < \overline{q}^G$ always holds. Since the environmental quality investment that is higher than the retailer's advertisement level does not have a revenue-increasing impact for the supplier, the supplier limits its investment level if γ is larger than $\overline{\gamma}^N$ under the non-greenwashing case and we can get C solution.

Proposition 15 *The environmental quality investment level of the supplier q is always higher under the non-greenwashing case with the same sharing ratio γ, that is $q^N(\gamma) > q^G(\gamma)$.*

Proposition 15 shows us that whenever the retailer deceives the consumers with greenwashing, anticipation of the retailer's greenwashing makes the supplier decrease its environmental quality investments. This fact indicates the importance of the regulations and auditing for greenwashing activities of the firms due to its demotivating impact on the supplier's environmental quality investment.

When we substitute the supplier's best response function into the profit function of the manufacturer, we obtain the following piece-wise profit function:

$$\pi_m(\gamma) = \begin{cases} \pi_m^G(\gamma) = \left(\theta + \delta a^G(\gamma)\right)(1 - k(a^G(\gamma) - q^G(\gamma)))p_m - y\gamma\left(q^G(\gamma)\right)^2, & R^G, \\ \pi_m^N(\gamma) = \left(\theta + \delta \dfrac{\delta p_s}{2y(1-\gamma)}\right)p_m - y\gamma\left(\dfrac{\delta p_s}{2y(1-\gamma)}\right)^2, & R^N, \\ \pi_m^C(\gamma) = \left(\theta + \delta \dfrac{\delta p_r}{2t}\right)p_m - y\gamma\left(\dfrac{\delta p_r}{2t}\right)^2, & R^C. \end{cases}$$

Proposition 16 *The equilibrium actions of the manufacturer, the supplier and the retailer* *under the delegation setting can be characterized as*

$$\gamma^* = \begin{cases} \gamma^{G0} = 0, & \gamma^G \leq 0 \;\&\; A1,\ A2a,\ C1a,\ C1bx,\ E \\ \gamma^G = \dfrac{2p_m - p_s}{2p_m + p_s} + \dfrac{\delta^2 k^2 {p_s}^2 p_r(2t + \delta k p_r)}{4y(t + \delta k p_r)^2(2p_m + p_s)}, & \gamma^G > 0 \;\&\; A1,\ A2a,\ C1a,\ C1bx,\ E \\ \gamma^{N0} = 0, & \gamma^N \leq 0 \;\&\; C1by,\ C2a,\ D1,\ D2a \\ \gamma^N = \dfrac{2p_m - p_s}{2p_m + p_s}, & \gamma^N > 0 \;\&\; C1by,\ C2a,\ D1,\ D2a \\ \gamma^{C0} = 0, & \gamma^C \leq 0 \;\&\; F1 \\ \gamma^C = 1 - \dfrac{p_s t}{p_r y}, & \gamma^C > 0 \;\&\; F1 \\ \gamma^{NX} = \gamma^X + \varepsilon, & A2b+,\ B+,\ C2b+,\ D2b+,\ F2+ \\ \gamma^{GX} = \gamma^X - \varepsilon, & A2b-,\ B-,\ C2b-,\ D2b-,\ F2- \end{cases}$$

where $\gamma^X = \{\gamma \mid \pi_s^N(\gamma) = \pi_s^G(\gamma)\}$

γ^N and γ^G represents the optimal cost sharing rate of the manufacturer for the cases where the retailer does not greenwash and where the retailer greenwashes, respectively. We can observe from Proposition 16 that the manufacturer is willing to support more to the supplier, that is $\gamma^G > \gamma^N$, if the retailer greenwashes. Proposition 15 shows that the environmental quality investment of the supplier is lower under the greenwashing case with the same level of cost-sharing, thus the manufacturer takes responsibility to diminish the greenwashing level and increases its sharing ratio γ to motivate the supplier to invest more in environmental quality.

When the optimal sharing ratio of the manufacturer has a negative value, it sets $\gamma = 0$. When $\gamma = 0$, $G0$, $N0$ and $C0$ represent the same outcome considering greenwashing strategy with G, N and C, respectively. GX and NX are the greenwashing and non-greenwashing regions where the firms have conflicting interests regarding greenwashing strategy. We observe GX and NX when (i) and (ii) happen at the same time.

(i) γ^G causes the supplier to set q higher than the greenwashing threshold of the retailer, $q^*(\gamma^G) = q^N(\gamma^G) > \overline{q}^G$, and the end outcome is non-greenwashing.

(ii) γ^N causes the supplier to set q lower than the greenwashing threshold of the retailer, $q^*(\gamma^N) = q^G(\gamma^N) < \overline{q}^G$, and the end outcome is greenwashing.

When these two happen at the same time, the manufacturer sets its sharing ratio to make the supplier indifferent between greenwashing and non-greenwashing, $\gamma^X = \{\gamma \mid \pi_s^N(\gamma) = \pi_s^G(\gamma)\}$. With that sharing ratio, the manufacturer can dictate the greenwashing strategy of the entire supply chain. $\gamma^X - \varepsilon$ is the highest sharing ratio that causes greenwashing, and $\gamma^X + \varepsilon$ is the lowest sharing ratio to prevent greenwashing. If greenwashing is of manufacturer's interest, sharing ratio is set to $\gamma^{GX} = \gamma^X - \varepsilon$, otherwise sharing ratio is set to $\gamma^{NX} = \gamma^X + \varepsilon$.

When this conflicting greenwashing cases are observed, the manufacturer increases its sharing ratio just enough to motivate the supplier to invest on environmental quality higher than the retailer's greenwashing threshold, $\gamma^X > \gamma^N$, if the manufacturer's profit is higher with greenwashing, the manufacturer reduces its sharing ratio to trigger greenwashing by guaranteeing the environmental quality investment of the supplier wouldn't be sufficient to prevent greenwashing, $\gamma^X < \gamma^G$, otherwise.

The feasibility of profit-maximizing sharing ratios under the greenwashing and non-greenwashing scenarios have to be investigated by the manufacturer thoroughly. Even when only one of γ^G and γ^N is an interior solution, setting sharing ratio to that value can give the opportunity for the supplier to deviate from the intended greenwashing strategy of the manufacturer. We analyze under what conditions there can be a deviation from the intended outcome and define the equilibrium accordingly by evaluating every possible scenario. The regions presented in Proposition 16 are the result of this analysis.

For the brevity of the expressions, we will call $\tilde{\gamma}^G = max\{0, \gamma^G\}$, $\tilde{\gamma}^N = max\{0, \gamma^N\}$,$\tilde{\gamma}^C = max\{0, \gamma^C\}$.

As already discussed, the greenwashing strategies of the three firms can be unaligned, thus in order to determine whether there would be a deviation from the intended greenwashing strategy, we need to check all possible conditions. The following procedure explains the derivations of the regions that define the equilibrium solution in Proposition

16.

- **A:** $\tilde{\gamma}^G < \overline{\gamma}^G$ & $\tilde{\gamma}^N < \underline{\gamma}^N$: Both $\tilde{\gamma}^G$ and $\tilde{\gamma}^N$ are not high enough to encourage the supplier to invest in environmental quality higher than the greenwashing threshold of the retailer $\overline{q}^G$, hence we expect that the manufacturer sets the sharing ratio to $\tilde{\gamma}^G$. Still, we need to check whether the sharing ratio of the manufacturer can give the supplier the opportunity to invest higher than $\overline{q}^G$.
  - **A1:** $\tilde{\gamma}^G < \underline{\gamma}^N \Rightarrow G$: Even if the supplier uses the sharing ratio of the greenwashing case for non-greenwashing case, the profit-maximizing environmental quality is not high enough to deter the retailer's greenwashing activities, $q^N(\tilde{\gamma}^G) < \overline{q}^G$, and the supplier sets its environmental quality investment level for the greenwashing case.
  - **A2:** $\tilde{\gamma}^G \geq \underline{\gamma}^N$: Since both $q^N(\tilde{\gamma}^G)$ and $q^G(\tilde{\gamma}^G)$ are interior solutions, the supplier can enforce its profit-maximizing greenwashing strategy to the whole supply chain.
    - **A2a:** $\pi_s^N(q^N(\tilde{\gamma}^G)) < \pi_s^G(q^G(\tilde{\gamma}^G)) \Rightarrow G$: The expected greenwashing strategy of the manufacturer is chosen by the supplier, thus the manufacturer does not adjust its sharing ratio.
    - **A2b:** $\pi_s^N(q^N(\tilde{\gamma}^G)) \geq \pi_s^G(q^G(\tilde{\gamma}^G))$: The supplier's greenwashing strategy is the opposite of the manufacturer's intended strategy, then the manufacturer sets sharing ratio to regain its power on the greenwashing strategy of the supply chain by using γ^X.
      - **A2b+:** $\pi_m^N(\tilde{\gamma}^X, q^N(\tilde{\gamma}^X)) \geq \pi_m^G(\tilde{\gamma}^X, q^G(\tilde{\gamma}^X)) \Rightarrow NX$
      - **A2b−:** $\pi_m^N(\tilde{\gamma}^X, q^N(\tilde{\gamma}^X)) < \pi_m^G(\tilde{\gamma}^X, q^G(\tilde{\gamma}^X)) \Rightarrow GX$
- **B:** $\tilde{\gamma}^G \geq \overline{\gamma}^G$ & $\tilde{\gamma}^N < \underline{\gamma}^N$: Since neither $\tilde{\gamma}^G$ nor $\tilde{\gamma}^N$ is interior solution, the manufacturer sets its sharing ratio to γ^X and enforces greenwashing strategy of its interest to the supply chain.
  - **B+:** $\pi_m^N(\tilde{\gamma}^X, q^N(\tilde{\gamma}^X)) \geq \pi_m^G(\tilde{\gamma}^X, q^G(\tilde{\gamma}^X)) \Rightarrow NX$

- **B−:** $\pi_m^N(\tilde{\gamma}^X, q^N(\tilde{\gamma}^X)) < \pi_m^G(\tilde{\gamma}^X, q^G(\tilde{\gamma}^X)) \Rightarrow GX$

- **C:** $\tilde{\gamma}^G < \overline{\gamma}^G$ & $\underline{\gamma}^N < \tilde{\gamma}^N < \overline{\gamma}^N$: Both solutions are interior. $q^G(\tilde{\gamma}^G) < \overline{q}^G$ triggers the retailer to greenwash and $q^N(\tilde{\gamma}^N) > \overline{q}^G$ prevents the retailer to greenwash, hence the manufacturer and the supplier can act for both greenwashing strategies. Since $\gamma^G > \gamma^N$, we know that $\tilde{\gamma}^G$ can be used by the supplier for non-greenwashing scenario, $q^N(\tilde{\gamma}^G) > \overline{q}^G$, and $\tilde{\gamma}^N$ can be used by the supplier for the greenwashing scenario, $q^G(\tilde{\gamma}^N) < \overline{q}^G$.
  - **C1:** $\pi_s^G(q^G(\tilde{\gamma}^G)) \geq \pi_s^N(q^N(\tilde{\gamma}^G))$: If the manufacturer sets its sharing ratio to $\tilde{\gamma}^G$, the supplier uses that sharing ratio for the intended greenwashing strategy.
    - **C1a:** $\pi_s^G(q^G(\tilde{\gamma}^N)) \geq \pi_s^N(q^N(\tilde{\gamma}^N)) \Rightarrow G$: The supplier sets environmental quality investment level that is not sufficient to prevent the retailer's greenwashing activities if the sharing ratio is chosen for the non-greenwashing case. Since the supplier prefers greenwashing strategy for both $\tilde{\gamma}^G$ and $\tilde{\gamma}^N$, the manufacturer sets $\gamma = \tilde{\gamma}^G$.
    - **C1b:** $\pi_s^G(q^G(\tilde{\gamma}^N)) < \pi_s^N(q^N(\tilde{\gamma}^N))$: The supplier prefers non-greenwashing and invests in environmental quality to prevent the retailer's greenwashing activities if the manufacturer sets sharing ratio for non-greenwashing, which means the supplier follows the manufacturer's greenwashing strategy in perfect harmony and the manufacturer selects the greenwashing strategy of the supply chain.
      - **C1bx:** $\pi_m^N(\tilde{\gamma}^N) < \pi_m^G(\tilde{\gamma}^G) \Rightarrow G$
      - **C1by:** $\pi_m^N(\tilde{\gamma}^N) \geq \pi_m^G(\tilde{\gamma}^G) \Rightarrow N$
  - **C2:** $\pi_s^G(q^G(\tilde{\gamma}^G)) < \pi_s^N(q^N(\tilde{\gamma}^G))$: If the manufacturer sets its sharing ratio to $\tilde{\gamma}^G$, the supplier uses that sharing ratio for the unintended greenwashing strategy.
    - **C2a:** $\pi_s^G(q^G(\tilde{\gamma}^N)) < \pi_s^N(q^N(\tilde{\gamma}^N)) \Rightarrow N$: The supplier sets environmental quality investment level that is sufficient to prevent the retailer's green-

washing activities if the sharing ratio is chosen for the non-greenwashing case. Since the supplier prefers non-greenwashing strategy for both $\tilde{\gamma}^G$ and $\tilde{\gamma}^N$, the manufacturer sets $\gamma = \tilde{\gamma}^N$.

* **C2b:** $\pi_s^G(q^G(\tilde{\gamma}^N)) \geq \pi_s^N(q^N(\tilde{\gamma}^N))$: The supplier's greenwashing strategy is the opposite of the manufacturer's intended strategy, then the manufacturer sets sharing ratio to regain its power on the greenwashing strategy of the supply chain by using γ^X.
  · **C2b+:** $\pi_m^N(\tilde{\gamma}^X, q^N(\tilde{\gamma}^X)) \geq \pi_m^G(\tilde{\gamma}^X, q^G(\tilde{\gamma}^X)) \Rightarrow NX$
  · **C2b−:** $\pi_m^N(\tilde{\gamma}^X, q^N(\tilde{\gamma}^X)) < \pi_m^G(\tilde{\gamma}^X, q^G(\tilde{\gamma}^X)) \Rightarrow GX$

- **D:** $\tilde{\gamma}^G \geq \overline{\gamma}^G$ & $\underline{\gamma}^N < \tilde{\gamma}^N < \overline{\gamma}^N$: Both $\tilde{\gamma}^G$ and $\tilde{\gamma}^N$ are high enough to encourage the supplier to invest in environmental quality higher than the greenwashing threshold of the retailer $\overline{q}^G$, hence we expect that the manufacturer sets the sharing ratio to $\tilde{\gamma}^N$. Still, we need to check whether the sharing ratio of the manufacturer can be used by the supplier for the greenwashing scenario.
  – **D1:** $\tilde{\gamma}^N \geq \overline{\gamma}^G \Rightarrow N$: Even if the supplier uses non-greenwashing sharing ratio for greenwashing, the profit-maximizing environmental quality is high enough to deter the retailer's greenwashing activities, $q^G(\tilde{\gamma}^G) > \overline{q}^G$.
  – **D2:** $\tilde{\gamma}^N < \overline{\gamma}^G$: Since both q^N and q^G are interior with $\tilde{\gamma}^N$, the supplier can enforce its profit-maximizing greenwashing strategy to the whole supply chain.
    * **D2a:** $\pi_s^N(q^N(\tilde{\gamma}^N)) \geq \pi_s^G(q^G(\tilde{\gamma}^N)) \Rightarrow N$: Deviating from the non-greenwashing is not profitable for the supplier, so the manufacturer is confident that $\tilde{\gamma}^N$ does not cause greenwashing.
    * **D2b:** $\pi_s^N(q^N(\tilde{\gamma}^N)) < \pi_s^G(q^G(\tilde{\gamma}^N))$: The supplier's greenwashing strategy is the opposite of the manufacturer's intended strategy, then the manufacturer sets sharing ratio to regain its power on the greenwashing strategy of the supply chain by using γ^X.
      · **D2b+:** $\pi_m^N(\tilde{\gamma}^X, q^N(\tilde{\gamma}^X)) \geq \pi_m^G(\tilde{\gamma}^X, q^G(\tilde{\gamma}^X)) \Rightarrow NX$

· **D2b−:** $\pi_m^N(\tilde{\gamma}^X, q^N(\tilde{\gamma}^X)) < \pi_m^G(\tilde{\gamma}^X, q^G(\tilde{\gamma}^X)) \Rightarrow GX$

- **E:** $\tilde{\gamma}^G < \overline{\gamma}^G$ & $\overline{\gamma}^N < \tilde{\gamma}^N \Rightarrow G$: Both $\tilde{\gamma}^N$ and $\tilde{\gamma}^G$ produce intended outcomes considering greenwashing strategy, whereas the sharing ratio beyond $\overline{\gamma}^N$ has no impact on the level of environmental quality investment of the supplier. The manufacturer should compare the impact of $\tilde{\gamma}^G$ and $\tilde{\gamma}^C = [\overline{\gamma}^N]^+$. Thanks to concavity of π_s^G, we know that $\pi_s^G(q^G(\tilde{\gamma}^G)) \geq \pi_s^N(q^C(\tilde{\gamma}^G))$. The same is true for $\tilde{\gamma}^C$, $\pi_s^G(q^G(\tilde{\gamma}^C)) \geq \pi_s^N(q^C(\tilde{\gamma}^C))$ since $q^G(\tilde{\gamma}^C)$ is an interior solution due to $\tilde{\gamma}^C < \tilde{\gamma}^G < \overline{\gamma}^G$. Given that the supplier prefers greenwashing, the manufacturer acts for the greenwashing scenario.

- **F:** $\tilde{\gamma}^G \geq \overline{\gamma}^G$ & $\overline{\gamma}^N < \tilde{\gamma}^N$: Since the sharing ratio that is higher than $\overline{\gamma}^N$ does not benefit the manufacturer, it updates non-greenwashing sharing ratio with $\tilde{\gamma}^C$. Both $\tilde{\gamma}^G$ and $\tilde{\gamma}^C$ are high enough to encourage the supplier to invest in environmental quality higher than the greenwashing threshold of the retailer, hence we expect that the manufacturer sets the sharing ratio to $\tilde{\gamma}^C$. Still, we need to check whether the sharing ratio of the manufacturer can be used by the supplier for the greenwashing scenario.

  - **F1:** $\tilde{\gamma}^C \geq \overline{\gamma}^G \Rightarrow C$: Even if the supplier uses non-greenwashing sharing ratio for greenwashing the profit-maximizing environmental quality is high enough to deter the retailer's greenwashing activities, $q^G(\tilde{\gamma}^C) > \overline{q}^G$.

  - **F2:** $\tilde{\gamma}^C < \overline{\gamma}^G \Rightarrow NX$: We know that $\pi_s^G(q^G(\tilde{\gamma}^C)) \geq \pi_s^N(q^C(\tilde{\gamma}^C))$ due to concavity of π_s^G. The supplier's greenwashing strategy is the opposite of the manufacturer's intended strategy, then the manufacturer sets sharing ratio to regain its power on the greenwashing strategy of the supply chain by using γ^X.

    * **F2+:** $\pi_m^N(\tilde{\gamma}^X, q^C(\tilde{\gamma}^X)) \geq \pi_m^G(\tilde{\gamma}^X, q^G(\tilde{\gamma}^X)) \Rightarrow NX$
    * **F2−:** $\pi_m^N(\tilde{\gamma}^X, q^C(\tilde{\gamma}^X)) < \pi_m^G(\tilde{\gamma}^X, q^G(\tilde{\gamma}^X)) \Rightarrow GX$

3.4.2 Direct-support

In this setting, the retailer is the one supporting the supplier. The retailer takes responsibility for sharing the environmental quality investment cost of the retailer and advertises the product's environmental quality to enhance demand. The manufacturer becomes a passive player under the direct-support setting.

The only difference in the retailer's profit function in the direct-support setting is the addition of the cost of supporting the supplier with environmental quality investments.

$$\pi_r(a) = \begin{cases} \pi_r^G = (\theta + \delta a)(1 - k(a-q))p_r - ta^2 - \gamma y q^2, & if\ a > q, \\ \pi_r^N = (\theta + \delta a)p_r - ta^2 - \gamma y q^2, & if\ a \leq q. \end{cases}$$

Since the cost of supporting the supplier is not dependent on the advertisement level, the best response of the retailer in the direct-support setting is the same as the best response in the delegation setting. With the identical response function of the retailer, the supplier's environmental response function does not change either. Thanks to these, we can skip to the analysis of the equilibrium sharing ratio. In this setting, the manufacturer becomes a passive player and is affected by the decisions of other firms.

$\tilde{R}^G$, $\tilde{R}^N$ and $\tilde{R}^C$ are defined the same as R^G, R^N and R^C. The only difference is that $\overline{\gamma}^N$ should be replaced with $\tilde{\gamma}^N = 1 - \frac{p_s(t+y)}{(p_s+p_r)y}$.

$$\pi_r(\gamma) = \begin{cases} \pi_r^G(\gamma) = \left(\theta + \delta a^G(\gamma)\right)(1 - k(a^G(\gamma) - q^G(\gamma)))p_r & \\ \qquad - y\gamma\left(q^G(\gamma)\right)^2 - t\left(a^G(\gamma)\right)^2, & \tilde{R}^G, \\ \pi_r^N(\gamma) = \left(\theta + \delta \frac{\delta p_s}{2y(1-\gamma)}\right)p_r - (t + y\gamma)\left(\frac{\delta p_s}{2y(1-\gamma)}\right)^2, & \tilde{R}^N, \\ \pi_r^C(\gamma) = \left(\theta + \delta \frac{\delta p_r}{2t}\right)p_r - (t + y\gamma)\left(\frac{\delta p_r}{2t}\right)^2, & \tilde{R}^C. \end{cases}$$

Proposition 17 *The equilibrium actions of the manufacturer, the supplier, and the retailer* *under the direct-support setting can be characterized as*

$$\gamma^* = \begin{cases} \gamma^{G0} = 0, & \gamma^G \leq 0 \ \& \ A1,\ A2a,\ C1a,\ C1bx \\ \gamma^G, & \gamma^G > 0 \ \& \ A1,\ A2a,\ C1a,\ C1bx \\ \gamma^{N0} = 0, & \gamma^N \leq 0 \ \& \ \dfrac{p_s}{p_r} < \dfrac{y}{t} \ \& \ C1by,\ C2a,\ D1,\ D2a \\ \gamma^N = \dfrac{2p_r - p_s}{2p_r + p_s} - \dfrac{2tp_s}{y(2p_r + p_s)}, & \gamma^N > 0 \ \& \ C1by,\ C2a,\ D1,\ D2a \\ \gamma^{C0} = 0, & \gamma^N \leq 0 \ \& \ \dfrac{p_s}{p_r} > \dfrac{y}{t} \ \& \ C1by,\ C2a,\ D1,\ D2a \\ \gamma^{NX} = \gamma^X + \varepsilon, & A2b+,\ B+,\ C2b+,\ D2b+ \\ \gamma^{GX} = \gamma^X - \varepsilon, & A2b-,\ B-,\ C2b-,\ D2b- \end{cases}$$

where

$$\gamma^G = 1 - \frac{2p_s(\delta p_r(\delta - k\theta) + 2\theta(t + \delta k p_r)^2)}{\delta p_r(\delta - k\theta)(t + \delta k p_r)(2p_r + p_s) + 2\theta(t + \delta k p_r)^2(2p_r + p_s) + \delta p_r p_s t(\delta - k\theta)}$$
$$+ \frac{\delta^2 k^2 p_r p_s(\delta p_r p_s(\delta - k\theta)(2t + \delta k p_r)^2 + 2\theta(t + \delta k p_r)^2(p_s(t + \delta k p_r) - t(2p_r - p_s)))}{4y((t + \delta k p_r)^2)(\delta p_r(\delta - k\theta)(t + \delta k p_r)(2p_r + p_s) + 2\theta(t + \delta k p_r)^2(2p_r + p_s) + \delta p_r p_s t(\delta - k\theta))}$$
$$\gamma^X = \{\gamma \mid \pi_s^N(\gamma) = \pi_s^G(\gamma)\}$$

Since the retailer is the firm that determines both the environmental image of the supply chain and the sharing ratio, it can adjust these levels for its own benefit. Consequently, the region where the environmental quality improvement efforts of the supplier and the manufacturer are bounded by the retailer's advertisement level disappears under the direct-support setting if the constrained sharing ratio is positive, $\gamma^C > 0$. As opposed to the relationship of γ^N and γ^G under the delegation setting, there is no monotone relationship between the sharing ratio under the two greenwashing strategies. When we numerically check this relationship, we observe that $\gamma^G > \gamma^N$ usually holds.

3.4.3 Summary and comparison of the settings

Proposition 18 *Equilibrium advertisement level a and environmental quality q change in the same direction with the sharing ratio γ. A higher γ increases both a and q at the equilibrium but the rate of increase is higher for q compared to a in greenwashing case. As a result, an increase in γ decreases the green-washing level $a - q$.*

As it is stated, for a given sharing ratio, the equilibrium environmental quality investment q of the supplier and environmental advertisement level of the retailer are the same, hence Proposition 18 is valid for both cost-sharing settings. The environmental quality under both cost-sharing settings for both greenwashing cases increases with the level of cost sharing γ. In addition to its direct benefits on environmental performance, higher γ also benefits the customers. The retailer's motivation to overstate the environmental quality reduces with a higher q, thus the customers are misguided by the retailer less.

Proposition 19 *When the retailer greenwashes, the manufacturer supports the supplier under the delegation setting more than the retailer does under the direct-support setting when the profit margins of the retailer and the manufacturer are the same, $p_r = p_m$. When the retailer does not greenwash,*

1. *the manufacturer supports the supplier if $p_m > \frac{p_s}{2}$ under delegation setting and the retailer supports the supplier if $p_r > p_s\left(\frac{1}{2} + \frac{t}{y}\right)$ under direct-support setting,*
2. *the manufacturer supports the supplier more than the retailer if $p_m + \frac{t}{2y}(2p_m + p_s) > p_r$.*

From Proposition 19, we see that the manufacturer supports the supplier even if its profit margin is lower than the supplier, whereas the retailer expects its profit margin to be higher than the supplier's profit margin if the cost coefficient of advertising t is higher than $\frac{y}{2}$ when the retailer greenwashes. When the profit margins of the retailer and the manufacturer are equal, $p_r = p_m$, the manufacturer is more likely to support the supplier than the retailer, and the level of support by the manufacturer is higher than the retailer since the retailer bears not only the part of the cost of environmental quality investment but also the cost of advertisement to build up the environmental image of the product.

When we combine Propositions 18 and 19, we can conclude that the environmental quality investment of the supplier and the resulting environmental image of the supply chain are higher under the delegation setting if the profit margins of the retailer and the manufacturer are the same.

Proposition 20 *The delegation setting is more profitable than the direct-support setting when the retailer does not greenwash, given that $p_r = p_m$*

1. *for the retailer, if* $\frac{2p_r - p_s}{2p_r + p_s} > \frac{t^2}{y(t+y)}$,

2. *for the manufacturer, if* $\frac{2p_r - p_s}{2p_r + p_s} < \frac{t}{y}$,

3. *for the supplier.*

For non-greenwashing case, Proposition 20 shows us that under some conditions the retailer and the manufacturer prefer to take responsibility for supporting the supplier. The additional profit that the retailer or the manufacturer can surpass the cost of sharing environmental quality investment. The supplier is affected by the identity of the supporter by their sharing ratio and prefers the setting where the sharing ratio is higher, thus the supplier is better off if the supporter is the manufacturer as shown in Proposition 19.

Because of the complexity of the equilibrium outcome when the retailer greenwashes, we cannot make further analytical comments and we proceed with a numerical study.

3.5 Numerical Analysis

3.5.1 Delegation

As stated in Proposition 13, the retailer overstates the environmental quality when the supplier's environmental quality is lower than $\overline{q}^G = \frac{p_r(\delta - k\theta)}{2t + \delta k p_r}$. The implications of this can be seen in Figure 3.1; if the profit margin of the supplier is high, the supplier invests in environmental quality improvement sufficient to deter the retailer from greenwashing. As the cost of environmental quality investment y increases, the profit margin required to reach the environmental quality threshold rises. Consequently, we can observe that the region where the retailer greenwashes enlarges with y. Even though the supplier's motivation goes up with higher customer sensitivity for the environmental image of the product δ, the increase in the greenwashing threshold cannot be compensated for the

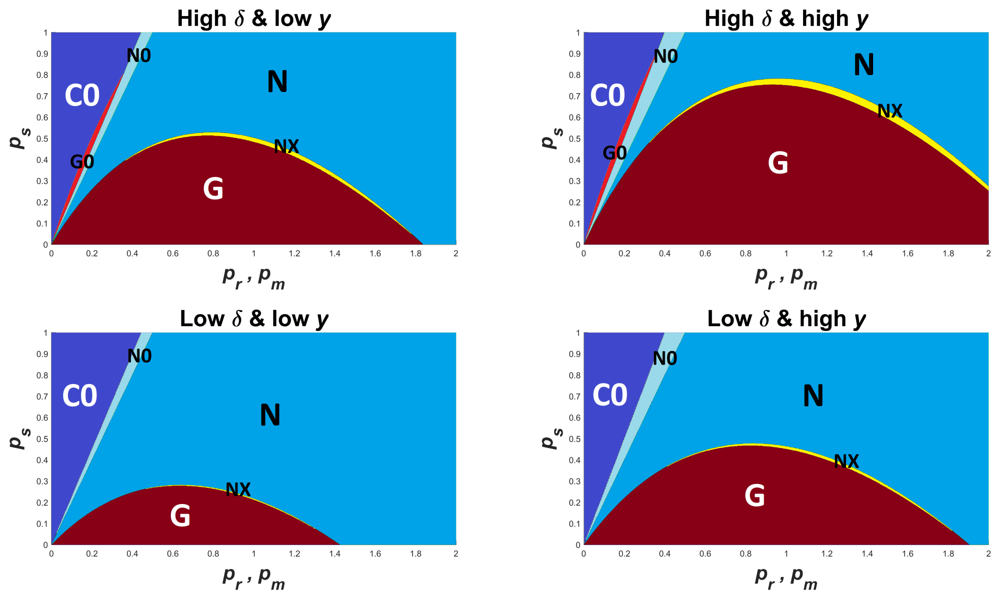

Figure 3.1: Greenwashing and cost-sharing strategies of the firms under the delegation setting

increase in the environmental quality investment. Hence, the retailer becomes more likely to greenwash with a high δ. The increase in the downstream firms' profit margins has opposite effects on greenwashing. While the retailer becomes more eager to greenwash with a higher profit margin p_r in order to benefit from boosted demand, the increase in the manufacturer's profit margin increases the collaboration between the manufacturer and the supplier, and enhances the environmental quality investments of the supplier, which decreases the additional benefits of an environmental quality overstatement for the retailer. We can numerically validate the analytical findings presented in Proposition 16 that the manufacturer does not share the supplier's environmental quality investment cost if the profit margin of the supplier is more than the twice the profit margin of the manufacturer and this condition is robust to the changes in other problem parameters. Nevertheless, we can observe from Figure 3.1 that the greenwashing strategy is not robust to the changes in δ and y when the manufacturer does not support the supplier. The effects of δ and y on the profitability of greenwashing are independent of the manufacturer's collaboration strategy. As δ and y increase, the retailer becomes more likely to greenwash when $\gamma = 0$ as it does when $\gamma > 0$.

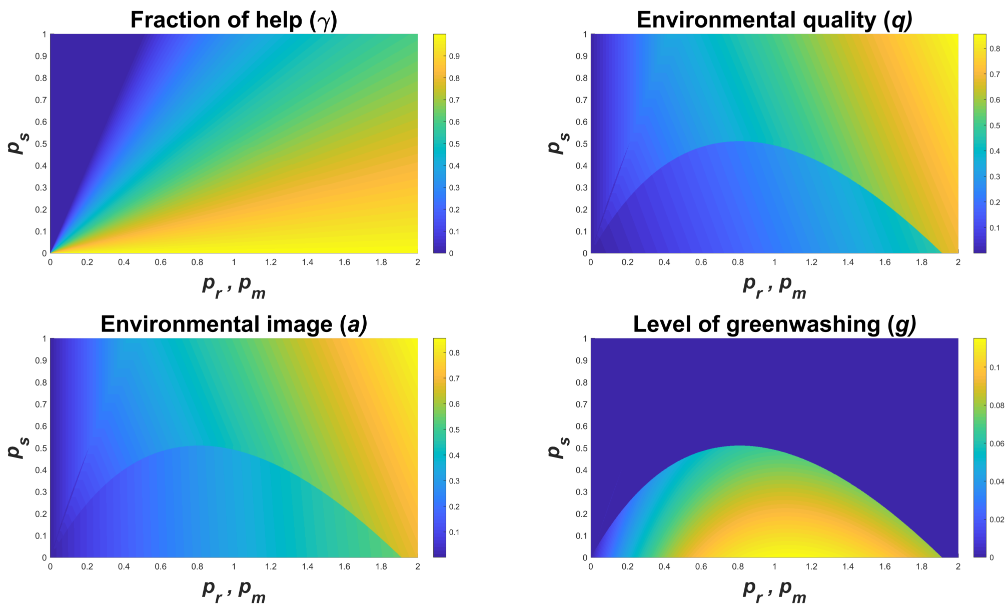

Figure 3.2: Equilibrium outcome under the delegation setting

The manufacturer becomes more sensitive to the changes in demand with an increase in its profit margin p_m, hence it becomes more motivated to support the supplier for the environmental quality investment and increases the rate of cost sharing γ. However, anticipating that an increase in the supplier's profit margin p_s will have the same effect on the supplier's environmental quality investment level with an increase in p_m, the manufacturer reduces its rate of support as p_s increases. Even though there are jumps in the manufacturer's sharing ratio when the equilibrium outcome lies in different regions, $\gamma^N < \gamma^X < \gamma^G$, these jumps are not very significant to be easily detected on Figure 3.2. Despite the higher fraction of support by the manufacturer in the greenwashing case, the supplier significantly decreases the environmental quality investment level. The supplier chooses to freeride on the greenwashing activities of the retailer instead of investing in environmental quality when the retailer greenwashes. With an increase in its profit margin p_s, the marginal revenue of the supplier increases and with an increase in the manufacturer's profit margin p_m, the marginal cost of environmental quality investment decreases as a result of a higher γ, hence the supplier becomes more motivated to invest on environmental quality with a higher p_s or p_m under both greenwashing cases. From Proposition

13, we can observe the linear relationship between environmental image a and environmental quality q in both N and G regions, which explains the parallel changes in a and q with the problem parameters. In region G, the retailer overstates the environmental quality by greenwashing, whereas from Figure 3.2, we can see that the decrease in the environmental quality cannot be compensated for with the greenwashing, thus the environmental image of the product drops with greenwashing. Even though the environmental quality investment of the supplier increases with the retailer's profit margin when the retailer greenwashes, $\frac{\partial q^G}{\partial p_r} > 0$, the rate of increase in greenwashing threshold with p_r is larger and the environmental quality increase cannot prevent the retailer to greenwash. As it can be seen from Figure 3.2, the level of greenwashing first increases and then decreases with the profit margins of the retailer and the manufacturer. The reason behind this non-monotone change is the opposite effects of p_r and p_m on the level of greenwashing. As p_r increases, the retailer becomes more eager to overstate the environmental quality of the product. The manufacturer supports the supplier more with a higher profit margin p_m, which decreases the greenwashing level as shown analytically in Proposition 18.

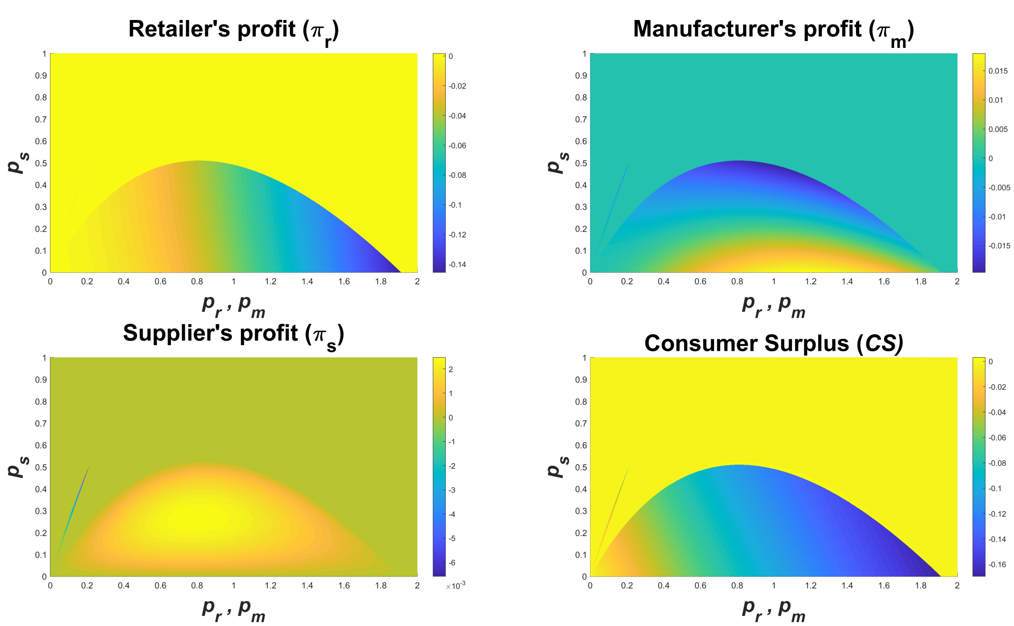

Figure 3.3: The impact of greenwashing on the firms and consumers under the delegation setting

Figure 3.3 presents some interesting results. Firstly, we can observe that the retailer cannot benefit from its own greenwashing activities since the supplier significantly reduces its investment in environmental quality if the retailer engages in greenwashing activities. The rate of environmental quality increase in the non-greenwashing case is higher than that in the greenwashing case as p_m or p_s increases, thus the profit loss of the retailer becomes more significant with higher p_m or p_s. The supplier benefits from greenwashing thanks to the decrease in its environmental quality investment cost if the retailer's profit margin is high enough to be motivated for overstating environmental quality, otherwise, the reduced environmental quality cannot be compensated for with the overstatement of the retailer. If the supplier's profit margin is very low and the manufacturer bears almost all of the environmental quality investment cost, the manufacturer prefers to freeride on the retailer's greenwashing activities instead of supporting true environmental quality investment, whereas greenwashing becomes detrimental for the manufacturer as p_s increases. Lastly, since the consumers are tricked to buy products with greenwashing that they won't buy otherwise, they lose the most with greenwashing and their loss increases with p_m and p_s.

3.5.2 Direct-support

Even though the greenwashing threshold is the same under the two settings, it can easily be observed by checking Figures 3.1 and 3.4 that the regions where the retailer greenwashes are significantly larger under the direct-support setting than the delegation setting. Since the response of the supplier and the retailer to the sharing ratio is the same under the two settings and the retailer's rate of support is lower under the direct-support setting than that of the manufacturer under the delegation setting, the supplier is less likely to invest in environmental quality sufficient to avoid greenwashing. With a lower rate of support from the retailer, the profit margin of the supplier should be higher to reach the threshold environmental quality level, $\overline{q}^L$. The deflated sharing ratio with the retailer being the collaborator of environmental quality investment is also the reason for observing larger regions where the greenwashing strategies are conflicting, GX and NX. Even though the

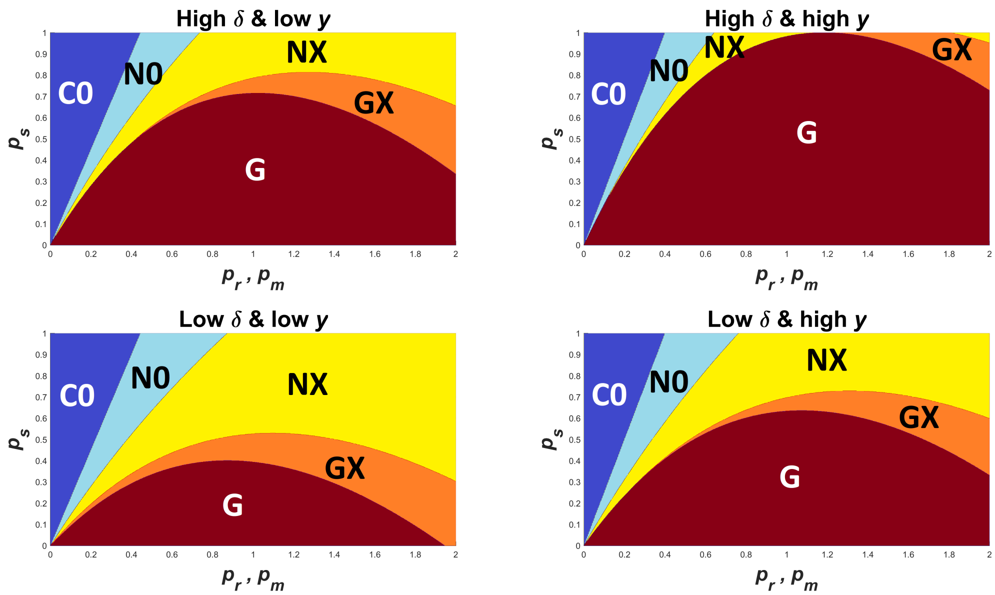

Figure 3.4: Greenwashing and cost-sharing strategies of the firms under the direct-support setting

decrease in γ^G as a result of the retailer being the collaborator makes it harder for the supplier to use that sharing ratio for investing on q higher than the greenwashing threshold, the decrease in γ^N makes it an interior solution for the supplier's both greenwashing strategies, $q^N(\gamma^N) > \overline{q}^G$ and $q^G(\gamma^N) < \overline{q}^G$. As a result, if γ^G is low enough to guarantee the retailer's greenwashing, the retailer sets its sharing ratio to γ^G and the outcome is greenwashing, otherwise the retailer can anticipate that γ^G and γ^N can be used by the supplier for any greenwashing strategy and we observe that the retailer adjusts its sharing ratio to γ^X for enforcing its profit-maximization greenwashing strategy. With an increase in customer sensitivity for environmental quality δ and cost of environmental quality investment y, the greenwashing strategy becomes more dominant and we can observe from Figure 3.4 that *NX* and *GX* regions shrink. As opposed to the robustness of the manufacturer's collaboration strategy to the changes in the problem parameters other than the profit margins under the delegation setting, Figure 3.4 validates the analytical findings that the retailer is more likely to support the supplier with a higher cost of environmental quality investment y and a lower cost of advertisement cost to build up the environmental image.

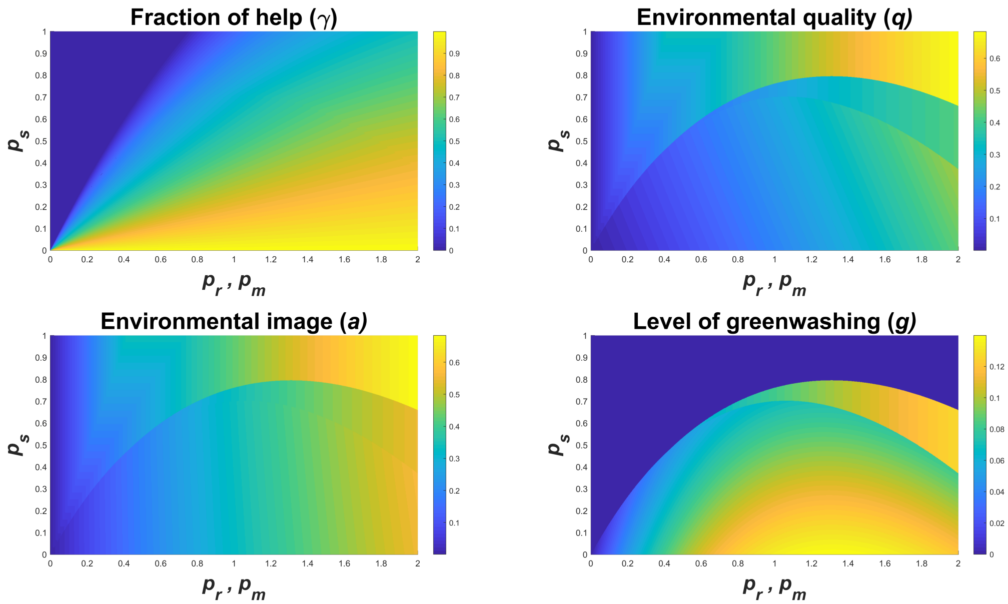

Figure 3.5: Equilibrium outcome under the direct-support setting

The sign of change in the equilibrium actions of the firms, γ, q, and a, under the direct-support setting, is parallel to the changes under the delegation setting as it can be seen in Figures 3.2 and 3.5 even though the levels and the rates of changes are not equal. The most significant difference between the two settings is the equilibrium environmental quality investment of the supplier in the GX region and the resulting greenwashing level under the direct-support setting. As explained analytically in Section 3.4, the downstream firm (the manufacturer or the retailer) adjusts its sharing ratio if it is used for an unintended greenwashing strategy. The supplier reduces its environmental quality investments if the retailer greenwashes, and the level of environmental quality investment further decreases due to a lower sharing ratio, $\gamma^X < \gamma^G$, if there is a conflict between the supplier and the downstream firm regarding the greenwashing strategy. As a result of a lower sharing ratio, the environmental quality level is the lowest in the GX region as can be seen in Figure 3.5. The opposite is true as well; the environmental quality level is the highest in NX region thanks to $\gamma^X > \gamma^N$ although we cannot observe this difference in Figure 3.5 since N region is not present. When the retailer greenwashes, the greenwashing level is higher with a lower environmental quality, hence in the GX region, the level of greenwashing is the highest.

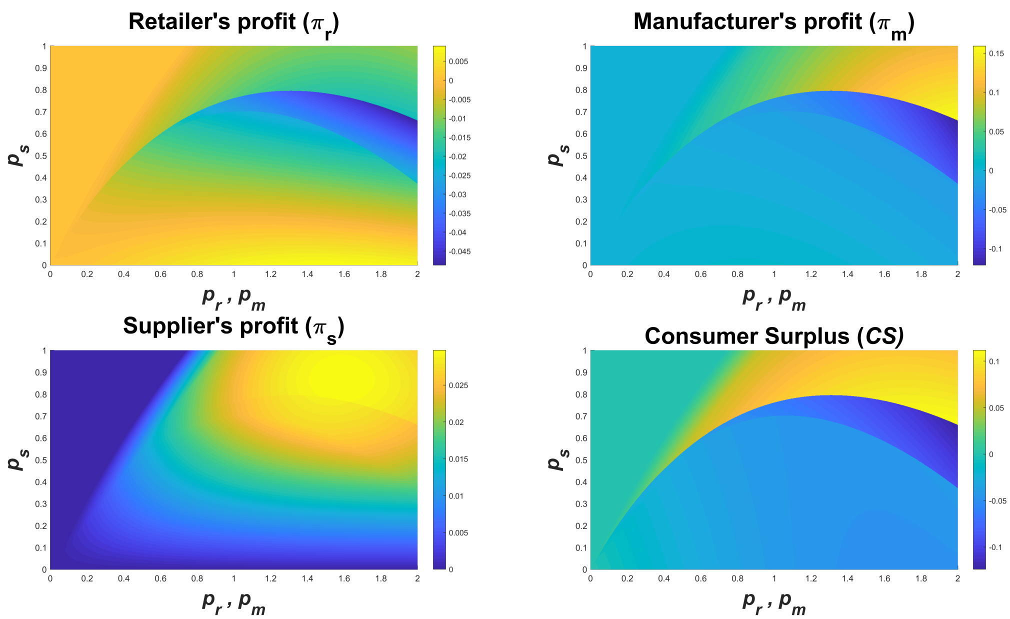

Figure 3.6: The impact of greenwashing on the firms and consumers under the direct-support setting

The supplier is the clear winner of the retailer's greenwashing activities under the direct-support setting as it is under the delegation setting. It can be seen in Figure 3.6 that the retailer does not always lose with greenwashing under the direct-support setting as opposed to the delegation setting. Since the retailer has more actions to manipulate the outcome for its own benefit, the retailer can use greenwashing for its benefit. The only exception is the GX region where the retailer has to deviate from its profit-maximizing sharing ratio γ^G to avoid the supplier using that for non-greenwashing. The manufacturer is a passive player under the direct-support setting and can only benefit from greenwashing if it makes the retailer raise the sharing ratio due to the strategy conflict, $\gamma^X > \gamma^N$, to motivate the supplier to invest in environmental quality higher than greenwashing threshold. Thanks to the higher sharing ratio to avoid greenwashing, consumers also thrive in the NX region compared to the environment where the retailer never greenwashes.

3.5.3 Comparison

In this section, we investigate the changes in the equilibrium actions, profits, and consumer surplus if the collaborator becomes the retailer instead of the manufacturer, i.e. switching from the delegation setting to the direct-support setting.

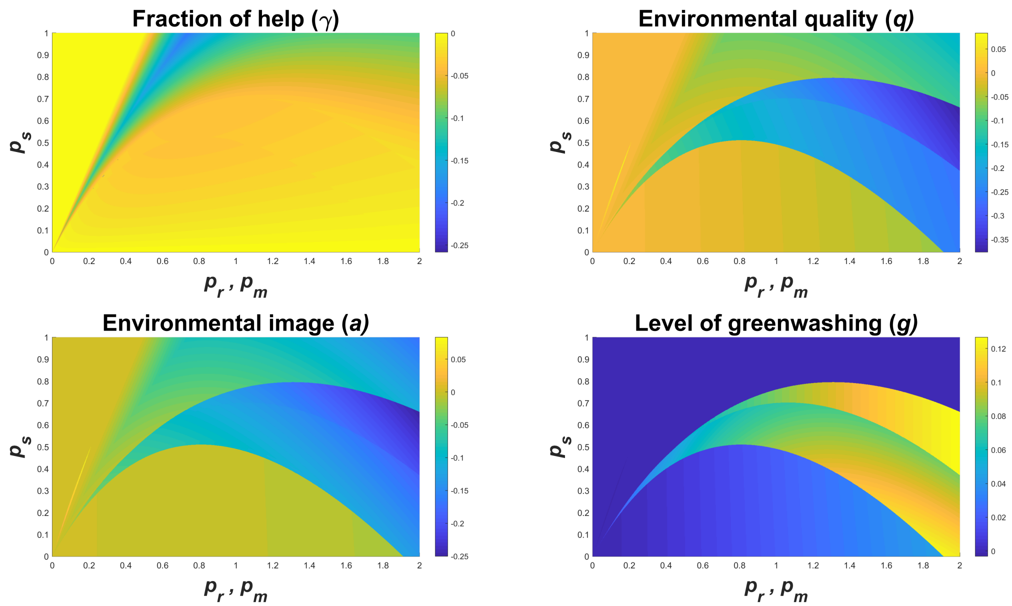

Figure 3.7: The changes in equilibrium outcome with switching from the delegation setting to the direct-support setting

As explained analytically in Proposition 19, the manufacturer supports the supplier more than the retailer when their profit margins are equal in N and G regions. From Figure 3.7, we can observe this fact even if the solution lies in different regions in the two settings, the manufacturer always supports more than the retailer, $\gamma^{Del} > \gamma^{DS}$. Under the direct-support setting, the retailer inflates its sharing ratio to enforce its greenwashing strategy in the NX region, still this inflation is not sufficient to reach the sharing ratio of the manufacturer without inflation in the N region under the delegation setting. The most significant decrease in γ is in the region where the manufacturer supports and the retailer does not. The change in the environmental quality, environmental image, and greenwashing can be analyzed by dividing it into three cases: (i) the retailer only greenwashes in the direct-support setting, (ii) the retailer only greenwashes in the delegation setting, and

(iii) the retailer's greenwashing strategy does not change with the settings. In the regions where we observe (i) and (ii), the difference comes from the supplier's reduction in the environmental quality investments as a result of the retailer's greenwashing even if the sharing ratios in the two settings are not significantly different. With a reduction in the environmental quality, the environmental image worsens, and the greenwashing level increases. When the greenwashing strategy of the retailer is the same under the two settings, the equilibrium environmental quality is higher and the greenwashing level is lower under the delegation setting. The delegation setting is inferior considering the environmental quality and the level of greenwashing only for (i) case, which is less likely to be observed compared to (ii) and (iii), as can be seen from Figure 3.7.

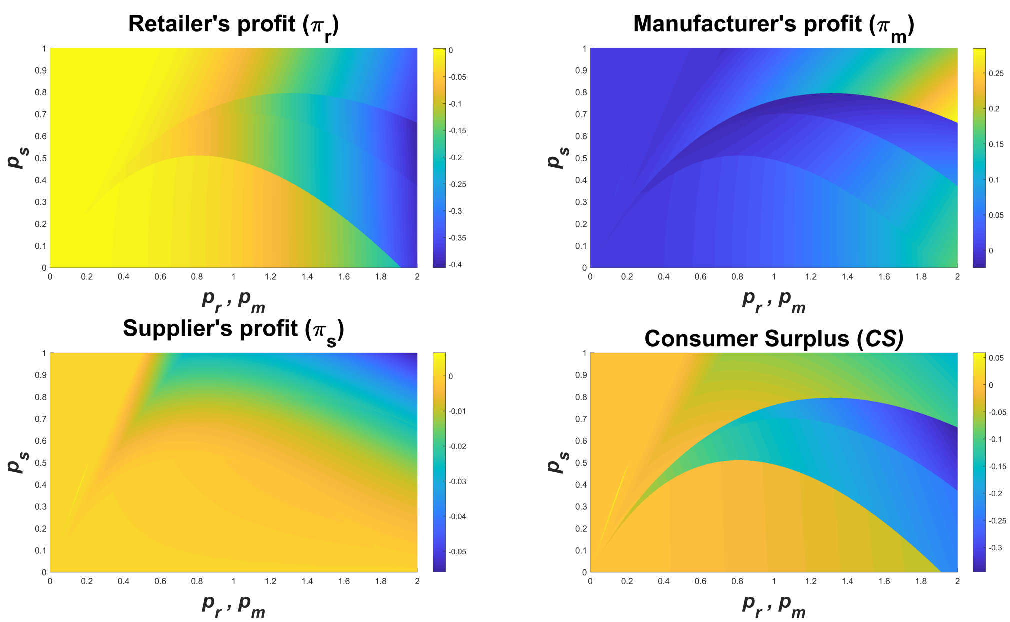

Figure 3.8: The impact of switching from the delegation setting to the direct-support setting on the firms and consumers

From Figure 3.8, we can observe that even with the advantage of controlling two actions in the supply chain, the retailer never prefers to take the responsibility of supporting the supplier's environmental quality investment cost. The same is almost always true for the supplier. Due to a lower rate of cost-sharing by the retailer than the manufacturer, the supplier usually prefers to get support from the manufacturer not from the retailer. The only exception to that preference is when the retailer greenwashes under the delegation setting while it does not under the direct-support setting with the same profit margins. The manufacturer is willing to take the responsibility of supporting the supplier when the retailer does not support while the manufacturer does and when the retailer greenwashes and the part of negative effects of greenwashing are not compensated for with a higher sharing ratio. For all other scenarios, the manufacturer's benefit of being an active player is not sufficient to cover the cost of supporting the supplier. Consequently, the firm that is more powerful in the supply chain enforces the other firm to support the supplier even though both firms prefer being the collaborator to no collaboration. Lastly, the consumers prefer the delegation setting more than the direct-support setting and their loss with the direct-support setting is very significant when the retailer greenwashes under the direct-support setting while it does not greenwash under the delegation setting.

3.6 Conclusion

We are motivated by the revelation of the suppliers' incompetence to follow high environmental standards and its negative impact on the demand, the collaboration of downstream firms (the retailer and the manufacturer in our setting) and their suppliers, and greenwashing activities of the downstream firms to cover up the low environmental performance of their suppliers. We developed a game-theoretical model to investigate the interaction between the firms' strategies; the manufacturer's or the retailer's cost-sharing strategy, the identity of the cost-sharing firm, the retailer's greenwashing strategy and the supplier's investment in environmental quality under the delegation and direct-support setting.

Our research reveals that the retailer's deceptive environmental practices, known as greenwashing, are influenced by the environmental performance of its supplier. If the supplier's environmental quality falls below a certain threshold, the retailer engages in greenwashing. The level of greenwashing decreases as the environmental quality of the supplier improves, and this improvement is correlated with the level of cost-sharing by the downstream firm (the retailer or the manufacturer). Interestingly, the manufacturer's rate of cost-sharing under the delegation setting is higher than that of the retailer under the direct-support setting. Consequently, when the retailer assists the supplier by sharing their investment costs, both the possibility and level of greenwashing are higher. Strikingly, even though the retailer usually (or the manufacturer always) offers more financial support in such cases, the supplier's investment in environmental quality decreases when the retailer engages in greenwashing. As a result of the reduced environmental investment of the supplier when the retailer greenwashes, surprisingly, the retailer cannot always benefit from greenwashing.

In this study, we focused on the environmental quality improvements that are investment intensive, such as investment in better filtration to reduce toxic emissions, and represented these improvements with a convex increasing fixed cost with the level of environmental quality. Our findings and managerial insights might differ in an industry where environmental progress causes a per-unit production cost increase, such as using biodegradable materials instead of polluting materials. Another future direction is to evaluate the efficiency of wholesale price premiums instead of investment cost-sharing. In addition to these research directions, there are two main limitations of our work that can be addressed in future studies. Firstly, we assumed an exogenous exposure rate for the retailer's greenwashing activities, which can be relaxed by considering the NGO as an active decision maker who determines its auditing level. Secondly, we modeled the problem with a complete information game, whereas one can relax this assumption and analyze the impact of not knowing whether the retailer is a greenwasher or not.

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General Conclusion

This thesis investigates the strategic interactions, both vertical and horizontal, between the firms focusing on product reuse, environmental quality investments, and greenwashing by benefiting game-theoretical modeling. Although the main objective of the firms that remanufacture their end-of-use products or the firms that invest in environmental quality advancements is increasing their profit, these actions have also impacts on the environment and consumers. We examine remanufacturing in an innovative industry, competition of green and greenwasher firms, and collaboration of supply chain members to build up environmental quality in the presence of greenwashing, moreover, we analyzed the impact of these profit-maximizing strategies on the environment and consumers.

The first essay of this thesis, entitled "Remanufacturing with innovative features: A strategic analysis" examines the remanufacturing strategies of an original equipment manufacturer (OEM) and an independent remanufacturer (IR), if the OEM chooses not to remanufacture its end-of-use products, in the presence of innovative features. It is crucial for an OEM to thoroughly assess the advantages and disadvantages of remanufacturing, particularly in an innovative industry. While remanufacturing can yield extra financial gains, it also carries the risk of diminishing the demand for new products, which can ultimately result in a decrease in overall profitability. We analyze two fundamental strategic decisions of the OEM and the IR: under what conditions the OEM and the IR remanufacture and under what conditions the OEM and the IR include the innovative features in remanufactured products.

We found that the cost advantage of remanufacturing and the relative valuation of remanufactured products are the most significant factors for the OEM and the IR to remanufacture and include innovative features. The IR is more prone to remanufacture than the OEM since the OEM should account for the decrease in new product demand with the introduction of an alternative product, while the IR does not have such concerns. The same reason is also valid for the IR being more motivated to include innovative features in remanufactured products. The overall profit is lower when the OEM and the IR compete. The result of competition is not dependent on whether the remanufacturing constraint is binding or not. When it is binding, the competition is beneficial for the consumers and detrimental to the environment since the total supply increases with the competition; however, when the constraint is non-binding, the result is the opposite since the OEM reduces its new product quantity to limit the IR's remanufacturing input.

Certain limitations in our study can be addressed in future research. Our analysis focused on a single-period steady-state model to examine the problem and answer our research inquiries, but a multi-period model would be more suitable for capturing the life-cycle impact of an original equipment manufacturer's (OEM) innovative product and the accumulation of end-of-use products for remanufacturing purposes. Additionally, it would be beneficial to explore alternative cost and demand functions. Initially, we assumed symmetry in the costs of producing goods and incorporating innovative features for both the OEM and independent remanufacturers (IR). Relaxing this assumption would allow us to evaluate the effects of production advancements by the two firms.

The second essay of this thesis, entitled "Strategic Pricing and Investment in Environmental Quality by an Incumbent Facing a Greenwasher Entrant" considers a market where a green incumbent firm competes with a greenwasher entrant firm. We investigate the effects of the entrant's greenwashing on the firms' pricing and environmental quality investments and consumer surplus. We present a two-stage game setting where an incumbent company, in the first stage, makes choices concerning pricing and environmental quality investment. Subsequently, it faces competition from an entrant in the second stage. The incumbent firm acts responsibly by accurately presenting the environmental quality of its product, while the entrant may be tempted to employ greenwashing tactics.

Our assumption is that only inexperienced consumers, those who have not previously bought the product, can be influenced by greenwashing.

Our findings indicate that the incumbent facilitates deceptive environmental practices of the entrant by raising prices in the first period while reducing investments in environmental sustainability, aiming to reduce the number of customers who have prior experience. This strategy can potentially lead to reduced profits for the entrant. If the incumbent firm fails to address greenwashing, the criteria for allowing such practices by entrants become more stringent. Both companies typically reduce their investments in environmental quality when the entrant engages in greenwashing. The overall benefit for consumers consistently diminishes when greenwashing occurs. Conversely, if greenwashing is ignored, both the environment and consumers experience better outcomes.

This paper primarily focuses on the entrant as the party engaging in greenwashing, although this may not always be the scenario. Exploring the possibility of the incumbent being a greenwasher while facing competition from the entrant presents an intriguing direction for future research. Additionally, examining competition in both stages of the game could provide further insights. Lastly, while government intervention is not addressed in our model, it is undoubtedly a relevant aspect that merits consideration in future studies.

The third essay of this thesis, entitled "Supplier Environmental Development with Greenwashing Activities of the Retailer" investigates the vertical interactions in a three-echelon supply chain where the retailer and the manufacturer are environmentally responsible and either one supports the supplier's environmental quality development efforts, which is appreciated by consumers and increases demand for the product. Still, the retailer can overstate the environmental quality of its supplier benefiting from the lack of visibility of the supplier's true environmental quality. We created a sequential move game model to examine the cooperative dynamics between supply chain partners, the investment decisions made by suppliers regarding environmental quality, and the greenwashing strategies adopted by retailers.

Based on our findings, we observed that the retailer's decision to engage in greenwashing depends on the environmental quality of the supplier. If the supplier's environmental quality falls below a certain threshold, the retailer resorts to greenwashing; otherwise, greenwashing is not employed. The extent of greenwashing and the improvement in environmental quality are both influenced by the cost-sharing rate. When the cost-sharing rate increases, the level of greenwashing decreases, while the environmental quality level increases. Moreover, the manufacturer tends to have a higher cost-sharing rate compared to the retailer. As a result, when the retailer shares the supplier's investment cost, both the probability and extent of greenwashing tend to increase. It is important to highlight that although the retailer has the final say in deciding whether to engage in greenwashing, this practice is not always advantageous, especially when the manufacturer provides support to the supplier due to the reduction in the supplier's environmental quality investment with greenwashing.

This study focused on investment-intensive environmental quality enhancements. These improvements were represented using a convex increasing fixed cost structure based on the level of environmental quality. It is important to acknowledge that our findings and managerial implications may vary in industries where environmental advancements result in per-unit production cost increases. Another potential avenue for future research is to assess the effectiveness of wholesale price premiums as an alternative to investment cost-sharing in promoting environmental sustainability.

Investigation of optimal remanufacturing and pricing strategies of an OEM in an innovative industry and the changes in these decisions in the presence of an IR, examination of conditions to trigger greenwashing activities of firms in a competitive market and the response of green firms to their competitors' greenwashing activities, and analysis of support by downstream firms to enhance their suppliers' environmental quality and the relationship between these environmental quality enhancement activities and greenwashing are the main contribution of this thesis to the literature.

Our results have shown that a social planner whose objective is to maximize both the economic and environmental performance should be very careful. While remanufacturing, which seems an environmentally friendly action, can cause material usage to increase and, in turn, can increase waste generated in that market, greenwashing, by definition is lying to customers, can help the firms to increase their environmental performance thanks to higher profit margins. These two findings shows the importance of evaluating the conditions before making an action to enhance environmental and economic performance of the market in concern.

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Appendix A – Derivations of the first essay

Derivations of demand functions

$$U_{On} = \theta(1+i) - p_{On}$$
$$U_{Ou} = \theta(1+i)\delta - p_{Ou}$$
$$U_{Iu} = \theta(1+\alpha i)\delta - p_{Iu}$$
$$U_{xr} = \theta\delta - p_{xr}$$

There will be no scenario in which 4 different types of product coexist. However, thanks to the master demand and price functions, we can easily obtain the demand and price functions with fewer product types. A customer purchases a product type when its utility is the highest among all options. In order for a customer to purchase a new product, the following inequality should hold:

$$\theta(1+i) - p_{On} \geq (1+i)\delta\theta - p_{Ou}$$
$$\theta \geq \frac{p_{On} - p_{Ou}}{(1+i)(1-\delta)}$$

In order for a customer to purchase an upgraded product from the OEM, the following inequalities should hold:

$$(1+i)\delta\theta - p_{Ou} \geq \theta(1+i) - p_{On}$$
$$(1+i)\delta\theta - p_{Ou} \geq \theta(1+\alpha i)\delta - p_{Iu}$$
$$\frac{p_{On}-p_{Ou}}{(1+i)(1-\delta)} \geq \theta \geq \frac{p_{Ou}-p_{Iu}}{(1-\alpha)\delta i}$$

In order for a customer to purchase an upgraded product from the IR, the following inequalities should hold:

$$\theta(1+\alpha i)\delta - p_{Iu} \geq (1+i)\delta\theta - p_{Ou}$$
$$\theta(1+\alpha i)\delta - p_{Iu} \geq \theta\delta - p_{xr}$$
$$\frac{p_{Ou}-p_{Iu}}{(1-\alpha)\delta i} \geq \theta \geq \frac{p_{Iu}-p_{xr}}{\alpha\delta i}$$

In order for a customer to purchase a remanufactured product, the following inequalities should hold:

$$\theta\delta - p_{xr} \geq \theta(1+\alpha i)\delta - p_{Iu}$$
$$\theta\delta - p_{xr} \geq 0$$
$$\frac{p_{Iu}-p_{xr}}{\alpha\delta i} \geq \theta \geq \frac{p_{xr}}{\delta}$$

The demand functions corresponding to these boundaries are as follows:

$$q_{On} = 1 - \frac{p_{On}-p_{Ou}}{(1+i)(1-\delta)},$$
$$q_{Ou} = \frac{p_{On}-p_{Ou}}{(1+i)(1-\delta)} - \frac{p_{Ou}-p_{Iu}}{(1-\alpha)\delta i},$$
$$q_{Iu} = \frac{p_{Ou}-p_{Iu}}{(1-\alpha)\delta i} - \frac{p_{Iu}-p_{xr}}{\alpha\delta i},$$
$$q_{xr} = \frac{p_{Iu}-p_{xr}}{\alpha\delta i} - \frac{p_{xr}}{\delta}.$$

When we turn those demand functions into price functions we get

$$p_{On} = (1+i)(1-q_{On}) - (1+i)\delta q_{Ou} - (1+\alpha i)\delta q_{Iu} - \delta q_{xr}$$
$$p_{Ou} = (1+i)\delta(1-q_{On}-q_{Ou}) - (1+\alpha i)\delta q_{Iu} - \delta q_{xr}$$
$$p_{Iu} = (1+\alpha i)\delta(1-q_{On}-q_{Ou}-q_{Iu}) - \delta q_{xr}$$
$$p_{xr} = \delta(1-q_{On}-q_{Ou}-q_{Iu}-q_{xr})$$

Derivation of consumer surplus

θ_{xy} is the lowest WTP level that consumers purchase type y products of producer x, where $x \in \{O, I\}$ and $y \in \{n, r, u\}$.

No Remanufacturing

$$
\begin{aligned}
CS^{NR} &= \int_{\theta_{On}}^{1} ((1+i)\theta - p_{On})d\theta \\
&= \int_{\frac{p_{On}}{(1+i)}}^{1} ((1+i)\theta - p_{On})d\theta \\
&= (1+i)\int_{1-q_{On}}^{1} (\theta - (1-q_{On}))d\theta \\
&= \frac{(1+i)(q_{On})^2}{2}
\end{aligned}
$$

Remanufacturing

$$
\begin{aligned}
CS^{R} = CS^{IR} &= \int_{\theta_{On}}^{1} ((1+i)\theta - p_{On})d\theta + \int_{\theta_{xr}}^{\theta_{On}} (\delta\theta - p_{xr})d\theta \\
&= \int_{\frac{p_{On}-p_{xr}}{(1+i-\delta)}}^{1} ((1+i)\theta - p_{On})d\theta + \int_{\frac{p_{xr}}{\delta}}^{\frac{p_{On}-p_{xr}}{(1+i-\delta)}} (\delta\theta - p_{xr})d\theta \\
&= \int_{1-q_{On}}^{1} ((1+i)\theta - ((1+i) - (1+i)q_{On} - \delta q_{xr}))d\theta \\
&+ \delta\int_{1-q_{On}-q_{xr}}^{1-q_{On}} (\theta - (1-q_{On}-q_{xr}))d\theta \\
&= \frac{(1+i)(q_{On})^2}{2} + \frac{\delta(q_{xr})^2}{2} + \delta q_{On}q_{xr}
\end{aligned}
$$

Upgrading

$$
\begin{aligned}
CS^U &= \int_{\theta_{On}}^{1} ((1+i)\theta - p_{On})d\theta + \int_{\theta_{Ou}}^{\theta_{On}} ((1+i)\delta\theta - p_{Ou})d\theta \\
&= \int_{\frac{p_{On}-p_{Ou}}{(1+i)(1-\delta)}}^{1} ((1+i)\theta - p_{On})d\theta + \int_{\frac{p_{Ou}}{(1+i)\delta}}^{\frac{p_{On}-p_{Ou}}{(1+i)(1-\delta)}} ((1+i)\delta\theta - p_{Ou})d\theta \\
&= (1+i)\int_{1-q_{On}}^{1} (\theta - (1-q_{On}-\delta q_{Ou}))d\theta \\
&+ (1+i)\delta \int_{1-q_{On}-q_{Ou}}^{1-q_{On}} (\theta - (1-q_{On}-q_{Ou}))d\theta \\
&= \frac{(1+i)(q_{On})^2}{2} + \frac{(1+i)\delta(q_{Ou})^2}{2} + (1+i)\delta q_{On}q_{Ou}
\end{aligned}
$$

$$
\begin{aligned}
CS^{IU} &= \int_{\theta_{On}}^{1} ((1+i)\theta - p_{On})d\theta + \int_{\theta_{Iu}}^{\theta_{On}} ((1+\alpha i)\delta\theta - p_{Iu})d\theta \\
&= \int_{\frac{p_{On}-p_{Iu}}{(1+i)(1-\delta)}}^{1} ((1+i)\theta - p_{On})d\theta + \int_{\frac{p_{Iu}}{(1+i)\delta}}^{\frac{p_{On}-p_{Iu}}{(1+i)(1-\delta)}} ((1+\alpha i)\delta\theta - p_{Iu})d\theta \\
&= (1+i)\int_{1-q_{On}}^{1} (\theta - (1-q_{On}-\delta q_{Iu}))d\theta \\
&+ (1+\alpha i)\delta \int_{1-q_{On}-q_{Iu}}^{1-q_{On}} (\theta - (1-q_{On}-q_{Iu}))d\theta \\
&= \frac{(1+i)(q_{On})^2}{2} + \frac{(1+\alpha i)\delta(q_{Iu})^2}{2} + (1+\alpha i)\delta q_{On}q_{Iu}
\end{aligned}
$$

Appendix B – Optimal and equilibrium profits of the first essay

No competition

OEM remanufactures

$$\pi_O^R = \begin{cases} \frac{(1-c_0+i(1-k_v))^2}{4(1+i)} - k_f i^2, & S_0^R, \\ \frac{(1-c_0+i(1-k_v)i)^2}{4(1+i)} + \frac{((\delta-\gamma)c_0+(\delta k_v-\gamma c_0)i)^2}{4\delta(1+i)(1+i-\delta)} - k_f i^2, & S_u^R, \\ \frac{(1+\delta-(1+\gamma)c_0+(1-k_v)i)^2}{4(1+i+3\delta)} - k_f i^2, & S_c^R. \end{cases}$$

OEM upgrades

$$\pi_O^U = \begin{cases} \frac{(1-c_0+i(1-k_v))^2}{4(1+i)} - k_f i^2, & S_0^U, \\ \frac{(1-c_0+i(1-k_v))^2}{4(1+i)} + \frac{((\delta-\gamma)c_0-(1-\delta)k_v i)^2}{4\delta(1+i)(1-\delta)} - k_f i^2, & S_u^U, \\ \frac{((1+i)(1+\delta)-(1+\gamma)c_0-2k_v i)^2}{4(1+i)(1+3\delta)} - k_f i^2, & S_c^U. \end{cases}$$

Competition

IR remanufactures

$$\pi_O^{IR} = \begin{cases} \frac{(1-c_0+(1-k_v)i)^2}{4(1+i)} - k_f i^2, & S_0^{IR} \\ \frac{(i+1)(2-\delta-(2-\gamma)c_0+2(1-k_v)i)^2}{(4+4i-\delta)^2} - k_f i^2, & S_u^{IR} \\ \frac{(1-c_0+(1-k_v)i)^2}{4(1+i+\delta)} - k_f i^2, & S_c^{IR} \end{cases}$$

$$\pi_I^{IR} = \begin{cases} 0, & S_0^{IR} \\ \frac{((1+i)\delta-(2(1+i)\gamma-\delta)c_0+\delta k_v i)^2}{\delta(4+4i-\delta)^2}, & S_u^{IR} \\ \frac{(1+i-c_0-k_v i)\left(\delta^2-(1+i+\delta)\gamma c_0+\delta(c_0-k_v i)\right)}{2(1+i+\delta)^2}, & S_c^{IR} \end{cases}$$

IR upgrades

$$\pi_O^{IU} = \begin{cases} \frac{(K_{On}(i))^2}{4(1+i)} - k_f i^2, & S_0^{IU}, \\ \frac{(i+1)(2K_{On}(i)-K_{Iu}(i))^2}{(4(1+i)-\delta(1+\alpha i))^2} - k_f i^2, & S_u^{IU}, \\ \frac{(K_{On}(i))^2}{4((1+i)+\delta(1+\alpha i))} - k_f i^2, & S_c^{IU}. \end{cases}$$

$$\pi_I^{IU} = \begin{cases} 0, & S_0^{IU}, \\ \frac{(2(1+i)K_{Iu}(i)-\delta(1+\alpha i)K_{On}(i))^2}{\delta(1+\alpha i)(4(1+i)-\delta(1+\alpha i))^2}, & S_u^{IU}, \\ \frac{K_{On}(i)K_{Iu}(i)}{2((1+i)+\delta(1+\alpha i))} - \frac{\delta(1+\alpha i)(K_{On}(i))^2}{2((1+i)+\delta(1+\alpha i))^2}, & S_c^{IU}. \end{cases}$$

Appendix C – Proofs of propositions of the first essay

Proof 1 (Proof of Proposition 1) *Assuming an interior solution, the first-order optimality condition is*

$$\frac{d\pi_O(q_{On})}{dq_{On}} = (1+i)(1-2q_{On}) - c_0 - k_v i = 0,$$

which gives q_{On}^{NR}. Note that, for $i > 0$, we have

$$\frac{d^2\pi_O(q_{On})}{d(q_{On})^2} = -2(1+i) < 0,$$

that is, the profit function is strictly concave with respect to q_{On}. Therefore, the solution is interior and unique.

Proof 2 (Proof of Proposition 2) *First, we show that the profit function is concave in q_{On} and q_{Or}. The second-order derivatives are given by*

$$\frac{\partial^2\pi_O(q_{On},q_{Or})}{\partial(q_{On})^2} = -2(1+i) < 0,$$
$$\frac{\partial^2\pi_O(q_{On},q_{Or})}{\partial(q_{Or})^2} = -2\delta < 0,$$
$$\frac{\partial^2\pi_O(q_{On},q_{Or})}{\partial q_{On}\partial q_{Or}} = -2\delta < 0,$$

and the determinant of the Hessian matrix by

$$|H| = 4\delta(1+i-\delta) > 0.$$

The signs follow from the positivity of i, and the facts that $\delta \in (0,1)$ and $(1+i-\delta) > 0$. Therefore, $\pi_O(q_{On},q_{Or})$ is strictly concave in q_{On} and q_{Or}.

The first-order optimality conditions are

$$\frac{\partial \pi_O(q_{On}, q_{Or})}{\partial q_{On}} = (1+i)(1-2q_{On}) - 2\delta q_{Or} - c_0 - k_v i = 0,$$
$$\frac{\partial \pi_O(q_{On}, q_{Or})}{\partial q_{Or}} = \delta(1-2q_{On}-2q_{Or}) - \gamma c_0 = 0.$$

If $q_{Or} < 0$, then q_{Or} is set equal to 0 and q_{On} can be found. If the result of the above linear equations does not satisfy the remanufacturing supply constraint, we need to update the profit function as follows:

$$\begin{aligned}\pi_O(q_{On}, q_{Or} = q_{On}) = q_{On}((1+i)(1-q_{On}) - \delta q_{On} - c_0 - k_v i) \\ + q_{On}(\delta(1-2q_{On}) - \gamma c_0) - k_f i^2,\end{aligned}$$

and we have

$$\frac{\partial^2 \pi_O(q_{On})}{\partial (q_{On})^2} = -2(1+i+3\delta) < 0,$$

that is, the profit function is concave in q_{On}. Consequently, we can use the first derivative of the profit function to get the optimal manufacturing quantity, i.e.,

$$\frac{\partial \pi_O(q_{On})}{\partial q_{On}}(1+i+\delta) - 2(1+i+3\delta)q_{On} - (1+\gamma)c_0 - k_v i = 0.$$

The optimal quantities are given in the statement of the proposition.

Proof 3 (Proof of Proposition 3) *First, we note that the profit function is always concave in q_{On} and q_{Ou}. Indeed, the second-order derivatives and the determinant of the Hessian matrix are given by*

$$\frac{\partial^2 \pi_O(q_{On}, q_{Ou})}{\partial (q_{On})^2} = -2(1+i) < 0,$$
$$\frac{\partial^2 \pi_O(q_{On}, q_{Ou})}{\partial (q_{Ou})^2} = -2(1+i)\delta < 0,$$
$$\frac{\partial^2 \pi_O(q_{On}, q_{Ou})}{\partial q_{On} d q_{Ou}} = -2(1+i)\delta,$$
$$|H| = 4\delta(1+i)^2(1-\delta) > 0,$$

with the signs following from the fact that $i \geq 0$ and $\delta \in (0,1)$.

The first-order optimality conditions are as follows:

$$\frac{\partial \pi_O(q_{On}, q_{Ou})}{\partial q_{On}} = (1+i)(1-2q_{On}) - 2(1+i)\delta q_{Ou} - c_0 - k_v i = 0,$$
$$\frac{\partial \pi_O(q_{On}, q_{Ou})}{\partial q_{Ou}} = (1+i)\delta(1-2q_{On}-2q_{Ou}) - \gamma c_0 - k_v i = 0.$$

We solve the above linear equations to find the optimal production quantities q_{On} and q_{Ou}. If $q_{Ou} < 0$, then q_{Ou} is set equal to 0 and q_{On} can be found. If the result of the above linear equations does not satisfy the remanufacturing supply constraint, we need to update the profit function,

$$\begin{aligned}\pi_O(q_{On}, q_{Ou} = q_{On}) = q_{On}((1+i)(1-(1+\delta)q_{On}) - c_0 - k_v i) \\ + q_{On}((1+i)\delta(1-2q_{On}) - \gamma c_0 - k_v i) - k_f i^2,\end{aligned}$$

and have

$$\frac{d^2 \pi_O(q_{On})}{d(q_{On})^2} = -2(1+i)(1+3\delta).$$

Since the innovation level i and δ are always greater than or equal to 0, the profit function is always concave with respect to q_{On}, and we can use the first derivative of the profit function to get the optimal manufacturing quantity.

$$\frac{d\pi_O(q_{On})}{dq_{On}}(1+i)(1+\delta) - 2(1+i)(1+3\delta)q_{On} - (1+\gamma)c_0 - 2k_v i = 0.$$

The equilibrium quantities are given in the statement of the proposition.

Proof 4 (Proof of Proposition 4) *By comparison of profits realized in the different cases.*

Proof 5 (Proof of Proposition 5) *First, we show that the profit functions of the OEM and the IR are concave with respect to q_{On} and q_{Ir}, respectively. The second-order derivatives are given by*

$$\frac{d^2 \pi_O(q_{On})}{d(q_{On})^2} = -2\,(1+i) < 0,$$
$$\frac{d^2 \pi_I(q_{Ir})}{d(q_{Ir})^2} = -2\delta < 0$$

The signs follow from the positivity of i and δ. Therefore, $\pi_O(q_{On})$ and $\pi_I(q_{Ir})$ are strictly concave in q_{On} and q_{Ir}, respectively.

The first-order optimality conditions are

$$\frac{\partial \pi_O(q_{On})}{\partial q_{On}} = (1+i)(1-2q_{On}) - \delta q_{Ir} - c_0 - k_v i = 0,$$
$$\frac{\partial \pi_I(q_{Ir})}{\partial q_{Ir}} = \delta(1-q_{On}-2q_{Ir}) - \gamma c_0 = 0.$$

If $q_{Ir} < 0$, then $q_{Ir} = 0$ and q_{On} can be found. If the result of the above linear equations does not satisfy the remanufacturing supply constraint, we need to update the profit functions as follows:

$$\pi_O(q_{On}|q_{Ir} = q_{On}) = q_{On}\left((1+i)(1-q_{On}) - \delta q_{On} - c_0 - k_v i\right) - k_f i^2,$$
$$\pi_I(q_{Ir} = q_{On}) = q_{On}\left(\delta\left(1-2q_{On}\right) - \gamma c_0\right),$$

and we have

$$\frac{d^2\pi_O(q_{On})}{d(q_{On})^2} = -2\left(1+i+\delta\right) < 0,$$

that is, the profit function of the OEM is concave in q_{On}. Consequently, we can use the first derivative of the profit function to get the optimal manufacturing quantity, i.e.,

$$\frac{d\pi_O(q_{On})}{dq_{On}} = (1+i) - 2(1+i+\delta)q_{On} - c_0 - k_v i = 0.$$

The equilibrium quantities are given in the statement of the proposition.

Proof 6 (Proof of Proposition 6) *First, we show that the profit functions of the OEM and the IR are concave with respect to q_{On} and q_{Iu}, respectively. The second-order derivatives are given by*

$$\frac{d^2\pi_O(q_{On})}{d(q_{On})^2} = -2\left(1+i\right) < 0,$$
$$\frac{d^2\pi_I(q_{Iu})}{d(q_{Iu})^2} = -2\delta\left(1+\alpha i\right) < 0.$$

The signs follow from the positivity of i, δ, and α. Therefore, $\pi_O(q_{On})$ and $\pi_I(q_{Iu})$ are strictly concave in q_{On} and q_{Iu}, respectively.

The first-order optimality conditions are

$$\frac{\partial \pi_O(q_{On})}{\partial q_{On}} = (1+i)(1-2q_{On}) - \delta\,(1+\alpha i)\,q_{Iu} - c_0 - k_v i = 0,$$
$$\frac{\partial \pi_I(q_{Iu})}{\partial q_{Iu}} = \delta\,(1+\alpha i)\,(1-q_{On}-2q_{Iu}) - \gamma c_0 - k_v \alpha i = 0.$$

If $q_{Iu} < 0$*, then* $q_{Iu} = 0$ *and* q_{On} *can be found. If the result of the above linear equations does not satisfy the remanufacturing supply constraint, we need to update the profit function as follows:*

$$\pi_O(q_{On}|q_{Iu} = q_{On}) = q_{On}\,((1+i)(1-q_{On}) - \delta\,(1+\alpha i)\,q_{On} - c_0 - k_v i) - k_f i^2$$
$$\pi_I(q_{Iu} = q_{On}) = q_{On}\,(\delta\,(1+\alpha i)\,(1-2q_{On}) - \gamma c_0 - k_v \alpha i)\,,$$

and we have

$$\frac{d^2\pi_O(q_{On})}{d(q_{On})^2} = -2\,(1+i+\delta\,(1+\alpha i)) < 0,$$

that is, the profit function of the OEM is concave in q_{On}*. Consequently, we can use the first derivative of the profit function to get the optimal manufacturing quantity, i.e.,*

$$\frac{d\pi_O(q_{On})}{dq_{On}} = (1+i) - 2(1+i+(1+\alpha i)\delta)q_{On} - c_0 - k_v i = 0 = 0.$$

The equilibrium quantities are given in the statement of the proposition.

Proof 7 (Proof of Proposition 7) *By comparison of profits realized in the different cases.*

Appendix D – Proofs of propositions of the second essay

Proof 8 (Proposition 8) *1. We have*

$$\begin{aligned}
\frac{\partial p_i^n}{\partial p_1} &= \frac{\partial p_e^n}{\partial p_1} = 0, \\
\frac{\partial p_i^n}{\partial q_1} &= \frac{\gamma_1\left(2-\gamma_e^2\right)}{4-\beta^2-2(\gamma_e^n)^2} > 0, \\
\frac{\partial p_e^n}{\partial q_1} &= \frac{\beta\gamma_1}{4-\beta^2-2(\gamma_e^n)^2} > 0.
\end{aligned}$$

2. We have

$$\begin{aligned}
\frac{\partial p_i^g}{\partial p_1} &= \frac{2c\beta(\gamma_e^g)^2(p_1-\gamma_1 q_1)}{1+\alpha}\frac{2\alpha+\beta+\beta\gamma_1 q_1(1+\alpha)}{\left(c\left((\gamma_e^g)^2-4+\beta^2\right)+2(\gamma_e^g)^2(p_1-\gamma_1 q_1)^2\right)^2} > 0, \\
\frac{\partial p_e^g}{\partial p_1} &= \frac{4c(\gamma_e^g)^2(p_1-\gamma_1 q_1)}{1+\alpha}\frac{2\alpha+\beta+\beta\gamma_1 q_1(1+\alpha)}{\left(c\left(2(\gamma_e^g)^2-4+\beta^2\right)+2(\gamma_e^g)^2(p_1-\gamma_1 q_1)^2\right)^2} > 0.
\end{aligned}$$

3. We have

a) $\frac{\partial p_e^g}{\partial q_1} = \frac{\gamma_1\left(\beta-\frac{4(\gamma_e^g)^2}{c}(p_1-\gamma_1 q_1)p_e^g\right)}{4-\beta^2-2(\gamma_e^g)^2 X}$, *which is positive when*
$p_e^g = \frac{\frac{2\alpha+\beta}{1+\alpha}+\beta\gamma_1 q_1}{4-\beta^2-2(\gamma_e^g)^2 X} < \frac{\beta c}{4(\gamma_e^g)^2(p_1-\gamma_1 q_1)}$.

b) $\frac{\partial p_i^g}{\partial q_1} = \frac{\gamma_1\left((4-2(\gamma_e^g)^2 X)-\frac{4(\gamma_e^g)^2\beta}{c}(p_1-\gamma_1 q_1)p_e^g\right)}{4-\beta^2-2(\gamma_e^g)^2 X}$, *which is positive when*
$p_e^g = \frac{\frac{2\alpha+\beta}{1+\alpha}+\beta\gamma_1 q_1}{4-\beta^2-2(\gamma_e^g)^2 X} < \frac{c(2-\gamma_e^g)^2 X}{2\beta(\gamma_e^g)^2(p_1-\gamma_1 q_1)}$.

c) $\frac{\partial g_e^g}{\partial q_1} = \frac{\gamma_e^g \gamma_1 \left(\beta(p_1-\gamma_1 q_1) - p_e^g \left(4-\beta^2-2(\gamma_e^g)^2\left(1-\frac{(p_1-\gamma_1 q_1)^2}{c}\right)\right)\right)}{c(4-\beta^2-2(\gamma_e^g)^2 X)}$*, which is positive when* $p_e^g = \frac{\frac{2\alpha+\beta}{1+\alpha}+\beta\gamma_1 q_1}{4-\beta^2-2(\gamma_e^g)^2 X} < \frac{\beta(p_1-\gamma_1 q_1)}{4-\beta^2-2(\gamma_e^g)^2\left(1-\frac{(p_1-\gamma_1 q_1)^2}{c}\right)}$.

4. *Derivating the profit functions with respect to* q_1 *and* p_1 *we get*

$$\begin{aligned}
\frac{\partial \pi_i^n}{\partial q_1} &= \frac{2\gamma_1}{1+\alpha}\frac{\left(2-(\gamma_e^n)^2\right)\left(\alpha\beta-(\gamma_e^n)^2+2+\left(\left(2-(\gamma_e^n)^2\right)(1+\alpha)\right)\gamma_1 q_1\right)}{\left(\beta^2+2(\gamma_e^n)^2-4\right)^2} > 0,\\
\frac{\partial \pi_e^n}{\partial q_1} &= \frac{\beta\gamma_1}{1+\alpha}\frac{\left(2-\gamma_e^2\right)\left(2\alpha+\beta+\beta\gamma_1 q_1(1+\alpha)\right)}{\left(\beta^2+2\gamma_e^2-4\right)^2} > 0.\\
\frac{\partial \pi_i^n}{\partial p_1} &= \frac{\partial \pi_e^n}{\partial p_1} = 0.
\end{aligned}$$

Proof 9 (Proposition 9) *The difference*

$$p_e^g - p_e^n = \frac{2\left(\frac{2\alpha+\beta}{1+\alpha}+\beta\gamma_1 q_1\right)}{\left(4-\beta^2-2(\gamma_e^g)^2 X\right)\left(4-\beta^2-2(\gamma_e^n)^2\right)}\left((\gamma_e^g)^2 X-(\gamma_e^n)^2\right),$$

is positive when $(\gamma_e^g)^2 X > (\gamma_e^n)^2$.

The difference

$$p_i^g - p_i^n = \frac{\beta}{2}\left(p_e^g - p_e^n\right),$$

is positive when $(\gamma_e^g)^2 X > (\gamma_e^n)^2$.

Proof 10 (Proposition 10) *difference in entrant's qualities is given by*

$$q_e^g - q_e^n = \left(\frac{2\alpha+\beta}{1+\alpha}+\beta\gamma_1 q_1\right)\left(\frac{\gamma_e^g}{4-\beta^2-2(\gamma_e^g)^2 X} - \frac{\gamma_e^n}{4-\beta^2-2(\gamma_e^n)^2}\right)$$

and is positive when

$$\frac{\gamma_e^g}{\gamma_e^n} > \frac{4-\beta^2-2(\gamma_e^g)^2 X}{4-\beta^2-2(\gamma_e^n)^2} = \frac{p_e^n}{p_e^g}.$$

Substituting for X, the above inequality is equivalent to

$$(1-D_1)^2 > \frac{c\left(\gamma_e^n-\gamma_e^g\right)\left(2\gamma_e^g\gamma_e^n+4-\beta^2\right)}{2\gamma_e^n(\gamma_e^g)^2}.$$

Proof 11 (Proposition 11) *1. The difference in entrant's profits is given by*

$$\pi_e^g - \pi_e^n = \frac{1}{2}\left(\frac{2\alpha+\beta}{\alpha+1} + \beta\gamma_1 q_1\right)^2 \left(\frac{\left(2-(\gamma_e^g)^2 X\right)}{\left(4-\beta^2-2(\gamma_e^g)^2 X\right)^2} - \frac{\left(2-(\gamma_e^n)^2\right)}{\left(4-\beta^2-2(\gamma_e^n)^2\right)^2}\right),$$

and is positive when

$$\frac{2-(\gamma_e^g)^2 X}{2-(\gamma_e^n)^2} > \frac{\left(4-\beta^2-2(\gamma_e^g)^2 X\right)^2}{\left(4-\beta^2-2(\gamma_e^n)^2\right)^2}.$$

2. The difference in incumbent's second-period profits is given by

$$\pi_i^g - \pi_i^n = \left(\frac{\frac{1}{1+\alpha} + \gamma_1 q_1 + \beta_i p_e^g}{2}\right)^2 - \left(\frac{\frac{1}{1+\alpha} + \gamma_1 q_1 + \beta_i p_e^n}{2}\right)^2,$$

and is positive when $p_e^g > p_e^n$, which is equivalent to $\frac{\gamma_e^n}{\gamma_e^g} < \sqrt{X}$.

Proof 12 (Proposition 12)

$$\begin{aligned}
\frac{\partial \pi_1^g}{\partial p_1} &= (1+\gamma_1 q_1) - 2p_1 + p_i^g \frac{\partial p_i^g}{\partial p_1} \\
p_1^g &= \frac{(1+\gamma_1 q_1)}{2} + \frac{p_i^g}{2}\frac{\partial p_i^g}{\partial p_1} \\
\frac{\partial \pi_1^n}{\partial p_1} &= (1+\gamma_1 q_1) - 2p_1 + p_i^n \frac{\partial p_i^n}{\partial p_1} \\
p_1^n &= \frac{(1+\gamma_1 q_1)}{2} + \frac{p_i^n}{2}\frac{\partial p_i^n}{\partial p_1} \\
p_1^g - p_1^n &= \frac{1}{2}\left(p_i^g \frac{\partial p_i^g}{\partial p_1} - p_i^n \frac{\partial p_i^n}{\partial p_1}\right)
\end{aligned}$$

We know that $\frac{\partial p_i^n}{\partial p_1} = 0$ and $\frac{\partial p_i^g}{\partial p_1} > 0$ from Proof of Proposition 8, hence we can conclude that the price difference is positive.

Proof 13 (The second period equilibrium's sensitivity analysis)

$$\frac{\partial p_e^n}{\partial \gamma_1} = \frac{\beta q_1}{4-\beta^2-2(\gamma_e^n)^2} > 0$$
$$\frac{\partial q_e^n}{\partial \gamma_1} = \gamma_e^n \frac{\partial p_e^n}{\partial \gamma_1} > 0$$
$$\frac{\partial p_i^n}{\partial \gamma_1} = \frac{(2-(\gamma_e^n)^2)q_1}{4-\beta^2-2(\gamma_e^n)^2} > 0$$
$$\frac{\partial p_e^n}{\partial \gamma_e^n} = \frac{4\gamma_e^n\left(\frac{2\alpha+\beta}{1+\alpha}+\beta\gamma_1 q_1\right)}{\left(4-\beta^2-2(\gamma_e^n)^2\right)^2} > 0$$
$$\frac{\partial q_e^n}{\partial \gamma_e^n} = \frac{\left(4-\beta^2+2(\gamma_e^n)^2\right)\left(\frac{2\alpha+\beta}{1+\alpha}+\beta\gamma_1 q_1\right)}{\left(4-\beta^2-2(\gamma_e^n)^2\right)^2} > 0$$
$$\frac{\partial p_i^n}{\partial \gamma_e^n} = \frac{2\beta\gamma_e^n\left(\frac{2\alpha+\beta}{1+\alpha}+\beta\gamma_1 q_1\right)}{\left(4-\beta^2-2(\gamma_e^n)^2\right)^2} > 0$$
$$\frac{\partial p_e^n}{\partial \beta} = \frac{2\beta\left(\frac{2\alpha+\beta}{1+\alpha}+\beta\gamma_1 q_1\right)}{\left(4-\beta^2-2(\gamma_e^n)^2\right)^2} + \frac{\frac{1}{1+\alpha}+\gamma_1 q_1}{4-\beta^2-2(\gamma_e^n)^2} > 0$$
$$\frac{\partial q_e^n}{\partial \beta} = \gamma_e^n \frac{\partial p_e^n}{\partial \beta} > 0$$
$$\frac{\partial p_i^n}{\partial \beta} = \frac{p_e^n}{2} + \frac{\beta}{2}\frac{\partial p_e^n}{\partial \beta} > 0$$
$$\frac{\partial p_e^n}{\partial \alpha} = \frac{2-\beta}{(1+\alpha)^2(4-\beta^2-2(\gamma_e^n)^2)} > 0$$
$$\frac{\partial q_e^n}{\partial \alpha} = \gamma_e^n \frac{\partial p_e^n}{\partial \alpha} > 0$$
$$\frac{\partial p_i^n}{\partial \alpha} = -\frac{2-\beta-(\gamma_e^n)^2}{(1+\alpha)^2(4-\beta^2-2(\gamma_e^n)^2)} < 0$$
$$\frac{\partial p_e^g}{\partial c} = -\frac{\frac{2(\gamma_e^g)^2}{c^2}(p_1-\gamma_1 q_1)^2\left(\frac{2\alpha+\beta}{1+\alpha}+\beta\gamma_1 q_1\right)}{\left(4-\beta^2-2(\gamma_e^g)^2\left(1+\frac{(p_1-\gamma_1 q_1)^2}{c}\right)\right)^2} < 0$$
$$\frac{\partial q_e^g}{\partial c} = \gamma_e^g \frac{\partial p_e^g}{\partial c} < 0$$
$$\frac{\partial g_e^g}{\partial c} = -\frac{\frac{\gamma_e^g}{c^2}(p_1-\gamma_1 q_1)\left(4-\beta^2-2(\gamma_e^g)^2\right)\left(\frac{2\alpha+\beta}{1+\alpha}+\beta\gamma_1 q_1\right)}{\left(4-\beta^2-2(\gamma_e^g)^2\left(1+\frac{(p_1-\gamma_1 q_1)^2}{c}\right)\right)^2} < 0$$
$$\frac{\partial p_i^g}{\partial c} = \frac{\beta}{2}\frac{\partial p_e^g}{\partial c} < 0$$

$$\frac{\partial p_e^g}{\partial \gamma_1} = \frac{q_1\left(\beta - \frac{4(\gamma_e^g)^2}{c}(p_1-\gamma_1 q_1)p_e^g\right)}{4-\beta^2-2(\gamma_e^g)^2\left(1+\frac{(p_1-\gamma_1 q_1)^2}{c}\right)}$$

$$\frac{\partial q_e^g}{\partial \gamma_1} = \gamma_e^g \frac{\partial p_e^g}{\partial \gamma_1}$$

$$\frac{\partial g_e^g}{\partial \gamma_1} = \frac{\gamma_e^g q_1\left(\beta\,(p_1-\gamma_1 q_1) - p_e^g\left(4-\beta^2-2(\gamma_e^g)^2\left(1-\frac{(p_1-\gamma_1 q_1)^2}{c}\right)\right)\right)}{c\left(4-\beta^2-2(\gamma_e^g)^2\left(1+\frac{(p_1-\gamma_1 q_1)^2}{c}\right)\right)}$$

$$\frac{\partial p_i^g}{\partial \gamma_1} = \frac{q_1\left((4-2(\gamma_e^g)^2\left(1+\frac{(p_1-\gamma_1 q_1)^2}{c}\right)) - \frac{4(\gamma_e^g)^2\beta}{c}\,(p_1-\gamma_1 q_1)\,p_e^g\right)}{4-\beta^2-2(\gamma_e^g)^2\left(1+\frac{(p_1-\gamma_1 q_1)^2}{c}\right)}$$

$$\frac{\partial p_e^g}{\partial \alpha} = \frac{2-\beta}{(1+\alpha)^2\left(4-\beta^2-2(\gamma_e^g)^2\left(1+\frac{(p_1-\gamma_1 q_1)^2}{c}\right)\right)} > 0$$

$$\frac{\partial q_e^g}{\partial \alpha} = \gamma_e^g \frac{\partial p_e^g}{\partial \alpha} > 0$$

$$\frac{\partial g_e^g}{\partial \alpha} = \frac{\gamma_e^g(p_1-\gamma_1 q_1)}{c}\frac{\partial p_e^g}{\partial \alpha} > 0$$

$$\frac{\partial p_i^n}{\partial \alpha} = -\frac{2-\beta-(\gamma_e^g)^2\left(1+\frac{(p_1-\gamma_1 q_1)^2}{c}\right)}{(1+\alpha)^2\left(4-\beta^2-2(\gamma_e^g)^2\left(1+\frac{(p_1-\gamma_1 q_1)^2}{c}\right)\right)} < 0$$

$$\frac{\partial p_e^g}{\partial \beta} = \frac{2\beta\left(\frac{2\alpha+\beta}{1+\alpha}+\beta\gamma_1 q_1\right)}{\left(4-\beta^2-2(\gamma_e^g)^2\left(1+\frac{(p_1-\gamma_1 q_1)^2}{c}\right)\right)^2} + \frac{\frac{1}{1+\alpha}+\gamma_1 q_1}{\left(4-\beta^2-2(\gamma_e^g)^2\left(1+\frac{(p_1-\gamma_1 q_1)^2}{c}\right)\right)} > 0$$

$$\frac{\partial q_e^g}{\partial \beta} = \gamma_e^g \frac{\partial p_e^g}{\partial \beta} > 0$$

$$\frac{\partial g_e^g}{\partial \beta} = \frac{\gamma_e^g(p_1-\gamma_1 q_1)}{c}\frac{\partial p_e^g}{\partial \beta} > 0$$

$$\frac{\partial p_i^g}{\partial \beta} = \frac{p_e^g}{2} + \frac{\beta}{2}\frac{\partial p_e^g}{\partial \beta} > 0$$

$$\frac{\partial p_e^g}{\partial \gamma_e^g} = \frac{4\gamma_e^g\left(1+\frac{(p_1-\gamma_1 q_1)^2}{c}\right)\left(\frac{2\alpha+\beta}{1+\alpha}+\beta\gamma_1 q_1\right)}{\left(4-\beta^2-2(\gamma_e^g)^2\left(1+\frac{(p_1-\gamma_1 q_1)^2}{c}\right)\right)^2} > 0$$

$$\frac{\partial q_e^g}{\partial \gamma_e^g} = p_e^g + \gamma_e^g \frac{\partial p_e^g}{\partial \gamma_e^g} > 0$$

$$\frac{\partial g_e^g}{\partial \gamma_e^g} = \frac{(p_1-\gamma_1 q_1)}{c}\left(p_e^g + \gamma_e^g\frac{\partial p_e^g}{\partial \gamma_e^g}\right) > 0$$

$$\frac{\partial p_i^g}{\partial \gamma_e^g} = \frac{\beta}{2}\frac{\partial p_e^g}{\partial \gamma_e^g} > 0$$

Appendix E – Equilibrium outcomes of the third essay

Delegation

$$q^* = \begin{cases} q^{G0}, & \gamma^G \le 0 \;\&\; A1,\ A2a,\ C1a,\ C1bx,\ E \\ q^G, & \gamma^G > 0 \;\&\; A1,\ A2a,\ C1a,\ C1bx,\ E \\ q^{N0} = \dfrac{\delta p_s}{2y}, & \gamma^N \le 0 \;\&\; C1by,\ C2a,\ D1,\ D2a \\ q^N = \dfrac{\delta(2p_m + p_s)}{4y}, & \gamma^N > 0 \;\&\; C1by,\ C2a,\ D1,\ D2a \\ q^C = q^{C0} = \dfrac{\delta p_r}{2t}, & F1 \\ q^{NX} = q^N(\gamma^X), & A2b+,\ B+,\ C2b+,\ D2b+,\ F2+ \\ q^{GX} = q^G(\gamma^X), & A2b-,\ B-,\ C2b-,\ D2b-,\ F2- \end{cases}$$

where

$$q^{G0} = \frac{kp_s(\delta p_r(\delta - k\theta)(2t + \delta kp_r) + 2\theta(t + \delta kp_r)^2)}{4y(t + \delta kp_r)^2 - \delta^2 k^2 p_r p_s(2t + \delta kp_r)}$$

$$q^G = \frac{k(2p_m + p_s)(\delta p_r(\delta - k\theta)(2t + \delta kp_r) + 2\theta(t + \delta kp_r)^2)}{2(4y(t + \delta kp_r)^2 - \delta^2 k^2 p_r(p_m + p_s)(2t + \delta kp_r))}$$

$$a^* = \begin{cases} a^{G0}, & \gamma^G \leq 0 \;\&\; A1,\ A2a,\ C1a,\ C1bx,\ E \\ a^G, & \gamma^G > 0 \;\&\; A1,\ A2a,\ C1a,\ C1bx,\ E \\ a^{N0} = \dfrac{\delta p_s}{2y}, & \gamma^N \leq 0 \;\&\; C1by,\ C2a,\ D1,\ D2a \\ a^N = \dfrac{\delta(2p_m + p_s)}{4y}, & \gamma^N > 0 \;\&\; C1by,\ C2a,\ D1,\ D2a \\ a^C = q^{C0} = \dfrac{\delta p_r}{2t}, & F1 \\ a^{NX} = q^N(\gamma^X), & A2b+,\ B+,\ C2b+,\ D2b+,\ F2+ \\ a^{GX} = \dfrac{p_r(\delta - k\theta)}{2(t+\delta k p_r)} + \dfrac{\delta k p_r}{2(t+\delta k p_r)} q^G(\gamma^X), & A2b-,\ B-,\ C2b-,\ D2b-,\ F2- \end{cases}$$

where

$$a^{G0} = p_r \frac{(t+\delta k p_r)(2y(\delta - k\theta) + \delta k^2 \theta p_s)}{4y(t+\delta k p_r)^2 - \delta^2 k^2 p_r p_s (2t + \delta k p_r)}$$

$$a^G = p_r \frac{2(t+\delta k p_r)^2(4y(\delta - k\theta) + \delta k^2 \theta(2p_m + p_s)) - \delta^2 k^2 p_r p_s (\delta - k\theta)(2t + \delta k p_r)}{4(t+\delta k p_r)(4y(t+\delta k p_r)^2 - \delta^2 k^2 p_r (p_m + p_s)(2t + \delta k p_r))}$$

Direct-support

$$q^* = \begin{cases} q^{G0}, & \gamma^G \leq 0 \;\&\; A1,\ A2a,\ C1a,\ C1bx \\ q^G, & \gamma^G > 0 \;\&\; A1,\ A2a,\ C1a,\ C1bx \\ q^{N0} = \dfrac{\delta p_s}{2y}, & \gamma^N \leq 0 \;\&\; \dfrac{p_s}{p_r} < \dfrac{y}{t} \;\&\; C1by,\ C2a,\ D1,\ D2a \\ q^N = \dfrac{\delta(2p_r + p_s)}{4(t+y)}, & \gamma^N > 0 \;\&\; C1by,\ C2a,\ D1,\ D2a \\ q^{C0} = \dfrac{\delta p_r}{2t}, & \gamma^N \leq 0 \;\&\; \dfrac{p_s}{p_r} > \dfrac{y}{t} \;\&\; C1by,\ C2a,\ D1,\ D2a \\ q^{NX} = q^N(\gamma^X), & A2b+,\ B+,\ C2b+,\ D2b+ \\ q^{GX} = q^G(\gamma^X), & A2b-,\ B-,\ C2b-,\ D2b- \end{cases}$$

where

$$q^{G0} = \frac{kp_s(\delta p_r(\delta - k\theta)(2t + \delta kp_r) + 2\theta(t + \delta kp_r)^2)}{4y(t + \delta kp_r)^2 - \delta^2 k^2 p_r p_s(2t + \delta kp_r)}$$

$$q^G = \frac{k((2p_r + p_s)(\delta p_r(\delta - k\theta)(2t + \delta kp_r) + 2\theta(t + \delta kp_r)^2) + 2\delta p_r^2 t(\delta - k\theta))}{2(4y(t + \delta kp_r)^2 - \delta^2 k^2 p_r((t + \delta kp_r)(p_r + p_s) + tp_s))}$$

$$a^* = \begin{cases} a^{G0}, & \gamma^G \leq 0 \ \& \ A1,\ A2a,\ C1a,\ C1bx \\ a^G, & \gamma^G > 0 \ \& \ A1,\ A2a,\ C1a,\ C1bx \\ a^{N0} = \dfrac{\delta p_s}{2y}, & \gamma^N \leq 0 \ \& \ \dfrac{p_s}{p_r} < \dfrac{y}{t} \ \& \ C1by,\ C2a,\ D1,\ D2a \\ a^N = \dfrac{\delta(2p_r + p_s)}{4(t+y)}, & \gamma^N > 0 \ \& \ C1by,\ C2a,\ D1,\ D2a \\ a^{C0} = \dfrac{\delta p_r}{2t}, & \gamma^N \leq 0 \ \& \ \dfrac{p_s}{p_r} > \dfrac{y}{t} \ \& \ C1by,\ C2a,\ D1,\ D2a \\ a^{NX} = q^N(\gamma^X), & A2b+,\ B+,\ C2b+,\ D2b+ \\ a^{GX} = \dfrac{p_r(\delta - k\theta)}{2(t + \delta kp_r)} + \dfrac{\delta kp_r}{2(t + \delta kp_r)} q^G(\gamma^X), & A2b-,\ B-,\ C2b-,\ D2b- \end{cases}$$

where

$$a^{G0} = p_r \frac{(t + \delta kp_r)(2y(\delta - k\theta) + \delta k^2 \theta p_s)}{4y(t + \delta kp_r)^2 - \delta^2 k^2 p_r p_s(2t + \delta kp_r)}$$

$$a^G = \frac{p_r(2(t + \delta kp_r)^2(4y(\delta - k\theta) + \delta k^2\theta(2p_r + p_s)) - \delta^2 k^2 p_r p_s(\delta - k\theta)(2t + \delta kp_r))}{4(t + \delta kp_r)(4y(t + \delta kp_r)^2 - \delta^2 k^2 p_r((t + \delta kp_r)(p_r + p_s) + tp_s))}$$

Appendix F – Proofs of propositions of the third essay

Proof 14 (Proposition 13) *The profit function of the retailer is always concave in a when the retailer greenwashes. The second order derivative is given by*

$$\frac{d^2\pi_r^G(a)}{da^2} = -2(t+\delta k p_r) < 0$$

The sign follows from the positivity of t, δ, k, and p_r. Therefore, $\pi_r^G(a)$ is strictly concave in a. The first-order optimality condition for the retailer is

$$\frac{d\pi_r^G(a)}{da} = p_r(\delta - k\theta) + \delta k p_r q - 2(t+\delta k p_r)a = 0$$

The profit function of the retailer is always concave in a when the retailer does not greenwash. The second order derivative is given by

$$\frac{d^2\pi_r^N(a)}{da^2} = -2t < 0$$

The sign follows the positivity of t. Therefore, $\pi_r^N(a)$ is strictly concave in a. The first-order optimality condition for the retailer is

$$\frac{d\pi_r^N(a)}{da} = \delta p_r - 2ta = 0$$

The profit-maximizing advertisement level for environmental quality without greenwashing is min$\left\{\frac{\delta p_r}{2t}, q\right\}$. If $\frac{\delta p_r}{2t} < q$, then the advertisement level of the retailer becomes $a^*(q(\gamma)) = a^C = \frac{\delta p_r}{2t}$, otherwise $a^* = q$

Proof 15 (Proposition 14) *When the retailer greenwashes, the concavity of the profit function of the supplier is dependent on a condition.*

$$\frac{d^2\pi_s^G(q)}{dq^2} = -4y(t+\delta k p_r)^2(1-\gamma) + \delta^2 k^2 p_r p_s(2t+\delta k p_r) < 0$$

In order for $\pi_s^G(q)$ to be concave with respect to q, the sharing ratio of the manufacturer γ should be less than a certain threshold,

$$\gamma < 1 - \frac{\delta^2 k^2 p_r p_s(2t+\delta k p_r)}{4y(t+\delta k p_r)^2}. \tag{1}$$

We enforce this condition for our analysis and it is checked numerically that this condition is not violated with reasonable levels of parameters.

The first order optimality condition for the tier-2 supplier is

$$\begin{aligned}\frac{d\pi_s^G(q)}{dq} &= \frac{kp_s(\delta p_r(\delta - k\theta)(2t+\delta k p_r) + 2\theta(t+\delta k p_r)^2)}{2(t+\delta k p_r)^2} \\ &\quad + \frac{(-4y(t+\delta k p_r)^2(1-\gamma) + \delta^2 k^2 p_r p_s(2t+\delta k p_r))q}{2(t+\delta k p_r)^2} = 0\end{aligned}$$

The profit function of the supplier is always concave in q when the buyer does not greenwash. The second order derivative is given by

$$\frac{d^2\pi_s^N(q)}{dq^2} = -2y(1-\gamma) < 0$$

The sign of the second order derivative follows the positivity of y and γ being in $[0,1]$. *Therefore, $\pi_s^N(q)$ is concave in q. The first-order optimality condition of the supplier is*

$$\frac{d\pi_s^N(q)}{dq} = \delta p_s - 2y(1-\gamma)q = 0$$

The profit function of the supplier in region C is always concave.

$$\frac{d^2\pi_s^C(q)}{dq^2} = -2y(1-\gamma) < 0$$

The first-order optimality condition of the supplier is

$$\frac{d\pi_s^C(q)}{dq} = -2y(1-\gamma)q < 0$$

Since the first order derivative of π_s^C is always negative, the tier-2 supplier sets q^C to the corner solution $\frac{\delta p_r}{2t}$.

Proof 16 (Proposition 15) *$q^N(\gamma) > q^G(\gamma)$ can be reduced to the following inequality with the algebraic operations:*

$$\gamma < 1 - \frac{\delta^3 k^2 p_r p_s (2t + \delta k p_r)}{2y(\delta - k\theta)(t^2 + (t + \delta k p_r)^2)} \tag{2}$$

The parameter space that makes Inequality 1 is a subset of the parameter space satisfying Inequality 2, hence we can conclude that Inequality 2 is always true for the defined parameter space.

Proof 17 (Proposition 16) *The profit function of the manufacturer is quasi-concave and has a unique profit-maximizer when the retailer greenwashes. There is only one root of first-order optimality conditions.*

$$\begin{aligned}\frac{d\pi_m^G(\gamma)}{d\gamma} &= -kp_s y(\delta p_r(\delta - k\theta)(2t + \delta k p_r) + 2\theta(t + \delta k p_r)^2)) \\ &\quad * \frac{4y(t + \delta k p_r)^2((2p_m + p_s)\gamma - (2p_m - p_s)) - \delta^2 k^2 p_r {p_s}^2 (2t + \delta k p_r)}{(4y(t + \delta k p_r)^2(1 - \gamma) - \delta^2 k^2 p_r p_s (2t + \delta k p_r))^3} = 0\end{aligned}$$

The profit function of the manufacturer is locally concave at the unique root of the optimality condition.

$$\left.\frac{d^2\pi_m^G(\gamma)}{d\gamma^2}\right|_{\gamma=\gamma^G} = -\frac{k^2 y^2 (t + \delta k p_r)^2 (2p_m + p_s)^4 (\delta p_r(\delta - k\theta)(2t + \delta k p_r) + 2\theta(t + \delta k p_r)^2)^2}{(4y(t + \delta k p_r)^2 - \delta^2 k^2 p_r (p_m + p_s)(2t + \delta k p_r))^4} < 0$$

The sign of the denominator is dependent on the condition for the concavity of $\pi_s^G(q)$ hence we can conclude that $\pi_m^G(\gamma^G)$ is a local maximum thanks to positivity of the parameters. Combining local maximum and the uniqueness of the root of the first order optimality condition, we can conclude that γ^G is the global profit maximizer under greenwashing scenario.

If $\gamma^G < 0$, we can set $\gamma^{G0} = 0$ and update the equilibrium the environmental quality q^{G0} and the environmental image a^{G0}, accordingly. Since we enforced $\gamma^G < 1 - \frac{\delta^2 k^2 p_r p_s (2t + \delta k p_r)}{4y(t + \delta k p_r)^2}$ for the concavity of π_s^G, γ^G cannot violate the upper bound.

The profit function of the manufacturer is quasi-concave and has a unique profit maximizer when the buyer does not greenwash. There is only one root of first-order optimality *conditions.*

$$\frac{d\pi_m^N(\gamma)}{d\gamma} = -\frac{\delta^2 p_s(\gamma(2p_m + p_s) - (2p_m - p_s))}{4(1-\gamma)^3} = 0$$

The profit function of the tier-1 supplier is locally concave at the unique root of the optimality condition.

$$\left.\frac{d^2\pi_m^N(\gamma)}{d\gamma^2}\right|_{\gamma=\gamma^N} = -\frac{\delta^2(2p_m + p_s)^4}{32{p_s}^2 y} < 0$$

Combining local maximum and the uniqueness of the root of the first-order optimality condition, we can conclude that γ^N is the global profit maximizer. If $\gamma^N < 0$, we can set $\gamma^{N0} = 0$ and update the equilibrium the environmental quality q^{N0} and the environmental image a^{N0} accordingly.

The first-order optimality condition of the tier-1 supplier is

$$\frac{d\pi_m^C(\gamma)}{d\gamma} = -\frac{\delta^2 {p_r}^2 y}{4t^2} < 0$$

Since the first order derivative of π_m^C is always negative, the manufacturer sets γ^C to its lower corner solution $1 - \frac{p_s t}{p_r y}$.

Proof 18 (Proposition 17) *The profit function of the retailer is quasi-concave and has a unique profit maximizer when the retailer greenwashes. There is only one root of first-order optimality condition.*

$$\frac{d\pi_r^G(\gamma)}{d\gamma} = \frac{-kp_s y(\delta p_r(\delta - k\theta)(2t + \delta k p_r) + 2\theta(t + \delta k p_r)^2))(A + B\gamma)}{(4y(t + \delta k p_r)^2(1-\gamma) - \delta^2 k^2 p_r p_s(2t + \delta k p_r))^3} = 0$$

where A and B are positive terms dependent only on positive parameters. ***I could not simplify A and B, but they only depend on the parameters.***

The profit function of the tier-1 supplier is locally concave at the unique root of the optimality condition.

$$\left.\frac{d^2\pi_r^G(\gamma)}{d\gamma^2}\right|_{\gamma=\gamma^G} = -\frac{k^2 y^2 (t + \delta k p_r)^2}{2{p_s}^2(\delta p_r(\delta - k\theta)(2t + \delta k p_r) + 2\theta(t + \delta k p_r)^2))^2} * \frac{((2p_r + p_s)(t + \delta k p_r)(\delta p_r(\delta - k\theta) + 2\theta(t + \delta k p_r)) + \delta p_r t p_s(\delta - k\theta))^4}{(4y(t + \delta k p_r)^2 - \delta^2 k^2 p_r(p_r + p_s)(2t + \delta k p_r))^3} < 0$$

The sign of the denominator is dependent on the condition for the concavity of $\pi_s^G(q)$ *hence we can conclude that* $\pi_r(\gamma^G)$ *is a local maximum thanks to positivity of the parameters. Combining local maximum and the uniqueness of the root of the first order optimality condition, we can conclude that* γ^G *is the global profit maximizer.*

If $\gamma^G < 0$, *we can set* $\gamma^{G0} = 0$ *and update the equilibrium the environmental quality* q^{G0} *and the environmental image* a^{G0} *accordingly. Since we enforced* $\gamma^G < 1 - \frac{\delta^2 k^2 p_r p_s (2t+\delta k p_r)}{4y(t+\delta k p_r)^2}$ *for the concavity of* π_s^G, γ *cannot violate the upper bound.*

The profit function of the retailer is quasi-concave and has a unique profit maximizer when the buyer does not greenwash. There is only one root of first-order optimality conditions.

$$\frac{d\pi_r^N(\gamma^N)}{d\gamma^N} = -\frac{\delta^2 p_s (y(2p_r - p_s) - 2tp_s - y(2p_r + p_s)\gamma)}{4y^2(1-\gamma)^3} = 0$$

The profit function of the tier-1 supplier is locally concave at the unique root of the optimality condition.

$$\left.\frac{d^2\pi_r^N(\gamma)}{d\gamma^2}\right|_{\gamma=\gamma^N} = -\frac{\delta^2 y^2 (2p_r + p_s)^4}{32 {p_s}^2 (t+y)^3} < 0$$

Combining local maximum and the uniqueness of the root of the first-order optimality condition, we can conclude that γ^N *is the global profit maximizer. If* $\gamma^N < 0$, *we can set* $\gamma^{N0} = 0$ *and update the equilibrium the environmental quality* q^{N0} *and the environmental image* a^{N0} *accordingly.*

The first-order optimality condition of the retailer is

$$\frac{d\pi_m^C(\gamma)}{d\gamma} = -\frac{\delta^2 {p_r}^2 y}{4(t+\gamma y)^2} < 0$$

Since the first order derivative of π_m^C *is always negative, the manufacturer sets* γ^C *to its lower corner solution* $1 - \frac{p_s(t+y)}{(p_s+p_r)y}$. *Since* γ^N *is always smaller than* $\overline{T}^N = \gamma^C$, *we never observe the region sharing ratio to be bounded, whereas* $q^N(\gamma) > \frac{\delta p_r}{2(t+\gamma y)}$ *can be observed with* $\gamma^N = 0$. *In that case, the supplier sets its environmental quality investment level to* $\frac{\delta p_r}{2t}$. *Still, we cannot observe C region since a positive* γ^N *never violates the upper bound.*

Proof 19 (Proposition 18)

$$\frac{da^N}{dq} = 1 > 0$$
$$\frac{da^N}{d\gamma} = \frac{\delta p_s}{2y(1-\gamma)} > 0$$
$$\frac{dq^N}{d\gamma} = \frac{\delta p_s}{2y(1-\gamma)} > 0$$
$$\frac{da^G}{dq} = \frac{\delta k p_r}{2(t+\delta k p_r)} > 0$$
$$\frac{dq^G}{d\gamma} = \frac{4kp_s y(t+\delta k p_r)^2(\delta p_r(\delta+k\theta)(2y+\delta k p_r)+2\theta t^2)}{(4y(1-\gamma)(t+\delta k p_r)^2-\delta^2 k^2 p_r p_s(2t+\delta k p_r)^2)^2} > 0$$
$$\frac{da^G}{d\gamma} = \frac{da^G}{dq^G}\frac{dq^G}{d\gamma} = \frac{2\delta k^2 p_r p_s y(t+\delta k p_r)(\delta p_r(\delta+k\theta)(2y+\delta k p_r)+2\theta t^2)}{(4y(1-\gamma)(t+\delta k p_r)^2-\delta^2 k^2 p_r p_s(2t+\delta k p_r)^2)^2} > 0$$
$$\frac{d(a^G-q^G)}{d\gamma} = -\frac{2kp_s y(2t+\delta k p_r)(t+\delta k p_r)(\delta p_r(d+k\theta)(2y+\delta k p_r)+2\theta t^2)}{(4y(1-\gamma)(t+\delta k p_r)^2-\delta^2 k^2 p_r p_s(2t+\delta k p_r)^2)^2} < 0$$

Proof 20 (Proposition 19) *By comparison of the equilibrium sharing ratios, γ^{Del} and γ^{DS}, under the two settings.*

Proof 21 (Proposition 20) *By comparison of the profits under the two settings.*