Managing Technology and Operations in Emerging Markets

by

Jiong Sun

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Dissertation Committee:

Professor Laurens Debo (co-chair)
Professor Sunder Kekre (co-chair)
Professor Bahar Biller
Professor Peter Boatwright (outside reader)
Professor Jinhong Xie

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Abstract

Firms increasingly face both opportunities and risks: on the positive side, they can exploit fast-burgeoning markets in emerging economies and leverage low factor costs in these countries; on the negative side, they face mounting cost pressures due to intensified competition and eroding price premium due to fast commoditization and shorter product life cycles. The new competitive landscape of the business world is therefore more and more shaped by *globalization* and *technology*. My dissertation concentrates on the study of technological systems, in which technology, firms, and markets interact. Motivated by strategic issues faced by executives in different industries, this dissertation tends to answer fundamental issues and choices when firms enter emerging markets: new economies or new technologies.

Chapter one studies the implications for global sourcing and technology transfer in the presence of technological imitators. Technology transfer offers global firms an opportunity to reduce costs of serving emerging markets as well as source from the low-cost country for their home markets. However, it also poses risks of potential technology imitation by local competitors who may enter the emerging market and invade subsequently the global firms' home markets as well. We study the competition between a global firm and a local imitator in both markets and examine how the competition affects the global firm's technology transfer and sourcing decisions, and the local competitor's imitation and exporting choices. We examine the impact of various factors, such as market characteristics, cost structures, intellectual property protection policies, firm-specific advantages and disadvantages in production and distribution. Our model broadens the traditional view of firms balancing between avoiding technology leakage and exploiting factor-cost difference by incorporating sourcing opportunities for their home markets. We find three possible optimal strategies: "Local Content", "Export Platform", and "Global Platform", and characterize the above factors that drive which of these strategy will result in equilibrium. Some interesting results arise. For instance, in some cases, larger size of the emerging market could induce the global firm to transfer less technology, and higher imitation cost does not necessarily lead to more technology transfer. The model is also interpreted in conjunction with field data obtained from a critical equipment producer in U.S.A. This company faces similar choices in levels of technology transfer to its Chinese affiliate. Our model provides insights in the fundamental drivers of imitative competition that emerge in this industry.

Chapter two studies the optimal green vehicle introduction strategies subject to scarce green fuel supplies. Concerns of environmental impacts coupled with high oil prices spur a trend of green vehicles powered by biofuels. The scarce biofuel supply however remains a major obstacle to the development of the green vehicle market. The scarcity of the complementary product causes the consumers utility to be endogenously determined by the consumers' vehicle choice: the conventional or green vehicle. We study vehicle manufacturers' product and pricing strategy: when to offer a single vehicle or both vehicles, and at what prices. We examine the impact of various factors, such as green segment sizes, biofuel price sensitivities, vehicles performance, and fluctuating petroleum fuel prices. Our results confirm that the factors exhibit interactions that

must be well balanced. Some interesting results arise. For example, as the number of green consumers increases, it is less likely that the firm will adopt the green vehicle only strategy, but the two-vehicle strategy. The green vehicle's fuel flexibility has its value only in the presence of uncertain petroleum fuel prices. Surprisingly, under uncertain petroleum fuel prices, the green vehicle only strategy emerges as an optimal strategy when the petroleum fuel price is both low and high, due to the value generated from its fuel flexibility.

Chapter three studies coordination of a two-firm supply chain through repeated interaction: In each period, the upstream firm, the manufacturer, determines the wholesale price and the downstream firm, the retailer, subsequently sets the order quantity before the market demand is realized. The environment is characterized by uncertain market demand and discounting of the future profits. No inventory is carried over between periods. In a single-period interaction, the wholesale price contract cannot achieve supply chain efficiency (or coordination). With repeated interactions, we show that supply chain efficiency can be achieved with the wholesale price contract if the supply chain members have a sufficiently high discount factor. At the minimum possible discount factor, we show that the manufacturer decreases the wholesale price, in return for a larger order quantity from the retailer. We show that information about the demand distribution available to both players in the beginning of each period may decrease the retailer's expected profit in a coordinated supply chain, or constrain supply chain coordination.

Contents

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Chapter 1

Imitative Competition: Implications for Global Sourcing and Technology Transfer

1.1 Introduction

Technological imitators in newly-emerging markets are posing threats to global firms who transfer technology to these new economies. According to the World Custom Organization, IP counterfeiting accounts for 5 to 7 percent of global merchandise trade, equivalent to lost sales of as much as US$512 billion in 2004 (*BusinessWeek Online* 2005a). General Motor filed a lawsuit in 2004 against Chery, a Chinese domestic auto maker, of copying technology of GM's Chevy Spark mini model manufactured in Shanghai GM. Due to Chery's cost advantage as a local manufacturer, Chery offers its QQ very attractively and outsells the Chevy Spark in the Chinese market by nearly five to one (*BusinessWeek Online* 2005b). Similarly, PPG, a major flat glass producer, is losing its Chinese markets to local windshield technological imitators. Facing also their threats of cannibalizing its U.S. home markets, PPG launched an anti-dumping lawsuit in the U.S. and Canada against several Chinese windshield manufacturers in 2001 (*China Daily* 2005). Imitative competition is fierce. In some cases, firms use technology transfer as a strategic lever when facing competition with local imitators. For example, Israel-based Netafim, the world leader in irrigation systems, makes a core component complex and keeps its production at home so as to make copying very difficult (*Business Week* 2006).

The pluses and minuses of the dynamics involved are significant. There can be little doubt that the emergence of vast markets, such as, Brazil, China, India, and Russia, represent a vast potential of untapped market opportunity, and also ample supplies of cheap labor. Firms are recognizing this and exploring the enormous business opportunity by transferring technology and doing some value add in emerging markets. Technology transfer to these new economies offers the firms an opportunity to (1) tap the emerging markets; and/or (2) source from these cost-effective locations. An empirical study by Blalock and Veloso (2006) shows evidence that sourcing is a key driver of technology transfer. On the negative side, these developing countries usually lack home grown advanced technology, and have poor Intellectual Property (IP) protection systems. This creates risks of potential technology imitation by local competitors. Strengthening IP protection does imply costly imitation for local rivals (Mansfield et al. 1981). Leakage of know-how, however, cannot be avoided, despite such legal barriers. Besides entering the local markets, the technology imitators also develop significant potential to export to the home markets of the global firms by leveraging their local advantage in production costs.

Taken together, this situation poses critical questions for the managers of global firms: How to balance cost savings of serving home markets, revenues from emerging markets and the threats of imitators? What should be the corresponding sourcing strategy, i.e., where and how much to make and market your product? It is also conceivable that due to their first-mover advantage, firms can alter the market outcome in their favor despite technology leakage. More importantly, foreign affiliates do not always sell locally, but may serve as export platforms to home markets. This implies that the firms' transfer decision should not be considered separately from their target market decisions, i.e., their reasons of going abroad: whether to gain access to host-country markets or to exploit international factor-cost differences.

In this paper, we address the key managerial issues faced by global firms that consider transferring their process technology of making a product to an emerging market to manufacture and sell the product locally and/or source for their home market. By doing so, they face potential technology imitation from local competitors. Along with sourcing decision, the global firm decides whether to deter or accommodate the imitator's entry by deciding the "amount" of technology to transfer. This in turn places limits on the amount of technology that the imitator can potentially copy. Interesting research questions that emerge are: Facing the potential technology imitation, do larger potentials of the emerging markets induce the global firms to transfer more technology? Does higher imitation cost always result in more technology to transfer? In some cases, there are compelling reasons for transferring less technology. Also, how does the optimal sourcing strategy change with the transfer decision, the imitation costs, and import cost structure? We obtain some interesting analytical results, and interpret them by relating to observations from our field study with a critical equipment producer in U.S.A.

Another salient feature of this paper is the study of the relative impact of the local imitators' production cost advantage in the emerging market, as well as the global firms' distribution advantage in its home market. Shifting production to a low-cost location affiliates by the global firms lowers production costs, but not necessarily to the production cost levels of the potential local rivals. Affiliates of the multinationals are often disadvantaged relative to local firms when operating in an unfamiliar environment, i.e., intimate knowledge of business practices, language and culture (Markusen 1995). The local companies usually have a far better market presence than FDIs, and incur lower costs in procuring materials and hiring employees. This cost advantage works in favor of local rivals and makes it possible for the imitators to "enter" the emerging and even sometimes the global firms' home markets as well. Their cost advantage is the reason why the imitators in emerging markets usually adopt copycat strategies, i.e., photocopying (*Wall Street Journal* 1988). However, the local firms encounter many hurdles. The imitators face disadvantage in the export market, such as, disadvantage in distribution channel, brand awareness, and aftermarket service. Such high costs incurred before arriving at target consumers (hereafter, referred to as landed costs) may prevent the imitators from entering the global firms' home markets. In high-technology industries, for example, mobile telephones and DVD players, the actual landed costs of imitative products in the U.S. are higher than global brands (PricewaterhouseCoopers 2005). We study how the imitators' cost advantage and the global firms' distribution advantage impact the global firms' technology transfer and sourcing decisions.

Global firms transfer technologies from lead affiliates to other affiliates, and the host country firms imitate and learn from the recipient affiliates (Das 1987). We model the firms' strategic interaction by the sequential stages of technology transfer and imitation, and pricing decisions of the two firms, global and local. In the literature, global firms' two reasons for entering a new economy, tapping the new market and sourcing for their home market, are discussed separately from each other. Our paper complements the literature by jointly considering the global firm's technology transfer decision with its sourcing decision. Secondly, we assess potential vulnerability of both the emerging and home markets from imitators. The vulnerability of the home markets from imitators is however generally neglected in the literature. Accordingly, the global firm's technology transfer decision is examined along two dimensions. The first dimension is whether the imitator poses threats to the global firm's home market in addition to the emerging market. The second dimension is whether the product characteristics and import cost structure prevent the global firm from transporting its goods among its affiliates. Under this framework, we examine the market characteristics, cost structures and host country policies that drive which optimal strategy will result in equilibrium in each case. Three possible types of equilibrium optimal strategies may arise. For the first strategy, a global firm transfers a low amount of technology, and the imitator decides not to enter. The global firm's foreign affiliate only serves its local market and may or may not use intermediate goods made by home country depending on affiliate's process capabilities. Ferdows (1997) refers to this as a "Server" type factory. We term this "Local Content". In a local content strategy, home country serves to transfer appropriate technology and leverage sourcing to capture emerging markets as well as protect home market. For the second strategy, a global firm might transfer a high amount of technology, allowing the imitator to enter and capture the emerging market. The global firm's foreign affiliate chooses to sell its output solely in export markets. We adopt the term of Ekholm et al. (2003), "Export Platform", for this strategy. A hybrid of these two strategies is that a global firm's foreign affiliate serves both its local market and export markets. The emerging market may or may not be split between the two firms, depending on how much technology the global firm transfers, and the firms' competitive advantages. Ferdows (1997) refers to this as a "Source" type factory. We term this as "Global Platform" strategy.

The remainder of this paper is structured as follows. We review related literature in §1.2. We introduce the model and the game setup in §1.3. We solve and interpret the global firm's optimal strategy first in a case where the imitative product is not sold in the global firm's home market in §1.4, the other case being when it is offered in §1.5. A comparative study of the two cases is presented in §1.6. In §1.7, we conclude with managerial implications, limitations, and directions for future research. We give proofs in Appendix A, and more results of the comparative study in Appendix B. In Appendix C, we interpret our model using field data obtained from a critical equipment manufacturer in U.S.A., and compare our results from our model to the choices made by the firm.

1.2 Related Literature

Our research is related to three streams of literature. One stream of literature models issues related to imitation and competition. In this literature, researchers study which entry mode, such as exporting, FDI, licensing, etc., to choose in the presence of imitation (e.g., Ethier and Markusen 1996), or what technology level to introduce (e.g., Pepall and Richards 1994, Pepall 1997), or both (e.g., Fosfuri 2000). These decisions impact the imitators' imitation costs. Because of their focus on the emerging market only, these papers find that it is the size of the imitation cost that determines whether or not an entry-deterrence strategy is preferred by the first mover. Our paper complements the literature by jointly considering the entry-deterrence decision with the global firm's sourcing decision, taking into account the possibility of the aggressive imitator entering the home market of the global firm as well. Therefore, not only the imitation cost, but also other factors, such as, market characteristics, and firms' competitive advantage play a key role in determining the global firm's optimal strategy.

The second stream of related literature is about sequential market entry models. Based upon vertical product differentiation framework of Gabszewicz and Thisse (1979) and Shaked and Sutton (1982), many researchers use product quality as an instrument to preempt potential entry (e.g., Hung and Schmitt 1992, Donnenfeld and Weber 1995, Lutz 1997), while others use excess capacity (e.g., Dixit 1980, Maskin 1999), informative signals (e.g., Milgrom and Roberts 1982), etc. In similar vein, we also adopt a vertical product differentiation framework, but introduce a new "strategic" instrument, technology transfer amount, to deter the later entrant. We capture the effects of global firm's technology transfer raising imitative product quality through imitation and affecting market dynamics. In addition, we incorporate the effect of the later entrant (the imitator) having a lower production cost and thus competing head on with the global firm. Tyagi (2000) considers such a second-mover's cost advantage in a horizontal differentiation framework, and shows that the larger the second-mover's cost advantage, the farther away the first mover positions its product. One of our results complements this finding by determining under which circumstances the global firm will allow the imitator with a strong cost advantage to position its product quality close to its own, and thus switch its focus from capturing the emerging market to sourcing for its home market.

The literature on supply chains has also covered these issues from an operations management perspective to analyze technology transfer and sourcing networks. However, imitation aspects have remained largely unexplored. Roth et al. (1997), Prasad and Babbar (2000) conduct comprehensive reviews of research in the international production and operations management area. Kogut (1985) qualitatively describes the design of global strategies to capitalize on the comparative advantage of countries in conjunction with the competence of the global firms. Some conceptual articles address the challenges of coordinating a multi-plant network. For example, Flaherty (1986) derives a multi-plant configuration in terms of material flows, Ferdows (1997) describes the role of the plants relative to a network, DuBois et al. (1993) study the relationship between multi-plant configurations and manufacturing strategy, Shi and Gregory (1998) identify several key benefits of geographically dispersed manufacturing networks, which include penetrating into new markets and access to favorable production factors. Cohen and Lee (1989) develop a mathematical programming model to analyze deployment of resources in a global manufacturing and distribution network. However, none of the studies model imitation and sourcing interactions in shaping network strategy and technology transfer choices. Also, much of the recent economic literature on international technology diffusion, reviewed in Keller (2004), ignores the potential of changes in IP protection on knowledge spillovers.

1.3 The Model

We introduce our assumptions concerning the firms, markets, products in §1.3.1, the decision set in §1.3.2, and the cost structures in §1.3.3. The game setup is described in §1.3.4.

1.3.1 Players, Products, Markets and Consumers

Players, Products and Markets

There are two players: a global firm and a technology imitator. Two markets are considered: a home market of the global firm (denoted by market 1), and an emerging market (denoted by market 2). The global firm has production facilities in both markets, which are referred to as the home and foreign affiliate, respectively. The imitator has a production facility only in the emerging market. The global firm has developed a production process which delivers a product of quality q. This quality q is exogenously given. All the process technology of the product is available in the global firm's home affiliate, but not in its foreign affiliate unless transferred. The imitator has no process technology of its own to make this product (or equivalently, only a production process delivering quality 0) before imitating from the global firm.

Consumers

Consumers in each market have the same ranking of preferences about products and, therefore, they buy the product with the highest quality, if all varieties are sold at the same prices. Consumers differ however, in their marginal willingness-to-pay for quality. This is due to differences in their income level. This willingness-to-pay is assumed to be uniformly distributed on the intervals: $\theta_1 \in [\alpha_1, \beta_1]$, $\theta_2 \in [\alpha_2, \beta_2]$, for consumers in the home and emerging markets, respectively. Willingness-to-pay of a consumer θ for a product of quality q is then $\theta \cdot q$. This consumer θ thus has a utility $U = \theta \cdot q - p$, if she buys the product with quality q at price p; $U = 0$ if she does not buy the product. Consumers have unit demands, i.e., they consume at most one unit of the product. By maximizing her utility, the consumer chooses one unit of the substitutive products available from the competitors - the global firm and the imitator. The total market sizes are denoted by N_1 and N_2 for the home and emerging markets, respectively. We assume that the demand is independent across the two markets.

1.3.2 Decisions

We elaborate on the decisions by the global firm and the imitator relating to manufacturing, sourcing, pricing and quality of product offered in both the markets. First consider the global firm.

Global Firm's Decisions

A production process consists of a number of subprocesses (e.g., corresponding to making one component) that all contribute to the quality. For sake of simplicity, we assume that the process can be divided into infinitely many small subprocesses that each equally contributes to the quality. The global firm thus chooses which subprocesses to perform in its foreign affiliate and transfers them. This choice does not impact its quality q. This transfer decision is captured by the global firm's decision to transfer x fraction of the total process technology to its foreign affiliate.[1] The global firm's decisions are thus (i) what fraction to transfer: $x \in [0, 1]$; (ii) whether to source from its foreign affiliate for its home market demand: $s \in \{1, 2\}$, where $s = 1$ represents that the global firm uses its home affiliate to produce everything for its demand in the home market; $s = 2$ represents that the global firm transports and exports the components (x) made by its foreign affiliate to its home affiliate and assembles them with the locally-made components $(1 - x)$ for its demand in the home market; and (iii) what prices to charge in both the markets: $p_{Gi} \in [0, +\infty)$, $i = 1, 2$.

Imitator's Decisions

The imitator potentially imitates process technology from the global firm. The more process technology the imitator copies, the higher its product quality. The imitator's decisions are (i) how much process technology, $y \in [0, x]$, to imitate; and (ii) what prices to charge in both the markets: $p_{Li} \in [0, +\infty)$, $i = 1, 2$. $y = 0$ is equivalent to non-entry. Its quality is then $q_L(y)$. This is upper-bounded by x since the imitator obtains the highest possible quality if it spends resources to imitate and apply all the process technology of the global firm that is locally available. We assume a linear form: $q_L(y) = q \cdot y$. The imitator achieves the same quality as the global firm's only when all process technology is learnt from the latter.

1.3.3 Costs

The decisions taken by both the firms are driven by the relative cost structures of both players in the home and emerging markets. Firms' cost structures in either market are explained in the

[1] We make this assumption since in our field study, assembly of the product takes place in stages and the transfer decision is to move x fraction of the stages to emerging market. Each stages involved are distinct component or sub-assembly.

following, and validated in Appendix C using field data obtained from an equipment manufacturer in U.S.A.

Product Cost Structures in Emerging Market

The global firm's unit product cost in the emerging market has three components: the production cost of x fraction of production process transferred, the production cost of $1-x$ fraction of production process remaining in its home affiliate, and the import (transportation) costs of the latter. As $1-x$ fraction of process is performed by the home affiliate, transport of components delivered by these subprocesses to the foreign affiliate is necessary. The sum of the first two components are captured by a function $c(x)$, which decreases as more subprocesses (x) are performed by the foreign affiliate, considering the fact that the factor (labor and materials) costs in the emerging market are usually lower than those in the home market. The import cost is modeled by a function $c_{t2}(x)$, which decreases as more process technology is transferred. We assume the following forms for the above cost functions: $c(x) = (c_0 + \triangle c) \cdot (1-x) + c_0 \cdot x$, and $c_{t2}(x) = c_{t2} \cdot (1-x)$. Here, $\triangle c$ measures the factor-cost difference between the two markets. Note that $x = 0$ implies the global firm keeps all production processes in its home country. In this case, the global firm's unit production cost is $c(0) = c_0 + \triangle c$. At the other extreme, if all production processes are transferred to the emerging market, $x = 1$. In this case, $c(1) = c_0$. The global firm's unit product cost in the emerging market is thus:

$$c_{G2}(x) = c(x) + c_{t2}(x) \tag{1.1}$$

The imitator's unit product cost in the emerging market are independent of y, denoted by c_{L2}, because the imitator performs all production processes locally, including those that are not learnt from the global firm. We recognize the fact that the imitator operates in a familiar environment, so it incurs lower costs in manufacturing and distributing the products compared to the global firm. This advantage is captured by a difference, Δ_2, and the imitator's unit product cost in the emerging market is thus: $c_{L2} = c(1) - \Delta_2$. Thus, Δ_2 measures the cost advantage of the imitator if the global firm fully transfers all technology $x = 1$ to its foreign affiliate, and the affiliate has cost c_0 in the emerging market.

Product Cost Structures in Home Market

The global firm's unit product cost in the home market depends on its sourcing decision. If it chooses to source locally ($s = 1$), its unit product cost is its home affiliate's unit production cost, $c(0)$. If it chooses to source from its foreign affiliate ($s = 2$), its unit product cost has three components: the production cost of $1-x$ fraction of production process remaining in the home affiliate, the production cost of x fraction of production process transferred to the foreign affiliate, and the import costs of the latter. The import cost is modeled by a function $c_{t1}(x)$, which increases as more subprocesses (x) are performed by the foreign affiliate. It is assumed to take the following form: $c_{t1}(x) = c_{t1} \cdot x$. The global firm's unit product cost in its home market is thus:

$$c_{G1}(x, s) = \begin{cases} c(0) & \text{if } s = 1 \text{, i.e., the global firm sources locally} \\ c(x) + c_{t1}(x) & \text{otherwise} \end{cases} \tag{1.2}$$

The imitator's unit product cost in the home market has three components: its unit production cost c_{L2}, the import cost c_{t1}, and its distribution disadvantage Δ_1, due to its poor distribution channel in this market, and/or extra duties or tariffs imposed by the government of home market on the imitative product. The imitator's unit product cost likewise in the global firm's home market is thus: $c_{L1} = c_{L2} + c_{t1} + \Delta_1$.

Technology Costs

Here, we describe separately the costs of the global firm and the imitator. The imitator faces costs of technology imitation, and the global firm faces costs of technology transfer.

Imitation cost. In order to imitate the technology for making the product $(y > 0)$, the imitator undertakes an investment, denoted by fixed cost K. Empirical evidence indicates that technology imitation is a complex and costly activity (Mansfield et al. 1981, Galbraith 1990). Imitation costs comprise of all costs of developing and introducing the imitative product, including applied research, product specification, pilot plant or prototype construction, investment in plant and equipment (Mansfield et al. 1981). The imitation cost here thus include expenses incurred in setting up all production processes of the product, and are therefore assumed to be fixed, and independent of the quality level of the imitative product. The imitation cost may also include the costs of inventing around or developing a non-infringing imitation (Gallini 1992), and it thus increases with the strength of IP protection, stemming from stricter uniqueness requirement (Glass and Saggi 2002). Empirical evidence also shows that patents raise imitation costs (Levin and Reiss 1988).

Transfer cost. Transfer is the replication of manufacturing capabilities, and involves the shift of codified knowledge (e.g., blueprints, formulas, and management techniques) and tacit knowledge (e.g., know-how and information gained from experience) (Teece 1977). The cost thus incurred is assumed to be negligible, and set to zero.

Market Covered Condition

For simplicity, we assume that the production cost is sufficiently low such that in equilibrium, all consumers will buy a product from either a monopolist or one of the duopolists, i.e., markets are covered.

Assumption 1. *The cost structure satisfies*

$$c_0 \leq \overline{c_0} \tag{1.3}$$

where, $\overline{c_0} = \min\left[\left(2\alpha_1 - \beta_1\right)q - \max\left(\triangle c, c_{t1}\right), \left(2\alpha_2 - \beta_2\right)q - \left(\triangle c + c_{t2}\right)\right]$.

1.3.4 The Game Setup

As imitation is local and can only occur after technology has been transferred, we model technology transfer and imitation as a sequential process. We consider three stages: technology transfer, imitation, followed by price competition. The global firm is a Stackelberg leader, and the local imitator is a follower. Each player has perfect information about its rival and the distribution of consumers' tastes.

In stage I, the global firm decides how much technology to transfer and where to source, $a_G = (x, s) \in [0,1] \times \{1,2\}$. In stage II, after observing a_G, the potential imitator decides whether to enter or not, and if entering chooses technology level $a_L = y \in (0, x]$, which determines its quality level. Because entry incurs a fixed cost K, a potential imitator decides to enter only if profits exceed the entry cost. In the last stage, firms observed each other's decision, and compete in prices (if the prospective imitator enters) given respective qualities. Then either the global firm sets prices as a monopolist or firms choose prices simultaneously in both markets contingent on the established technology levels and sourcing decision: $\left(p_{G1}(a), p_{G2}(a)\right) \in [0, +\infty) \times [0, +\infty)$, and $\left(p_{L1}(a), p_{L2}(a)\right) \in [0, +\infty) \times [0, +\infty)$, where $a = (a_G, a_L)$.

Imitator Does Not Enter

If the imitator does not enter ($y = 0$), the global firm sets prices: $p^M_{Gj} = \alpha_j q$, which maximizes its monopoly profit in market $j = 1, 2$:

$$\Pi^M_{Gj}(a_G) = \left(p^M_{Gj} - c_{Gj}(x, s)\right) N_j \tag{1.4}$$

Imitator Enters

If the imitator enters ($y > 0$), given prices $p_G \doteq (p_{G1}, p_{G2})$, and $p_L \doteq (p_{L1}, p_{L2})$, the firms' market demands in market $j = 1, 2$ are: $Q_{Gj} = \frac{\beta_j - \max\left(\widehat{\theta}_j, \alpha_j\right)}{\beta_j - \alpha_j} N_j$, and $Q_{Lj} = \frac{\min\left(\widehat{\theta}_j, \beta_j\right) - \alpha_j}{\beta_j - \alpha_j} N_j$, where $\widehat{\theta}_j = \frac{p_{Gj} - p_{Lj}}{q - qy}$ is a marginal consumer who is indifferent in buying the global firm's and imitative products. Therefore, the consumers with $\theta_j \geq \max\left(\widehat{\theta}_j, \alpha_j\right)$ buy the global firm's (high quality) product, and the consumers with $\theta_j < \min\left(\widehat{\theta}_j, \beta_j\right)$ buy the imitator's (low quality) product. The price equilibrium can then be characterized by the cases in which the imitator's product is preempted from the market, i.e., only the global firm's product is sold ($\widehat{\theta}_j \leq \alpha_j$); the global firm's product is preempted from the market, i.e, only the imitator's product is sold ($\widehat{\theta}_j \geq \beta_j$); or both products are present in the market ($\beta_j < \widehat{\theta}_j < \alpha_j$). The firms' payoffs in market j are (if the imitator enters): $\Pi_{Gj}\left(p_{Gj}, p_{Lj}, a\right) = \left(p_{Gj} - c_{Gj}\left(x, s\right)\right) \frac{\beta_j - \max\left(\frac{p_{Gj}-p_{Lj}}{q-qy}, \alpha_j\right)}{\beta_j - \alpha_j} N_j$, and $\Pi_{Lj}\left(p_{Gj}, p_{Lj}, a\right) = \left(p_{Lj} - c_{Lj}\right) \frac{\min\left(\frac{p_{Gj}-p_{Lj}}{q-qy}, \beta_j\right) - \alpha_j}{\beta_j - \alpha_j} N_j$.

Taken together, the global firm's payoff function is:

$$\Pi_G\left(p_G, p_L, a\right) = \begin{cases} \sum_{j=1}^{2} \Pi_{Gj}^{M}\left(a_G\right) & \text{if } y = 0 \\ \sum_{j=1}^{2} \Pi_{Gj}\left(p_{Gj}, p_{Lj}, a\right) & \text{otherwise} \end{cases}$$

The imitator incurs a fixed cost K if it enters (i.e., $y > 0$). Because it is assumed that the imitator is only able to copy the transferred technology, it is equivalent to assume that it incurs an infinite amount of imitation costs if $y > x$. The imitator's payoff function is thus:

$$\Pi_L\left(p_G, p_L, a\right) = \begin{cases} 0 & \text{if } y = 0 \\ \sum_{j=1}^{2} \Pi_{Lj}\left(p_{Gj}, p_{Lj}, a\right) - K & \text{if } 0 < y \leq x \\ -\infty & \text{otherwise} \end{cases}$$

Denote the firms' stage III Bertrand sub-game equilibrium prices in the case of the imitator's entry by: $p_G^*\left(a\right) = \left(p_{G1}^*\left(a\right), p_{G2}^*\left(a\right)\right)$ and $p_L^*\left(a\right) = \left(p_{L1}^*\left(a\right), p_{L2}^*\left(a\right)\right)$, which are given by:

$$\begin{cases} p_G^*\left(a\right) \in \arg\max\limits_{p_G} \Pi_G\left(p_G, p_L^*\left(a\right), a\right) \\ p_L^*\left(a\right) \in \arg\max\limits_{p_L} \Pi_L\left(p_G^*\left(a\right), p_L, a\right) \end{cases}$$

The firms' corresponding stage III Bertrand sub-game equilibrium profits $\Pi_G^*\left(a\right)$ and $\Pi_L^*\left(a\right)$ are:

$$\Pi_i^*\left(a\right) = \sum_{j=1}^{2} \Pi_{ij}^*\left(a\right) = \sum_{j=1}^{2} \Pi_{ij}\left(p_{Gj}^*\left(a\right), p_{Lj}^*\left(a\right), a\right)$$

where $i = G, L$.

The imitator's best response $a_L^*\left(a_G\right)$ at stage II is then given by:

$$a_L^*\left(a_G\right) \in \arg\max_{a_L \in [0,x]} \Pi_L^*\left(a_G^*\left(a_L\right), a_L\right)$$

The global firm's sub-game perfect equilibrium strategy a_G^* at stage I is given by:

$$a_G^* \in \underset{a_G \in [0,1]\times\{1,2\}}{\arg\max} \; \Pi_G^*\left(a_G, a_L^*\left(a_G\right)\right)$$

The equilibrium analysis of the model will provide us insights on how the global firm's technology transfer decision and corresponding sourcing strategy depend on the imitator's strategic reaction and market, cost structures. If the imitator chooses to enter, it competes for share in the emerging market, and if is aggressive, may also grab share in the home market by exporting. Confronting this imitator, the global firm needs to assess deterrence (the firm is a monopoly), accommodation (the firm and the competitor co-exist in the market(s)) as well as surrenderence (the firm gives up the whole market(s)) strategies by controlling the amount of technology to transfer and pricing properly in each market.

The global firm's technology transfer decision is examined along two possible dimensions. The first dimension is whether the imitator poses threats to the global firm's home market in addition to the local market. The second dimension is whether the product characteristics and import cost structure prevent the global firm from transporting its goods among its affiliates. We characterize the global firm's optimal strategy in the absence of imitator's threats to home market in §1.4, and the case of imitator's threats in §1.5. In each case, two sub-cases arise, depending on whether the global firm sources from the emerging market or not.

1.4 No Import of Imitative Product to Home Market Allowed

This is the situation where the IP protection in the home market is strictly enforced and no imitative product is allowed to be sold. The government of the global firm's home market can issue an injunction to ban the imitators' imports and impose stiff penalties by law. For example, Chinese router vendor Huawei Technologies was blocked in 2003 from distributing software and user manuals related to Cisco Systems software in the U.S. (*InfoWorld* 2003). The global firm is thus a monopoly in home market. The imitator's entry decision depends on its profits solely from emerging market. We solve the game by backward induction.

1.4.1 Price Decision (Stage III): Pricing as an Instrument to Preempt Imitative Product

If the imitator does not enter, the global firm is also a monopoly in the emerging market. In the following, we discuss the Bertrand equilibrium outcomes if the imitator enters the emerging market, contingent on established technologies x and y. We will show that prices can be used as an instrument to preempt the imitator's product from the market, but not always, especially when a high amount of technology is transferred. Let

$$x_{20} \doteq \frac{c_{L2}}{\alpha_2 q}, x_{21} \doteq 1 - \frac{c_{L2} - c_0 + [q - q_L(y)](2\alpha_2 - \beta_2)}{\triangle c + c_{t2}}, x_{22} \doteq 1 - \frac{c_{L2} - c_0 + [q - q_L(y)](2\beta_2 - \alpha_2)}{\triangle c + c_{t2}}$$

We then have:

Lemma 1. *Bertrand equilibrium:*

Tech Transfer:	$x \in [0, x_{20}]$	$x \in (x_{20}, x_{21}]$	$x \in (x_{21}, x_{22}]$	$x \in (x_{22}, 1]$
Pricing Strategy:	*Monopoly Pricing*	*Deter Pricing*	*Accommodate Pricing*	*Surrender Pricing*
Equil. Prices:	$\frac{\partial p^*_{G2}(a)}{\partial x} \geq 0,$	$\frac{\partial p^*_{G2}(a)}{\partial y} \leq 0,$	$\frac{\partial p^*_{L2}(a)}{\partial x} < 0,$	$\frac{\partial p^*_{L2}(a)}{\partial y} > 0$
Equil. Profits:	$\frac{\partial \Pi^*_{G2}(a)}{\partial x} > 0,$	$\frac{\partial \Pi^*_{G2}(a)}{\partial y} \leq 0,$	$\frac{\partial \Pi^*_{L2}(a)}{\partial x} < 0,$	$\frac{\partial \Pi^*_{L2}(a)}{\partial y} > 0$

Note: The firms' equilibrium prices and profits are shown in Appendix A.

Because the foreign affiliate's unit cost c_{G2} is independent of the sourcing decision s (see equation (1.1)), the above equilibrium prices are independent of the global firm's sourcing decision (s). As more technology (x) is transferred, the market equilibrium structure transitions from the global firm as a monopolist, to the two firms as duopolists, and ultimately to the imitator acting as a monopolist. Lemma 1 shows that the firms may use prices as an instrument to preempt the competitor's product from the market. A firm may also be better off to accommodate the competitor's product due to the competitor's cost or quality advantage.

We use a numerical example to illustrate this, as shown in Figure 1.1. In this example, $q = 1$, $\alpha_1 = 4$, $\beta_1 = 5$, $\alpha_2 = 4$, $\beta_2 = 4.5$, $N_1 = 500$, $N_2 = 10$, $\triangle c = 1$, $c_0 = 2$, $\Delta_1 = 0.8$, $\Delta_2 = 1$, $c_{t1} = 0.5$, $c_{t2} = 0.5$ (Note that this set of parameter values is applied in all the subsequent examples to facilitate comparisons). Assume that the imitator maximizes its quality, i.e., $y = x$. In this case, the critical technologies at which the market equilibrium structure switches are $x_{20} = \frac{c_{L2}}{\alpha_2 q}$, $x_{21} = 1 - \frac{c_0 - c_{L2}}{(2\alpha_2 - \beta_2)q - \triangle c - c_{t2}}$, $x_{22} = 1 - \frac{c_0 - c_{L2}}{(2\beta_2 - \alpha_2)q - \triangle c - c_{t2}}$. For $0 \leq x \leq x_{20}$, the imitator's quality is so low that even the least-value consumer (α_2) will not buy the imitative product

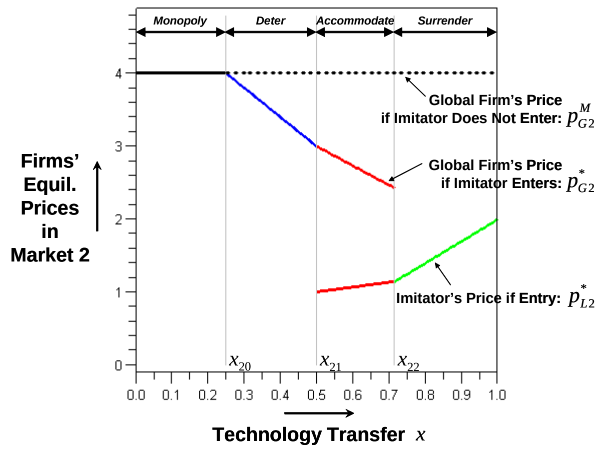

Figure 1.1: Equilibrium Prices in Emerging Market

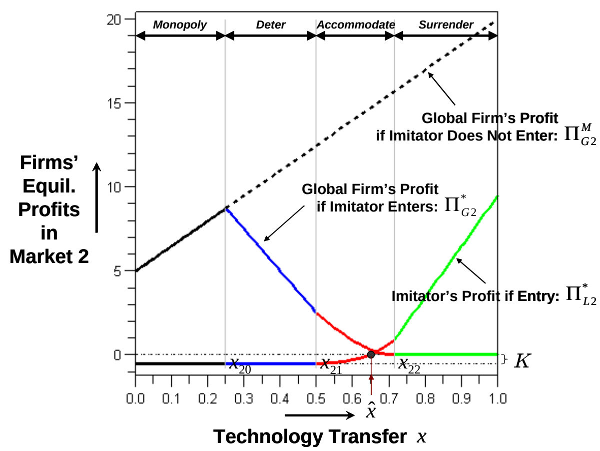

Figure 1.2: Equilibrium Profits in Emerging Market

priced at unit production cost, i.e., $\alpha_2 q_L(x) \leq c_{L2}$. The existence of the competitor has no impact on the price decision of the global firm who will set an optimal monopoly price. This region is shown as *Monopoly* in Figure 1.1. For $x_{20} < x \leq x_{21}$, the imitative product has positive utilities for some low-income consumers, but the global firm is able to preempt the sale of the imitative product (i.e., the imitator is not selling in equilibrium), by setting a price aggressively so that even the least-value consumer does not buy the imitative product priced at unit product cost. This pricing strategy is referred to as "Deter Pricing". The global firm is a natural monopolist. This region is shown as *Deter* in Figure 1.1. For $x_{21} < x \leq x_{22}$, the quality of the imitative product improves to such a level, that the global firm is better off to accommodate the imitative product, and we then have a duopoly market. This pricing strategy is referred to as

"Accommodate Pricing". This region is shown as *Accommodate* in Figure 1.1. For $x_{22} < x \leq 1$, the quality of the imitative product has improved to such a level that the imitator becomes a monopolist due to its production cost advantage (i.e., the global firm surrenders the market). By charging a price such that even the highest-value consumer does not buy from the foreign affiliate the high quality product priced at unit product cost, the imitator enjoys a natural monopolist position in emerging market. This pricing strategy is referred to as "Surrender Pricing". This region is shown as *Surrender* in Figure 1.1.

From $\frac{\partial \Pi^*_{L2}(a)}{\partial y} > 0$ (see Lemma 1), we know that the imitator will raise its product quality to the global firm's as close as possible. This intensifies the competition between the firms and undercuts the global firm's equilibrium price. As shown in Figure 1.1, the global firm's equilibrium price stays the same (the monopoly price) for the region $x \in [0, x_{20}]$, and starts to decrease beyond x_{20}. Above this level of transfer, the imitator creates threats to the global firm. But the imitator's equilibrium price increases because the imitator's quality improvement effect dominates negative effects of intensified price competition. Figure 1.2 shows how the equilibrium profits in the emerging market change with x. Firms' profits from the emerging market in two cases are illustrated. One case in which the imitator does not enter, and the global firm thus reaps monopoly profit $\Pi^M_{G2}(x, s)$. The other case in which the imitator enters with $y = x$, and the firms' equilibrium profits are then $\Pi^*_{G2}((x, s), x)$ and $\Pi^*_{L2}((x, s), x)$, respectively. All these profits in the emerging market are independent of the global firm's sourcing decision s. As shown in Figure 1.2, the global firm's monopoly profit increases as more technology is transferred. If the imitator enters, the global firm's equilibrium profit reaches a maximum level at $x = x_{20}$, and the imitator's equilibrium profit rises from x_{21} and increases to its maximum level at $x = 1$. Although the global firm's unit production cost decreases as more manufacturing is localized and factor cost differences leveraged, its profit margin decreases with potential competition and its profit erodes. One the other hand, the imitator's profit increases on account of both profit margin and market share increases.

1.4.2 Imitator's Entry Decision (Stage II): Whether to Enter and How Much Technology to Imitate

The imitator decides to enter if its profits exceed the entry cost, or $\Pi^*_{L2}(a) > 0$, where,

$$\Pi^*_{Lj}\left(\left(x,s\right),y\right) = \begin{cases} 0 & x \leq x_{j1} \\ \frac{\left[-c_{Lj}+c_{Gj}(x,s)+(q-q_L(y))\left(\beta_j-2\alpha_j\right)\right]^2}{9(q-q_L(y))}\frac{N_j}{\beta_j-\alpha_j} - K & x_{j1} < x \leq x_{j2} \\ \left[p^*_{Lj}\left(a\right) - c_{Lj}\right]N_j - K & x_{j2} < x \leq 1 \end{cases}$$

where $j = 1, 2$. Note that the global firm's sourcing decision affects the imitator's stage III equilibrium profit Π^*_{L1} in home market (if its import to the home market is allowed) because the sourcing decision impacts the global firm's cost structure $c_{G1}(x,s)$ in home market and in turn the firms' equilibrium profits in home market, but does not affect the imitator's profit Π^*_{L2} in emerging market. We show in the following Lemma 2 that the imitator enters only when sufficient technology has been transferred.

Lemma 2. *The imitator's best response function is:*

$$y^*\left(x,1\right) = y^*\left(x,2\right) = \begin{cases} 0 & \textit{if } x \leq \widehat{x} \\ x & \textit{otherwise} \end{cases} \tag{1.5}$$

i.e., the imitator decides to enter emerging market only if the global firm transfers a technology $x > \widehat{x}\left(s\right)$, where, the "critical technology stock" $\widehat{x}\left(s\right)$ solves:

$$\Pi^*_{L2}\left(\left(\widehat{x},s\right),\widehat{x}\right) = K$$

with $\widehat{x}\left(1\right) = \widehat{x}\left(2\right) = \widehat{x}$. $\widehat{x}$ has the following properties: $\partial\widehat{x}/\partial K \geq 0$, $\partial\widehat{x}/\partial q \geq 0$, $\partial\widehat{x}/\partial\Delta_2 \leq 0$, $\partial\widehat{x}/\partial c_{t2} \leq 0$, and $\partial\widehat{x}/\partial\triangle c \leq 0$.

The global firm's sourcing decision s has no impact on the imitator's best response function, i.e., $y^*\left(x,1\right) = y^*\left(x,2\right)$ because the imitator's entry decision depends on its profits solely from the emerging market. Lemma 2 defines a "critical technology stock" $\widehat{x}$ below which the imitator will not enter because its profits from imitating any technology $x \leq \widehat{x}$ cannot recover its fixed investment K. As shown in Figure 1.2, the imitator starts to make positive profit beyond a transfer level denoted by $\widehat{x}$. Because of its cost advantage, the imitator will not position its product away from the global firm's in the case of entry, which is indicated by its increasing equilibrium profit in x (see Figure 1.2). It therefore fully copies technology from the foreign affiliate to maximize its profits, i.e., $y^*(x,s) = x$ in the case of entry. According to Lemma 2, higher the imitation cost, or higher the quality of the global firm's product, more difficult is the imitation (i.e., higher is the "critical technology stock"). Also, higher the cost advantage of the imitator, or higher the import cost to emerging market, or higher the factor-cost difference between the markets, easier is the imitation (i.e., lower is the "critical technology stock").

1.4.3 Global Firm's Technology Transfer Decision (Stage I): How Much Technology to Transfer under Threats of Imitation

Consider now the strategic behavior of the global firm at its technology transfer stage. We classify the outcomes of the global firm's transferred technology as a means of limiting the prospective imitator's choices. Because of discontinuity in the prospective imitator's best response function described by equation (1.5), the size of the fixed cost determines whether a deterrence or accommodation or surrenderence strategy is preferred by the global firm.

Given the imitator's best response (1.5), the global firm's profit given its strategy $a_G = (x,s)$ is then:

$$\Pi_G^*((x,s), y^*(x,s)) = \Pi_{G1}((x,s), y^*(x,s)) + \Pi_{G2}((x,s), y^*(x,s))$$

where, its profit in its home market:

$$\Pi_{G1}((x,s), y^*(x,s)) = \Pi_{G1}^M(x,s)$$

is its monopoly profit because of no threat from imitative products; and its profit in the emerging market is:

$$\Pi_{G2}((x,s), y^*(x,s)) = \begin{cases} \Pi_{G2}^M(x,s) & x \leq \widehat{x} \\ \Pi_{G2}^*((x,s), y^*(x,s)) & otherwise \end{cases}$$

i.e., if the global firm transfers technology less than the "critical technology stock" $\widehat{x}$, it reaps monopoly profit $\Pi_{G2}^M(x,s)$ because the imitator does not enter; otherwise, it obtains duopoly equilibrium profit $\Pi_{G2}^*((x,s), y^*(x,s))$. It should be noted that the global firm's profit $\Pi_{G1}^M(x,1)$ from its home market if it does not source from the emerging market is independent of x; otherwise, $\Pi_{G1}^M(x,2)$ is linearly increasing in x. Its profit $\Pi_{G2}((x,s), y^*(x,s))$ from the emerging market is independent of its sourcing strategy (s), and takes the form as shown in Figure 1.2.

High Import Cost

Note that the global firm's decision depends on whether sourcing from affiliate makes economic sense and factor cost differences outweigh transportation costs. Hence, if the import cost to home market is higher than the factor cost difference between the two markets (i.e., $c_{t1} \geq \triangle c$), then $c_{G1}(x) \geq c(0)$ for any x, i.e., the unit production cost of the product in home market by sourcing components from the foreign affiliate is <u>not</u> lower than if the product is fully locally made. Therefore, the global firm decides not sourcing from its foreign affiliate, i.e., $s^* = 1$. The global firm in such cases will always choose to deter the imitator's entry.

Proposition 1. *In the case of $\triangle c \leq c_{t1}$, the global firm's optimal technology transfer strategy is $x^* = \widehat{x}$, the imitator's entry is deterred, and the global firm sources for its home market all the demand locally. This results in a "Local Content" strategy.*

When sourcing from foreign affiliate is not economically feasible ($\triangle c \leq c_{t1}$), the global firm's profit in its home market $\Pi^M_{G1}(x, 1)$ is not relevant in determining how much technology to transfer, and the global firm simply maximizes its profits in emerging market and thus chooses $x^* = \widehat{x}$ in order to deter the imitator's entry, because the global firm's monopoly profits $\Pi^M_{G2}(x, 1)$ is not lower than its duopoly profits $\Pi^*_{G2}((x, 1), x)$ for any x (see Figure 1.2).

Proposition 1 reveals that if its product is costly to transport, the global firm will transfer limited technology, and adjust its pricing strategy to deter the imitator's entry no matter how low the imitation cost is. The global firm's equilibrium profit is thus determined by the "critical technology stock". Hence, both its optimal technology transfer x^* and equilibrium profit $\Pi^*_G((x^*, 1), x^*)$ increase with the imitation cost K. That is to say, strengthening IP protection will increase the incentives of the global firm to transfer more technology to the emerging economy. This confirms an empirical evidence of Branstetter et al. (2005). They show that strengthening IP protection increases the transfer of technology to multinational affiliates, using firm and affiliate-level data on U.S. multinationals.

Examples are the steel and chemical industries. Their relatively low share of labor costs compared with total costs, and high expense of transporting products hamper their globalization. Global firms duplicate their facilities in new economies in order to gain access to the emerging markets, and the foreign affiliates produce for the local markets only. For example, Dow Chemical serves many local markets by replicating in each of these countries its U.S. production facilities (Hanson et al. 2001). For this kind of industries, strengthening IP protection will motivate technology transfer.

Low Import Cost

In Proposition 2 next, we discuss the case where the global firm benefits from sourcing from its foreign affiliate, i.e., $\triangle c > c_{t1}$, and $s^* = 2$. Products allowing economic sourcing have high value-to-weight or value-to-volume ratios, or labor accounts for the bulk of these products' production costs, such as, consumer electronics, apparel, jewelry, and automotive. For example, Ford and General Motors have production facilities in Brazil and Thailand, building vehicles not just for those local markets but for the broader regional markets of South America and Southeast Asia, respectively (Hanson et al. 2001). Daimler-Chrysler AG has plans to build subcompacts in China that would be exported and sold in the U.S. (*Wall Street Journal* 2005a). Likewise, manufacturers of consumer goods, like Motorola, Glanz and P&G, use their production facility in China to serve not only Chinese market but also consumers throughout the world (PricewaterhouseCoopers 2005).

A global firm in these industries faces a trade-off between capturing profit from the emerging market by transferring a low amount of technology to deter imitation, and saving high costs for serving its home market by transferring a high amount of technology. With the sourcing possibility, the global firm's profit from its home market $\Pi_{G1}^{M}(x, 2)$ is now determined by the amount of technology transferred: the more technology is transferred, the more costs the global firm saves and higher its profit from its home market. The global firm's total profit $\Pi_G^*((x, s), y^*(x, s))$ from both markets in this case takes the following form: linear increasing for $x \leq \widehat{x}$, and convex for $x > \widehat{x}$. Figure 1.3 shows an example when $\widehat{x} = 0.8$. The trade-off is measured by the following critical market size ratio in case of no import:

$$n \doteq \frac{\alpha_2 q - (\triangle c + c_{t2})(1 - \widehat{x}) - c_0}{(\triangle c - c_{t1})(1 - \widehat{x})}$$

The critical ratio n is increasing in the "critical technology stock" $\widehat{x}$. Thus, a high critical ratio n implies a high attraction of profit from the emerging market. We then have the following global firm's optimal strategy:

Proposition 2. *In the case of $\triangle c > c_{t1}$:*

Market Size Ratio:	$\frac{N_1}{N_2} < n$	$\frac{N_1}{N_2} \geq n$
Technology Strategy:	$x^* = \widehat{x}$	$x^* = 1$
Pricing Strategy:	*"Deter Pricing"*	*"Surrender Pricing"*
Operations Strategy:	*"Global Platform"*	*"Export Platform"*

According to Proposition 2, when the emerging market is relatively small, i.e., $N_1/N_2 \geq n$, the global firm transfers all production processes to the foreign affiliate which is used as an export base. Namely, the foreign affiliate produces only for home market, and emerging market is surrendered to the imitator, which is termed "Export Platform" strategy. Examples are luxury-goods companies, e.g., Valentino, Prada, etc., the number of consumers of which in those low-wage countries is still tiny. These high end fashion goods firms produce their most exclusive lines in developing countries, e.g., China, Turkey, etc., and then ship products solely to developed countries (*Wall Street Journal* 2005b). This is also consistent with empirical results of Hanson et al. (2001). When the emerging market is relatively big, the foreign affiliate is oriented toward both the local and export markets ("Global Platform"), but the global firm transfers limited technology, and keeps some production processes in its home country. This deters imitation and the global firm starts to reap profits from the emerging market. Doing this is more attractive than the extra cost savings for catering to its home market with transfer of higher level of technology to emerging market. The following proposition states how the critical market size ratio n changes with the imitation cost, K:

Proposition 3. *The critical market size ratio satisfies $\partial n/\partial K > 0$.*

Proposition 3 shows that higher the imitation cost (or stronger the IP protection strength), less likely the global firm is willing to transfer a high amount of technology, i.e., the global firm will switch from transferring full technology ("Export Platform") to partial technology ("Global Platform"). There exists a critical value of imitation cost, $\widehat{K}$, above which the global firm deters the imitator's entry. Rather than focus on home market for sourcing from foreign affiliate, the focus shifts to capture emerging market. This implies that the global firm is better off to deter the imitator's entry, by transferring the bare minimum technology $x = \widehat{x}$, and allowing less imitation.

The global firm either transfers all technology to maximally reduce costs in serving its home market; or transfers just the "critical technology stock" to deter imitation, keep competitors away, and reap the highest possible profits from the emerging market. In other words, as long as the global firm allows the imitator's entry, the global firm transfers full technology, allowing full technology imitation. Thus emerging market is not split - it is either given up, and $x = 1$, or fully covered with minimally required transfer $\widehat{x}$.

We illustrate the propositions using a numerical example. Figure 1.4 shows the sensitivity of critical ratio n with increasing imitation cost K. Figure 1.5 depicts the corresponding optimal technology to transfer, x^*, as a function of K. As the IP protection strength improves, the globalization degree increases. The foreign affiliate is oriented toward both the local and export

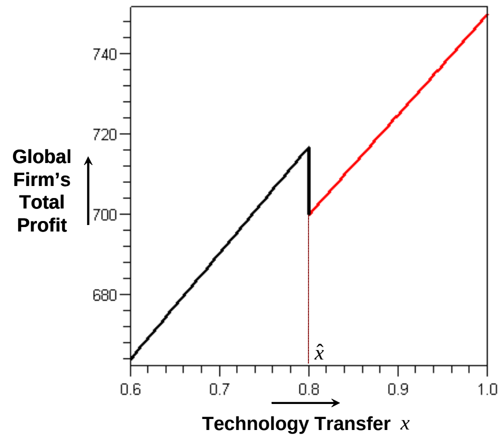

Figure 1.3: Global Firm's Total Profit from Both Markets

markets and serves global needs. However, less technology is transferred ($\widehat{x} < 1$). In the case of deterrence, the transferred technology $\widehat{x}$ increases with higher protection and imitation cost K. Note beyond $\widehat{K}$, the deterrence strategy now dominates to capture the emerging market fully and serve as source for home market. The global firm's optimal technology transfer strategy in Figure 1.5 can be explained by the profit changes in Figure 1.6. The global firm makes the deterrence-surrenderence decision by balancing between its profit loss in its home market and its profit gain from emerging market, when transferring limited technology $\widehat{x}$. If the former exceeds the latter, the global firm chooses to transfer full technology, limited technology $\widehat{x}$ otherwise. As shown in Figure 1.6, the difference increases with K, and is equal to zero at $K = \widehat{K}$. Therefore, for $K < \widehat{K}$, the global firm's equilibrium profit is independent of imitation cost K, and the imitator's profit is decreasing with K. For $K \geq \widehat{K}$, the global firm's equilibrium profit is increasing with the imitation cost K because more technology ($\widehat{x}$) will be transferred as imitation cost increases.

It also can be shown that the critical market size ratio n is decreasing in Δ_2. This implies that stronger is the imitator's cost advantage, more likely the global firm transfers a high amount of technology and surrenders the emerging market to the imitator's entry. Also, the critical market size ratio n is increasing in q, c_{t1}, and decreasing in c_{t2}, $\triangle c$. These are discussed in our comparative study in Appendix B.

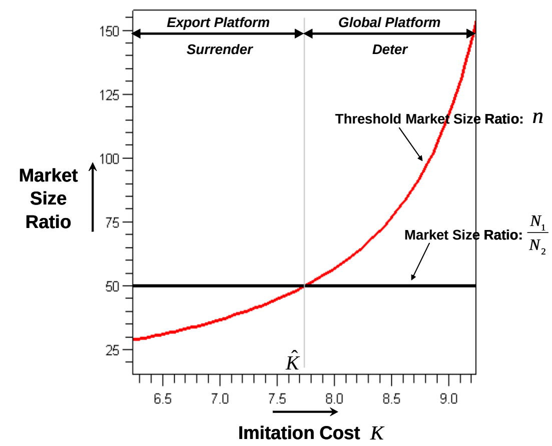

Figure 1.4: Threshold Market Size Ratio: Sensitivity to K

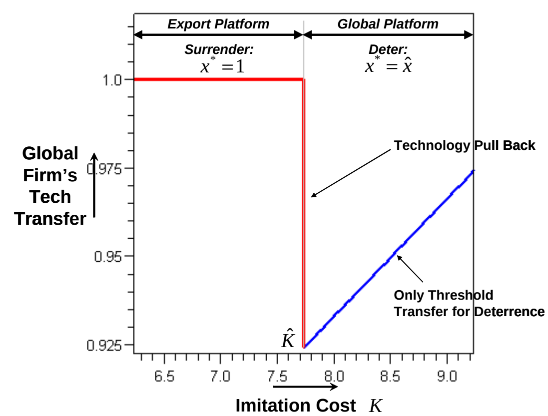

Figure 1.5: Optimal Technology Transfer Level: Sensitivity to K

1.5 Import of Imitative Product to Home Market Allowed

Lawsuits against IP infringements are usually complicated and consume significant managerial attention and money. Even in the most developed countries, they have proved difficult to win. As a result, imports of imitative products have continued for years before the technology-laden cases are settled by courts (Levin et al. 1987). In this section, we relax the above assumption that the IP protection in home market is perfect, and recognize that the import of imitative product to home market occurs, though is not legal.

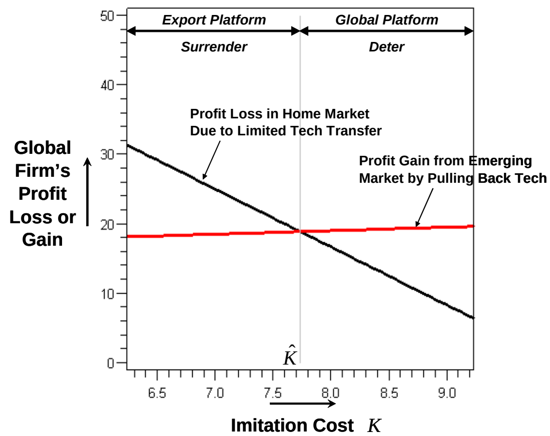

Figure 1.6: Profit Loss vs. Gain: Sensitivity to K

1.5.1 Price Decision (Stage III): Pricing as an Instrument to Preempt Imitative Product

The equilibrium prices in the home market are similar to those in the emerging market, but with different critical technologies, x_{10}, x_{11}, and x_{12} at which the market equilibrium structure switches. The equilibrium prices are now functions of the global firm's sourcing strategy because the sourcing strategy determines the global firm's unit cost c_{G1} in its home market (see equation (1.2)). See Lemma A2 in Appendix A for details.

1.5.2 Imitator's Entry Decision (Stage II): Import Possibility Makes Imitation Easier

The best response function of the imitator takes a similar form to Lemma 2, but the "critical technology stock" $\widehat{x}$ is replaced by $\widehat{x}^I(s)$ which is solved by:

$$\Pi^*_{L1}\left(\left(\widehat{x}^I(s), s\right), \widehat{x}^I(s)\right) + \Pi^*_{L2}\left(\left(\widehat{x}^I(s), s\right), \widehat{x}^I(s)\right) = K$$

i.e, the imitator decides to enter if the global firm transfers a technology $x > \widehat{x}^I(s)$. Contrary to §1.4.2, the "critical technology stock" $\widehat{x}^I(s)$ is now a function of the global firm's sourcing decision s because the imitator's entry decision now depends on its profits from both the markets. Compared with the no import case, the "critical technology stock" is lower: $\widehat{x}^I(s) < \widehat{x}$. This suggests that the the imitation is easier than in the no import case, given the same imitation cost. See Lemma A3 in Appendix A for details.

1.5.3 Global Firm's Technology Transfer Decision (Stage I): Import Possibility Induces Lower Technology Transfer

High Import Cost

In the case that the factor-cost difference is less than the transportation cost, i.e., $\triangle c \leq c_{t1}$, the global firm will not source from its foreign affiliate, i.e., $s^{I*} = 1$. However, the imitator may now sell to home market. Similar to the no import case, the global firm transfers limited technology $x^{I*} = \widehat{x}^I(1)$, and adjusts its pricing strategy to deter the imitator's entry no matter how low the imitation cost is. Both the global firm's optimal technology transfer x^{I*} and equilibrium profit $\Pi_G^*\left(\left(x^{I*}, 1\right), x^{I*}\right)$ increase with the imitation cost K. But compared with the no import case, the global firm transfers less technology, i.e., $x^{I*} \leq x^*$.

Low Import Cost

If $\triangle c > c_{t1}$, the global firm will source from its foreign affiliate, i.e., $s^{I*} = 2$. The global firm will balance between capturing profit from the emerging market by transferring a low amount of technology, and saving high costs for serving its home market by transferring a high amount of technology. This trade-off is measured by the following critical market size ratio in the import case:

$$n^I \doteq \frac{1}{\left(\triangle c - c_{t1}\right)\left(x_{10} - \widehat{x}^I(2)\right)}\left[\alpha_2 q - \left(\triangle c + c_{t2}\right)\left(1 - \widehat{x}^I(2)\right) - c_0 - \frac{1}{N_2}\Pi_{G2}^*\left(\left(x_{10}, 2\right), x_{10}\right)\right]$$

where $x_{10} = \frac{c_{L1}}{\alpha_1 q}$ is a technology transfer level beyond which the imitator's exports pose threats in the global firm's home market. In the case that the imitator's entry is not deterred, whether the global firm sells in the emerging market depends on a critical imitator's distribution disadvantage:

$$\overline{\Delta}_1 \doteq \Delta_2\left(1 - \frac{\alpha_1 q}{\left(2\beta_2 - \alpha_2\right)q - \triangle c - c_{t2}}\right) + \alpha_1 q - \left(c_0 + c_{t1}\right)$$

Proposition 4. *In the case of $\triangle c > c_{t1}$:*

Market Size Ratio:	$\frac{N_1}{N_2} < n^I$	$\frac{N_1}{N_2} \geq n^I$
Technology Strategy:	$x^{I*} = \widehat{x}^I(2)$	$x^{I*} = x_{10}$
Pricing Strategy:	*"Deter Pricing"*	*"Accommodate Pricing" if* $\Delta_1 < \overline{\Delta}_1$, *"Surrender Pricing" otherwise*
Operations Strategy:	*"Global Platform"*	*"Global Platform" if* $\Delta_1 < \overline{\Delta}_1$, *"Export Platform" otherwise*

The global firm adopts a "Global Platform" strategy by deterring the imitator' entry if the market size ratio is below n^I. Otherwise, the global firm does not deter. When not deterring, whether the global firm adopts an accommodation or surrenderence strategy depends on the global firm's distribution advantage. If accommodation, the emerging market is split between the two firms, which results in a "Global Platform" strategy. Otherwise, the emerging market is all given up to the imitator, which results in an "Export Platform" strategy. Note that, although the global firm faces threats from the imitator in its home market, the imitator never serves the home market in equilibrium. This is explained in details as follows.

If the emerging market is large such that $\frac{N_1}{N_2} < n^I$, the global firm is better off to deter the imitator's entry by transferring the "critical technology stock" $\widehat{x}^I(2)$. Note that n^I is a function of Δ_1. There exists a critical $\widehat{\Delta}_1$ such that for $\Delta_1 < \widehat{\Delta}_1$, $\frac{N_1}{N_2} < n^I$ holds; otherwise $\frac{N_1}{N_2} \geq n^I$. Global firm's weak distribution advantage ($\Delta_1 < \widehat{\Delta}_1$) implies that the global firm cannot transfer full amount of technology. This is true even in the accommodation and surrenderence cases in order to protect its home market from the imitator. In this case, capturing the emerging market is more attractive than sourcing from foreign affiliate for its home market, the global firm will focus on the emerging market by deterring the imitator's entry. Likewise, if the imitator's cost advantage Δ_2 is weak such that $\frac{N_1}{N_2} < n^I$ is satisfied, the global firm is better off to deter the imitator's entry. Local firm's weak cost advantage implies that the global firm can transfer a relatively high amount of technology ($\widehat{x}^I(2)$) in order to deter the imitator's entry. This implies a high level profit from both markets by deterring.

If the emerging market is small such that $\frac{N_1}{N_2} \geq n^I$, the global firm will focus on sourcing by transferring a relatively high amount of technology $x_{10}\left(\geq \widehat{x}^I(2)\right)$, and will not deter the imitator's entry. Different from the no import case, if there is no deterrence, the global firm's pricing strategy depends on the strength of the global firm's distribution advantage. If the global firm's distribution advantage is relatively weak, i.e., $\Delta_1 < \overline{\Delta}_1$, the global firm transfers a relatively small amount of technology in order to protect its home market. This in turn lets

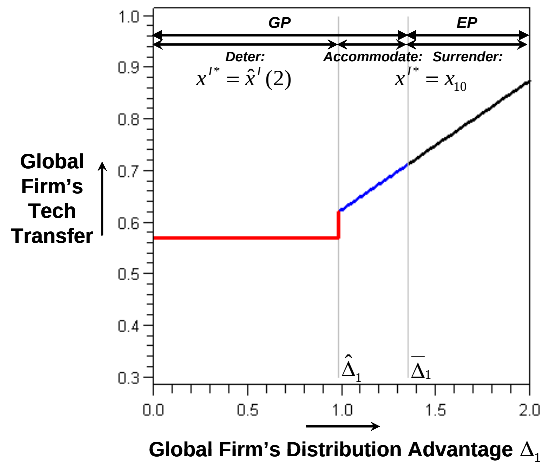

Figure 1.7: Optimal Technology Transfer Level: Sensitivity to Δ_1

the global firm capture some share of the emerging market, i.e., the global firm accommodates the imitator's entry into the emerging market. The emerging market is split between the two firms. This is contrary to the no import case, where the emerging market is never split. The global firm's strategy is thus "Global Platform". Otherwise, the global firm transfers a relatively high amount of technology, and the whole emerging market is surrendered to the imitator, which results in an "Export Platform"strategy.

It is easy to check that $\overline{\Delta_1}$ is increasing in Δ_2, decreasing in $\triangle c$, c_{t1} and c_{t2}. Stronger is the imitator's cost advantage Δ_2, or lower is the import cost to the home market c_{t1}, less likely the firm surrenders the emerging market. This is because all these induce the global firm to transfer less technology (x_{10}) when it chooses not to deter the imitation due to increased imitator's threats to the home market. Likewise, higher is the factor-cost difference $\triangle c$, or higher is the import cost to the emerging market c_{t2}, more likely the global firm surrenders the emerging market. This is because all these motivate the imitator to preempt the global firm's product (i.e., the critical technology level x_{22} at which the emerging market equilibrium structure changes to imitator being a monopoly is lower).

Similar to the no import case, when the imitation cost rises above a threshold, $\widehat{K}^I$, the global firm will switch from entry-accommodation to deterrence by transferring less technology.

Proposition 5. *The critical market size ratio satisfies $\partial n^I/\partial K > 0$.*

We illustrate Propositions 4 and 5 using a numerical example. Figure 1.7 shows the sensitivity of optimal technology transfer level x^{I*} with increasing distribution advantage Δ_1 of the global

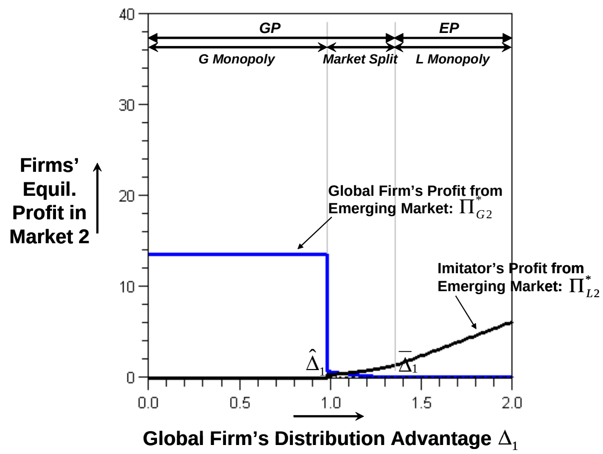

Figure 1.8: Firms' Equilibrium Profits in Emerging Market: Sensitivity to Δ_1

firm in the home market: x^{I*} is non-decreasing in Δ_1. Both firms' equilibrium profits increase with the global firm's distribution advantage Δ_1. The global firm's profit increases with Δ_1 due to its increasing profit from its home market. As more technology is transferred, the global firm is able to source more components from its foreign affiliate. The imitator's profit increases with Δ_1 due to its increasing profit from the emerging market. As more technology is transferred, the imitator's product quality improves and also more market share in emerging market is given up by the global firm. The firms' equilibrium profits from individual markets are shown in Figures 1.8 and 1.9 respectively. The global firm's profit in the emerging market is non-increasing in its distribution advantage (Figure 1.8), but its total profit from both markets is non-decreasing. Also note that the market is split between the two firms only when the global firm's distribution advantage is medium: $\Delta_1 \in \left[\widehat{\Delta}_1, \overline{\Delta}_1\right)$.

1.6 Comparative Study

In this section, we present our comparative study of the above two cases. We first discuss the differential impact of import possibility of imitative product to the home market. Define Δx^* as the technology restricted and is the difference of optimal technology transferring amounts between the two cases of no import, and import possibility, no matter sourcing is economic or not:

$$\Delta x^* \doteq x^* - x^{I*}$$

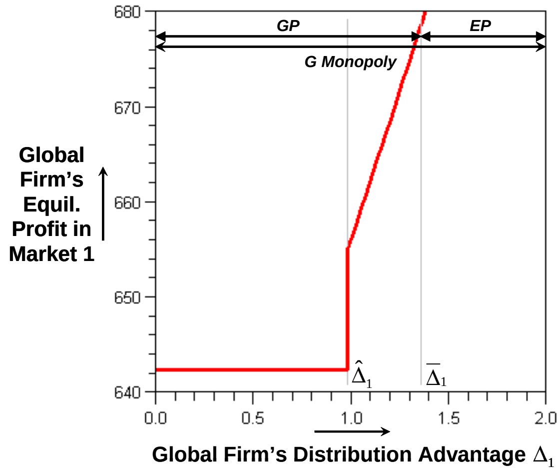

Figure 1.9: Global Firm's Equilibrium Profits in Home Market: Sensitivity to Δ_1

It captures the amount of technology withheld at home country by global firm for fear of attack in home market by imitator. We then have:

Proposition 6. *The following holds: (1) $\Delta x^* > 0$; (2) $\partial \Delta x^* / \partial q > 0$ for $K \leq \widehat{K}^I$, $\partial \Delta x^* / \partial q \leq 0$ for $K > \widehat{K}^I$, $\partial \Delta x^* / \partial \triangle c \geq 0$, $\partial \Delta x^* / \partial K \leq 0$, $\partial \Delta x^* / \partial c_{t1} \leq 0$, $\partial \Delta x^* / \partial \Delta_1 \leq 0$.*

$\Delta x^* > 0$ means that, no matter in the case of deterrence or accommodation or surrenderence, with the potential of import possibility, the global firm transfers less technology than in the no import case. Proposition 6 leads to the following interesting impacts of changing factors.

The impact of the global firm's product quality ($\partial \Delta x^* / \partial q$). Higher quality q will make the global firm less cautious in the case of deterrence ($K > \widehat{K}^I$), but more cautious with the import possibility in the case of non-deterrence ($K \leq \widehat{K}^I$). By cautious, we mean Δx^*, the technology restricted for fear of imports will increase. In the case of deterrence, the global firm's quality advantage makes it difficult for the potential imitator to enter the markets, which is only able to imitate a low amount of technology that the global firm transferred. In the case of non-deterrence, the global firm also faces a high quality imitative product (with cost advantage) if its own quality is high, and therefore strong threats from the imitator.

The impact of the factor-cost difference between the markets ($\partial \Delta x^* / \partial \triangle c$). Higher factor-cost difference $\triangle c$ will make the global firm more cautious. Higher factor-cost difference results in significant cost advantage of the imitator over the global firm (if the global firm does not move all production to emerging market). The other results in Proposition 6 are relatively intuitive. Factors that are not mentioned (c_{t2}, Δ_2) have no impact.

Proposition 7. *The critical market size ratio n for no import case is less than n^I for import case, i.e., $n < n^I$.*

According to Proposition 7, with the import possibility, the global firm has more incentives to deter the imitator's entry: the critical market size ratio n^I in case of import possibility is higher than the critical n in the no import case. Equivalently, the critical imitation cost $\widehat{K}^I$ of switching from non-deterrence to deterrence strategy in case of import possibility is lower than the critical $\widehat{K}$ in the no import case, i.e., $\widehat{K}^I < \widehat{K}$. Clearly, with the import possibility, the range of non-deterrence strategy decreases. More results on how the critical market size ratios change with different market and cost parameters are shown in Appendix B.

With our model, we are able to extend the insights from previous literature when the home market is vulnerable to imitators from emerging economies. From Propositions 6 and 7 and results in previous sections, the following conclusions can be made when the threats from imitative products to the home market do exist but are neglected by the global firm: (1) When the IP protection strength in the emerging market is relatively weak ($K \leq \widehat{K}$), the global firm loses both markets to the imitator. The global firm mistakenly transfers full technology in order to fully take advantage of sourcing opportunities. Even in the region where the global firm's optimal strategy is entry-accommodation, i.e., $K \leq \widehat{K}^I (< \widehat{K})$, the global firm transfers too much technology ($x^* = 1 > x^{I*} = x_{10}$) and therefore the imitator improves its product quality to a sufficient level such that the global firm is driven out of the home market as well. (2) When the IP protection strength is relatively strong ($K > \widehat{K}$), if the global firm's distribution advantage is weak enough ($\Delta_1 < \Delta c + \Delta_2 - c_{t1} - (1 - x_{22})(2\alpha_1 - \beta_1) q$), the imitator may still enter because of the additional profits from the home market that are out of the global firm's expectation, due to too much technology transfer ($x^* = \widehat{x} > x^{I*} = \widehat{x}^I(2)$). The two firms thus co-exist in both markets. The loss of both markets due to the ignored vulnerability of the home market shows the importance of our model.

1.7 Conclusions

1.7.1 Managerial Insights

This study of imitative competition was motivated by problems faced by several companies in diverse industries. In this paper, we examined the decision of a global firm considering transferring process technology to its foreign affiliate for manufacturing, selling in an emerging market, and/or sourcing for its home market. We assess potential vulnerability of both the

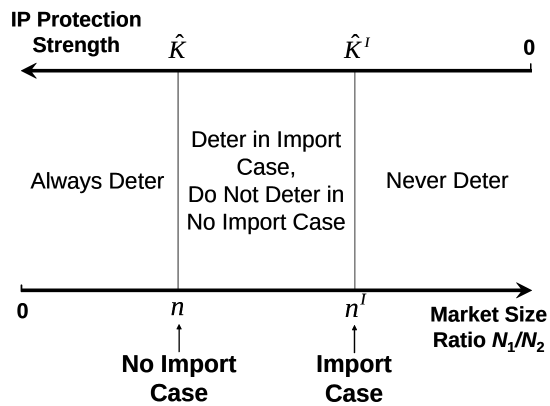

Figure 1.10: Impacts of Market Size and IP Protection Strength

emerging and home markets from imitators who can copy technology from the affiliates. The amount of process technology to transfer to foreign affiliates is used as a strategic instrument to deter or accommodate the imitator's entry into emerging market, and also a lever to leverage sourcing opportunities. Our model captures some of the key elements of market characteristics, cost structures and policies that drive or impede the firm's technology transfer and sourcing decisions. The models show conditions under which the imitator is either deterred or not, and the different roles played by the foreign affiliate as source for components for either market. Our paper complements the literature by jointly considering the global firm's technology transfer decision with its sourcing decision, and derive the following important managerial insights.

First, in an industry in which the costly transportation of intermediate and final goods from emerging markets to target markets is greater than savings in the factor-cost difference in emerging markets, the global firm deters the imitator's entry by transferring a low amount of technology, and adopts a "Local Content" strategy. Foreign affiliate of the global firm serves only the local market. Stronger IP protection motivates the global firm to transfer more technology.

Second, in an industry in which the goods are not costly to transport, technology transfer offers the global firm another major benefit of sourcing from the low-cost country for its demand in the home market as well. The global firm may thus consider not deterring the imitator's entry by transferring a high amount of technology. This happens when the cost savings for its home market are far more attractive than focus on capturing the emerging market. This is possible when the emerging market size or the imitation cost is low enough. As shown in Figure 1.10, in the no import case (or import case), when the market size ratio $\frac{N_1}{N_2}$ is higher than n (or n^I), or equivalently, when the imitation cost K is lower than $\widehat{K}$ (or $\widehat{K}^I$), the firm does not deter the

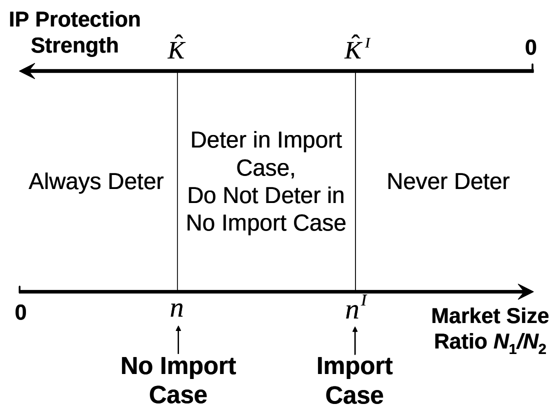

Figure 1.11: Import Case: Impacts of Cost and Distribution Advantages

imitator's entry. Higher $\frac{N_1}{N_2}$ (or lower N_2) implies less attractive profits from the emerging market if the global firm deters the imitator's entry. Lower K indicates that the deterrence strategy is more costly, i.e., lower is the "critical technology stock" it can only transfer, which in turn foregoes more sourcing opportunities for its home market. It also shows that the critical market size ratio n^I in case of import possibility is higher than the critical n in the no import case, or equivalently $\widehat{K} > \widehat{K}^I$. This means that with the import possibility, the global firm has more incentives to deter the imitator's entry. When the imitator's entry is not deterred, this results in an "Export Platform" strategy where foreign affiliates acts solely to export components for the home market when the global firm faces no threats from the imitator's imports in its home market. When the global firm faces threats, it is a "Global Platform" strategy where affiliates serves both markets if the imitator's cost advantage Δ_2 or the global firm's distribution advantage Δ_1 is relatively weak: the middle region in Figure 1.11; "Export Platform" strategy if the imitator's cost advantage or the global firm's distribution advantage is relatively strong: the right region in Figure 1.11. However, in some cases, larger size of the emerging market or stronger IP protection induces the global firm to transfer less technology. This happens when the global firm switches its focus from sourcing for its home market to capturing the emerging market, i.e., from non-deterrence to deterrence strategies. Although transferring less technology reduces the global firm's sourcing opportunities, the global firm deters imitation and thus reaps profits from the emerging market. The resultant strategy is "Global Platform" strategy.

Third, when the global faces threats from the imitator's imports in its home market, whether the emerging market is split between the two firms depends on the firms' distribution or cost advantage. As shown in Figure 1.11, the emerging market is solely served by the global firm (the imitator) when the global firm's distribution advantage or the imitator's cost advantage is weak (strong). The emerging market is split between the two firms when the global firm's distribution advantage or the imitator's cost advantage is medium. Facing the imitator's threats at home, the global firm's stronger distribution advantage Δ_1 induces the global firm to transfer more technology. Clearly, this raises both firms' equilibrium profits. Whenever the imitator is deterred or not, the imitator's stronger cost advantage Δ_2 induces the global firm to transfer less technology. This decreases the global firm's total equilibrium profit because less technology transfer reduces its sourcing opportunities for its home market and imitator's stronger cost advantage reduces its market share in the emerging market. This increases the imitator's equilibrium profit because increase of its market share in the emerging market dominates its quality decrease. However, in some cases, stronger imitator's cost advantage Δ_2 induces the global firm to transfer higher technology. This happens when the global firm switches its focus from capturing the emerging market to sourcing for its home market, i.e., from deterrence to non-deterrence strategies. In order to deter the entry of an imitator who has a strong cost advantage Δ_2, the global firm has to transfer a low amount of technology. Many sourcing opportunities are foregone, i.e., the deterrence strategy is too costly. It is this relationship between market split, sourcing and technology transfer that is counter-intuitive and shows the value of our imitative competition model.

Finally, the threats of the imitator to the global firm's home market induce the global firm to transfer less technology in both the deterrence and non-deterrence cases. If the global firm neglects the threats to its home market, the imitator may enter both the markets due to the global firm's too much technology transfer. Weaker the IP protection strength, more market shares the global firm loses.

1.7.2 Limitations and Future Research

Our model on strategic interaction between the firms is limited by some assumptions. The results and insights from our model have to be interpreted with caution keeping in mind these assumptions. We discuss next the impact of relaxing some of our assumptions.

First, we have assumed in the game that the markets are covered. On the one hand, if the home market is heterogeneous enough and thus not covered, given the lower costs of producing in the low-cost market, firms can offer products at differential prices and can thus penetrate new market segments (lower-income customer segments) at home. On the other hand, relaxing this assumption would decrease the competition intensity. The imitator will play less aggressively by differentiating its product farther away from the global firm's and targeting at lower segments, than in a covered one. Intuitively, such situations provide more incentives to the global firm to transfer technology, but formal results need to be derived. Second, the impact of technology transfer on imitation can be captured in two ways: technology transfer either raises product quality of the imitator or lowers the technology copy costs. Both have a similar impact on the imitator's strategic reaction, who is able to offset its fixed imitation costs only when enough amount of technology is transferred by the global firm. Further study is needed to see how the incorporation of decreasing imitation cost will exactly affect the strategic reaction of the imitator. Third, in our model, only the transportation cost is modeled as import cost. A modification can be done to include tariffs imposed on cost, insurance and freight (CIF).

The model can be extended in a few directions. One promising avenue for future research is to recognize both competition and cooperation between the global firms and the imitators. A manufacturing partnership with local companies will enable the global firm to produce at competitive cost and quality, as well as give the global firm an opportunity to leapfrog the competition. But the global firm also faces greater risk of creating a formidable competitor (*Wall Street Journal* 2006b). The second promising path is to incorporate the effects of several global firms competing or cooperating in emerging markets, while they are confronted with potential competition from local imitators. It would be interesting to study the impact of the rivalry or cooperation between firms on strategies of imitation, deterrence or accommodation by players engaged in the market dynamics.

Finally, one could view the emerging markets not just as product markets, but also innovators for the global markets. Large market potentials, low costs of factors, and pools of low wage talent are big attractions of the newly-emerging markets. Pushed by these impetuses, companies such as P&G Co., Motorola Inc. and IBM Corp. have been investing to expand their Chinese R&D operations to develop products for the global markets (*Wall Street Journal* 2006a). Inevitably, these firms all face obstacles like weak IP protections. With the advent of global R&D, such issues have come to the forefront: Will the prospects of eventual imitation dilute the gains for innovation? How does the sourcing strategy affect the innovation growth process? How do the market potentials affect the long-run rates of innovation and imitation? The answers to these questions are not obvious, and will require more research building on models such as those attempted in this paper. Imitation competition and innovation is a fertile ground for fascinating modeling in the future.

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1.9 Appendix A: Proofs

Lemma A 1. *The price equilibria are market-separable, i.e.,* $\left(p^*_{G1}(a), p^*_{G2}(a), p^*_{L1}(a), p^*_{L2}(a)\right) \equiv \left(\widehat{p}_{G1}(a), \widehat{p}_{G2}(a), \widehat{p}_{L1}(a), \widehat{p}_{L2}(a)\right)$*, where*

$$\begin{cases} \widehat{p}_{Gj}(a) \in \arg\max\limits_{p_{Gj}} \Pi_{Gj}\left(p_{Gj}, \widehat{p}_{Lj}(a), a\right) \\ \widehat{p}_{Lj}(a) \in \arg\max\limits_{p_{Lj}} \Pi_{Lj}\left(\widehat{p}_{Gj}(a), p_{Lj}, a\right) \end{cases}$$

Proof of Lemma A1: Suppose not. Either the global firm or the imitator will deviate. Hence,

$(p^*_G(a), p^*_L(a))$ are not equilibrium prices. ■

Proof of Assumption 1: Two cases:

(1) Monopoly Markets

The monopolist determines endogenously a covered or uncovered market. Denote by p^M_{G1} and p^M_{G2} the monopoly prices that the global firm sets in the two markets, respectively. A marginal consumer with taste parameter p^M_{Gi}/q in market i is indifferent between buying a good and not buying at all. The market demand is then $Q^M_{Gi} = \beta_i - p^M_{Gi}/q$. The global firm sets prices in the two markets in order to maximize its profit in each market for a given technology transfer level x:

$$\pi^M_{Gi}(x) = \left(p^M_{Gi} - c_{Gi}(x)\right) \frac{\beta_i - \frac{p^M_{Gi}}{q}}{\beta_i - \alpha_i} N_i$$

We know that in a covered-market case, the monopolist should set a price such that the least-value consumer (a_i) gives up all its surplus to purchase the good, i.e., $p^M_{Gi} = \alpha_i q$. Therefore, to ensure the market is covered, it is necessary that:

$$\frac{\partial \pi^M_{Gi}(x)}{\partial p^M_{Gi}}|_{p^M_{Gi}=\alpha_i q} = \left[\left(\beta_i - \frac{p^M_{Gi}}{q}\right) - \frac{1}{q}\left(p^M_{Gi} - c_{Gi}(x)\right)\right] \frac{N_i}{\beta_i - \alpha_i}|_{p^M_{Gi}=\alpha_i q} \leq 0 \Leftrightarrow \beta_i \leq 2\alpha_i - \frac{c_{Gi}(x)}{q}$$

In addition, demands in both markets are positive, therefore: $\beta_i q > c_{Gi}(x)$.

Taken gether, for the markets to be covered by a monopoly, we require:

$$\frac{c_{Gi}(x)}{q} < \beta_i \leq 2\alpha_i - \frac{c_{Gi}(x)}{q} \tag{1.6}$$

(2) Duopoly Markets

(i) Emerging Market 2. If the imitator enters, we have a duopoly market for $x \in [x_{21}, x_{22}]$, with equilibrium prices (assuming $y^* = x$):

$$p^*_{G2}((x,s), x) = \frac{1}{3}\left[(2c_{G2}(x) + c_{L2}) + (2\beta_2 - \alpha_2)(q - q_L(x))\right]$$

$$p^*_{L2}((x,s), x) = \frac{1}{3}\left[(c_{G2}(x) + 2c_{L2}) + (\beta_2 - 2\alpha_2)(q - q_L(x))\right]$$

For the emerging market to be covered in the region $[x_{21}, x_{22}]$, i.e., the least-value customer buys the low quality product, we have: $\frac{p^*_{L2}((x,s),x)}{q_L(x)}|_{x=x_{21}} \leq \alpha_2$, or,

$$c_0 \leq \left[1 - \frac{\Delta_2}{(2\alpha_2 - \beta_2)q - \triangle c - c_{t2}}\right]\beta_2 q + \Delta_2 \tag{1.7}$$

(ii) Home Market 1. Similarly, if $\triangle c \leq c_{t1}$:

$$c_0 \leq \left[1 - \frac{\triangle c + \Delta_2 - \Delta_1 - c_{t1}}{(2\alpha_1 - \beta_1)\, q}\right] \beta_1 q + \Delta_2 - \Delta_1 - c_{t1} \tag{1.8}$$

otherwise:

$$c_0 \leq \left[1 - \frac{\Delta_2 - \Delta_1}{(2\alpha_1 - \beta_1)\, q - \triangle c + c_{t1}}\right] \beta_1 q + \Delta_2 - \Delta_1 - c_{t1} \tag{1.9}$$

For emerging market to be covered by either a monopoly or two duopolists, from (1) and (2), we get:

$$\begin{aligned} c_0 &\leq \min\left((2\alpha_2 - \beta_2)\, q - \triangle c - c_{t2}, \left[1 - \frac{\Delta_2}{(2\alpha_2 - \beta_2)\, q - \triangle c - c_{t2}}\right] \beta_2 q + \Delta_2\right) \\ &= (2\alpha_2 - \beta_2)\, q - \triangle c - c_{t2} \end{aligned}$$

because $(2\alpha_2 - \beta_2)\, q > \Delta_2 + \triangle c + c_{t2} \Longleftrightarrow (2\alpha_2 - \beta_2)\, q - \triangle c - c_{t2} < \left[1 - \frac{\Delta_2}{(2\alpha_2 - \beta_2) q - \triangle c - c_{t2}}\right] \beta_2 q + \Delta_2$.
For home market to be covered by either a monopoly or two duopolists:
If $\triangle c \leq c_{t1}$, from (1) and (3), we get:

$$c_0 \leq \min\left((2\alpha_1 - \beta_1)\, q - c_{t1}, \left[1 - \frac{\triangle c + \Delta_2 - \Delta_1 - c_{t1}}{(2\alpha_1 - \beta_1)\, q}\right] \beta_1 q + \Delta_2 - \Delta_1 - c_{t1}\right) = (2\alpha_1 - \beta_1)\, q - c_{t1}$$

because $(2\alpha_1 - \beta_1)\, q > \Delta_2 - \Delta_1 \Leftrightarrow (2\alpha_1 - \beta_1)\, q < \left[1 - \frac{\triangle c + \Delta_2 - \Delta_1 - c_{t1}}{(2\alpha_1 - \beta_1) q}\right] \beta_1 q + \Delta_2 - \Delta_1$.
If $\triangle c > c_{t1}$, from (1) and (4), we get:

$$c_0 \leq \min\left((2\alpha_1 - \beta_1)\, q - \triangle c, \left[1 - \frac{\Delta_2 - \Delta_1}{(2\alpha_1 - \beta_1)\, q - \triangle c + c_{t1}}\right] \beta_1 q + \Delta_2 - \Delta_1 - c_{t1}\right) = (2\alpha_1 - \beta_1)\, q - \triangle c$$

because $(2\alpha_1 - \beta_1)\, q > \Delta_2 - \Delta_1 + \triangle c - c_{t1} \Longleftrightarrow (2\alpha_1 - \beta_1)\, q - \triangle c < \left[1 - \frac{\Delta_2 - \Delta_1}{(2\alpha_1 - \beta_1) q - \triangle c + c_{t1}}\right] \beta_1 q + \Delta_2 - \Delta_1 - c_{t1}$. ■

Proof of Lemma 1: (1) For $0 \leq x \leq x_{20}$: Because $a_2 q_L (y) \leq c_{L2}$, the existence of the imitator has no threat to the global firm who will set a monopoly price: $p^*_{G2} = a_2 q$. The firms' equilibrium profits in emerging market are then:

$$\Pi^*_{L2}\left((x, s), y\right) = 0, \Pi^*_{G2}\left((x, s), y\right) = \left(a_2 q - c_{G2}(x)\right) N_2$$

(2) For $x_{20} < x \leq x_{21}$: The global firm sets a price such that it captures the whole market, i.e.,

$\frac{p_{G2}-p_{L2}}{q-q_L(y)} = \alpha_2$, where $p_{L2} = c_{L2}$. Hence,

$$p^*_{G2}\left(\left(x,s\right),y\right) = \alpha_2\left(q - q_L\left(y\right)\right) + c_{L2}$$

The two firms' equilibrium profits are then:

$$\Pi^*_{L2}\left(\left(x,s\right),y\right) = 0, \Pi^*_{G2}\left(\left(x,s\right),y\right) = \left[p^*_{G2}\left(\left(x,s\right),y\right) - c_{G2}\left(x\right)\right]N_2$$

(3) For $x_{21} < x \leq x_{22}$: We have a duopoly emerging market. The profit functions of the two firms are:

$$\Pi_{G2} = \left(\beta_2 - \frac{p_{G2} - p_{L2}}{q - q_L\left(y\right)}\right)\left(p_{G2} - c_{G2}\left(x\right)\right)\frac{N_2}{\beta_2 - \alpha_2}, \Pi_{L2} = \left(\frac{p_{G2} - p_{L2}}{q - q_L\left(y\right)} - \alpha_2\right)\left(p_{L2} - c_{L2}\right)\frac{N_2}{\beta_2 - \alpha_2}$$

The two firms set prices simultaneously, and the equilibrium prices are then:

$$p^*_{G2}\left(\left(x,s\right),y\right) = \frac{1}{3}\left[\left(2c_{G2}\left(x\right) + c_{L2}\right) + \left(2\beta_2 - \alpha_2\right)\left(q - q_L\left(y\right)\right)\right] \tag{1.10}$$

$$p^*_{L2}\left(\left(x,s\right),y\right) = \frac{1}{3}\left[\left(c_{G2}\left(x\right) + 2c_{L2}\right) + \left(\beta_2 - 2\alpha_2\right)\left(q - q_L\left(y\right)\right)\right] \tag{1.11}$$

with equilibrium quantities being:

$$Q^*_{G2}\left(\left(x,s\right),y\right) = \frac{-c_{G2}(x) + c_{L2} + \left(q - q_L\left(y\right)\right)\left(2\beta_2 - \alpha_2\right)}{3\left(q - q_L\left(y\right)\right)}\frac{N_2}{\beta_2 - \alpha_2} \tag{1.12}$$

$$Q^*_{L2}\left(\left(x,s\right),y\right) = \frac{-c_{L2} + c_{G2}(x) + \left(q - q_L\left(y\right)\right)\left(\beta_2 - 2\alpha_2\right)}{3\left(q - q_L\left(y\right)\right)}\frac{N_2}{\beta_2 - \alpha_2} \tag{1.13}$$

and each firm's equilibrium profit being:

$$\Pi^*_{G2}\left(\left(x,s\right),y\right) = \frac{\left[-c_{G2}(x) + c_{L2} + \left(q - q_L\left(y\right)\right)\left(2\beta_2 - \alpha_2\right)\right]^2}{9\left(q - q_L\left(y\right)\right)}\frac{N_2}{\beta_2 - \alpha_2} \tag{1.14}$$

$$\Pi^*_{L2}\left(\left(x,s\right),y\right) = \frac{\left[-c_{L2} + c_{G2}(x) + \left(q - q_L\left(y\right)\right)\left(\beta_2 - 2\alpha_2\right)\right]^2}{9\left(q - q_L\left(y\right)\right)}\frac{N_2}{\beta_2 - \alpha_2} \tag{1.15}$$

Also, $\partial p^*_{G2}\left(\left(x,s\right),y\right)/\partial x > 0$, $\partial p^*_{G2}\left(\left(x,s\right),y\right)/\partial y < 0$, $\partial p^*_{L2}\left(\left(x,s\right),y\right)/\partial x < 0$, $\partial p^*_{L2}\left(\left(x,s\right),y\right)/\partial y > 0$; $\Pi^*_{G2}\left(\left(x,s\right),x\right)$ is convex, decreasing in $x \in [x_{21}, x_{22}]$; and $\Pi^*_{L2}\left(\left(x,s\right),x\right)$ is convex, increasing in $x \in [x_{21}, x_{22}]$.

(4) For $x_{22} < x \leq 1$: The imitator sets a price such that it captures the whole market

$(Q^*_{G2}((x,s),x)=0)$, i.e., $\frac{p_{G2}-p_{L2}}{q-q_L(x)}=\beta_2$, where, $p_{G2}=c_{G2}(x)$. Hence, $p^*_{L2}((x,s),y)=c_{G2}(x)-\beta_2(q-q_L(y))$. The two firms' equilibrium profits are then:

$$\Pi^*_{L2}((x,s),y)=[p^*_{G2}((x,s),y)-c_{L2}]N_2,\Pi^*_{G2}((x,s),y)=0$$

■

Proof of Lemma 2: (1) The best response function immediately follows from Lemma 1. Then it is easy to check $\partial\Pi^*_{L2}((x,s),x)/\partial x\geq 0$ for $x\in[x_{21},1]$.
(2) Properties of $\widehat{x}$: For $x\in[x_{21},x_{22}]$, $\frac{\partial}{\partial\Delta_2}\Pi^*_{L2}=\frac{2[\Delta_2+(\triangle c+c_{t2})(1-x)+q(1-x)(\beta_2-2\alpha_2)]}{9q(1-x)}\frac{N_2}{\beta_2-\alpha_2}\geq 0$,
$\frac{\partial}{\partial c_{t2}}\Pi^*_{L2}=\frac{2[\Delta_2+(\triangle c+c_{t2})(1-x)+q(1-x)(\beta_2-2\alpha_2)]}{9q}\frac{N_2}{\beta_2-\alpha_2}\geq 0$,
$\frac{\partial}{\partial q}\Pi^*_{L2}=\frac{[\Delta_2+[\triangle c+c_{t2}+q(\beta_2-2\alpha_2)](1-x)][[q(\beta_2-2\alpha_2)-(\triangle c+c_{t2})](1-x)-\Delta_2]}{9q^2(1-x)}\frac{N_2}{\beta_2-\alpha_2}\leq 0$,
$\frac{\partial}{\partial\triangle c}\Pi^*_{L2}=\frac{2[\Delta_2+(\triangle c+c_{t2})(1-x)+q(1-x)(\beta_2-2\alpha_2)]}{9q}\frac{N_2}{\beta_2-\alpha_2}\geq 0$.
For $x\in[x_{22},1]$, $\frac{\partial}{\partial\Delta_2}\Pi^*_{L2}=N_2>0$, $\frac{\partial}{\partial c_{t2}}\Pi^*_{L2}=(1-x)N_2>0$, $\frac{\partial}{\partial q}\Pi^*_{L2}=-\beta_2(1-x)N_2<0$, and $\frac{\partial}{\partial\triangle c}\Pi^*_{L2}=(1-x)N_2>0$. ■

Proof of Proposition 2:

(1) If $\widehat{x}\leq x_{22}$, the global firm needs to compare its profits at $x=\widehat{x}$ and 1. This is because $\Pi^*_G((x,s),x)$ is convex in x for $x\in[x_{21},x_{22}]$, and $\frac{\partial}{\partial x}\Pi^*_G((x,s),x)>0$ for $x\in[x_{22},1]$, also $\Pi^*_G((\widehat{x}^-,s),\widehat{x}^-)>\Pi^*_G((\widehat{x}^+,s),\widehat{x}^+)$, and $\Pi^*_G((x_{22},s),x_{22})<\Pi^*_{G2}((1,s),1)$. From $\Pi^*_G(\widehat{x}^-)=\Pi^M_{G1}(\widehat{x})+\Pi^M_{G2}(\widehat{x})$, and $\Pi^*_G(1)=\Pi^M_{G1}(1)$, we then have, if

$$\frac{N_1}{N_2}\geq\frac{\alpha_2q-(c_{t1}+c_{t2})(1-\widehat{x})-c_0}{(\triangle c-c_{t1})(1-\widehat{x})}-1\doteq n$$

$\Pi^*_G(\widehat{x})\leq\Pi^*_G(1)$; otherwise $\Pi^*_G(\widehat{x})>\Pi^*_G(1)$. $n>0$ because $\alpha_2q-(c_{t2}+\triangle c)(1-\widehat{x})-c_0\geq 0$ (since $\alpha_2q-c_{t2}-\triangle c-c_0\geq 0$).
(2) If $\widehat{x}>x_{22}$, it is similar.
In the following , we show that $\Pi^*_{G2}((x,s),x)$ is convex in x for $x\in[x_{21},x_{22}]$. We then know $\Pi^*_G(x)$ is convex because $\frac{\partial}{\partial x}\Pi^*_{G1}(x)=\triangle cN_1>0$. The convexity of $\Pi^*_{G2}((x,s),x)$ holds because $\frac{\partial^2}{\partial x^2}\Pi^*_{G2}=\frac{2(\Delta_2)^2}{9q(1-x)^3}\frac{N_2}{\beta_2-\alpha_2}>0$. In particular, $\frac{\partial}{\partial x}\Pi^*_{G2}|_{x=x_{21}}=0$, $\frac{\partial}{\partial x}\Pi^*_{G2}|_{x=x_{22}}=(\triangle c+c_{t2})N_1>0$. ■
Proof of Proposition 3: $\frac{\partial}{\partial c_{t1}}n=\frac{\alpha_2q-c_0-(1-\widehat{x})(\triangle c+c_{t2})}{(1-\widehat{x})(\triangle c-c_{t1})^2}>0$, $\frac{\partial}{\partial c_{t2}}n=\frac{\alpha_2q-c_0}{(\triangle c-c_{t1})(1-\widehat{x})^2}\frac{\partial\widehat{x}}{\partial c_{t2}}-\frac{1}{\triangle c-c_{t1}}<0$ because $\partial\widehat{x}/\partial c_{t2}<0$ and $\triangle c>c_{t1}$,
$\frac{\partial}{\partial\triangle c}n=\frac{(\widehat{x}-1)(\alpha_2q-c_0-c_{t1}-c_{t2})+(\alpha_2q-c_0)(\triangle c-c_{t1})\frac{\partial\widehat{x}}{\partial\triangle c}-(c_{t1}+c_{t2})(1-\widehat{x})\widehat{x}}{(\triangle c-c_{t1})^2(1-\widehat{x})^2}<0$ because $\alpha_2q-c_0-c_{t1}-c_{t2}>\alpha_2q-c_0-\triangle c-c_{t2}>0$, $\frac{\partial}{\partial\Delta_2}n=\frac{\alpha_2q-c_0}{(\triangle c-c_{t1})(1-\widehat{x})^2}\frac{\partial\widehat{x}}{\partial\Delta_2}<0$, $\frac{\partial}{\partial q}n=\frac{\alpha_2q-c_0}{(\triangle c-c_{t1})(1-\widehat{x})^2}\frac{\partial\widehat{x}}{\partial q}+\frac{\alpha_2}{(\triangle c-c_{t1})(1-\widehat{x})}>0$,
$\frac{\partial}{\partial K}n=\frac{\alpha_2q-c_0}{(\triangle c-c_{t1})(1-\widehat{x})^2}\frac{\partial\widehat{x}}{\partial K}>0$. ■

Lemma A 2. ***Bertrand Equilibrium Profits in Import Case.*** *The two firms profits in* *home market are:*

$$\Pi_{L1}^{*}\left(\left(x,s\right),x\right)=\begin{cases}0 & 0<x\leq x_{11}\doteq 1-\frac{\triangle c+\Delta_2-\Delta_1-c_{t1}}{(2\alpha_1-\beta_1)q}\\ \frac{\left[-c_{L1}+c_{G1}(x,s)+(q_G-q_L(x))(\beta_1-2\alpha_1)\right]^2}{9(q_G-q_L(x))}\frac{N_1}{\beta_1-\alpha_1} & x_{11}<x\leq x_{12}\doteq 1-\frac{\triangle c+\Delta_2-\Delta_1-c_{t1}}{(2\beta_1-\alpha_1)q}\\ \left(p_{L1}^{*}\left(\left(x,s\right),x\right)-c_{L1}\right)N_1 & x_{12}<x\leq 1\end{cases}$$

$$\Pi_{G1}^{*}\left(\left(x,s\right),x\right)=\begin{cases}\left(\alpha_1 q-c_{G1}(x,s)\right)N_1 & 0<x\leq x_{10}\doteq\frac{c_{L1}}{\alpha_1 q}\\ \left(p_{G1}^{*}\left(\left(x,s\right),x\right)-c_{G1}(x,s)\right)N_1 & x_{10}<x\leq x_{11}\\ \frac{\left[-c_{G1}(x,s)+c_{L1}+(q-q_L(x))(2\beta_1-\alpha_1)\right]^2}{9(q-q_L(x))}\frac{N_1}{\beta_1-\alpha_1} & x_{11}<x\leq x_{12}\\ 0 & x_{12}<x\leq 1\end{cases}$$

where

$$\begin{aligned}p_{L1}^{*}\left(\left(x,s\right),x\right) &= c_{G1}\left(x,s\right)-\beta_1\left[q-q_L\left(x\right)\right]\\ p_{G1}^{*}\left(\left(x,s\right),x\right) &= \alpha_1\left[q-q_L\left(x\right)\right]+c_{L1}\end{aligned}$$

Lemma A 3. *The imitator decides to enter only if the global firm transfers a technology $x>\widehat{x}^{I}\left(s\right)$, and imitates $y^{*}=x$. $\widehat{x}^{I}\left(s\right)$ has the following properties: (i) $\widehat{x}^{I}\left(s\right)\leq\widehat{x}$, (ii) $\partial\widehat{x}^{I}\left(s\right)/\partial K\geq 0$, $\partial\widehat{x}^{I}\left(s\right)/\partial q\geq 0$, $\partial\widehat{x}^{I}\left(s\right)/\partial c_{t1}\geq 0$, $\partial\widehat{x}^{I}\left(s\right)/\partial\Delta_1\geq 0$, $\partial\widehat{x}^{I}\left(s\right)/\partial\Delta_2\leq 0$, $\partial\widehat{x}^{I}\left(s\right)/\partial c_{t2}\leq 0$, and $\partial\widehat{x}^{I}\left(s\right)/\partial\triangle c\leq 0$.*

Proof of Lemma A3: Need to discuss two cases: $\triangle c\leq c_{t1}$ and $\triangle c>c_{t1}$. Similar to the proof of Lemma 2. ■

Proposition A 1. *In the import case, if $\triangle c\leq c_{t1}$, the global firm's optimal technology transfer strategy is $x^{I*}=\widehat{x}^{I}\left(1\right)$, the imitator's entry is deterred, and the global firm sources for its home market all the demand locally. This results in a "Local Content" strategy.*

Proof of Proposition A1: In the following, we first show that it must hold that $x_{11}=1-\frac{\triangle c+\Delta_2-\Delta_1-c_{t1}}{(2\alpha_1-\beta_1)q}\geq x_{20}$, we then know the global firm's optimal strategy is to transfer $x^{*}=\widehat{x}^{I}\left(s\right)$ (because $\partial\Pi_{G}^{*}\left(x\right)/\partial x<0$ for any $x\geq x_{20}$, and $\widehat{x}\geq x_{20}$), in which case the global firm is a monopolist in both markets. Suppose not, i.e., $x_{20}>x_{11}$, we then have

$$\frac{c_0-\Delta_2}{\alpha_2 q}>1-\frac{\triangle c+\Delta_2-\Delta_1-c_{t1}}{\left(2\alpha_1-\beta_1\right)q}$$

Because $\left(2\alpha_1-\beta_1\right)q>c_0+\triangle c,\alpha_2 q>c_0+\triangle c+c_{t2}$, we have

$$\left(c_0-\Delta_2\right)\left(c_0+\triangle c\right)>\left(c_0-\Delta_2+\Delta_1+c_{t1}\right)\left(c_0+\triangle c+c_{t2}\right)$$

which does not hold because $\Delta_2 > \Delta_2 - \Delta_1$. ■

Proof of Proposition 4: (1) If $\max(x_{10}, x_{20}) \leq \min(x_{11}, x_{21})$, i.e.,

$$\max\left(\frac{c_0 - \Delta_2 + \Delta_1 + c_{t1}}{\alpha_1 q}, \frac{c_0 - \Delta_2}{\alpha_2 q}\right) \leq \min\left(1 - \frac{\Delta_2 - \Delta_1}{(2\alpha_1 - \beta_1) q - \triangle c + c_{t1}}, 1 - \frac{\Delta_2}{(2\alpha_2 - \beta_2) q - \triangle c - c_{t2}}\right)$$

or,

$$\begin{aligned} \frac{c_0 - \Delta_2 + \Delta_1 + c_{t1}}{\alpha_1 q} &\leq 1 - \frac{\Delta_2}{(2\alpha_2 - \beta_2) q - \triangle c - c_{t2}} \Longleftrightarrow \\ \Delta_1 &\leq \Delta_2 \left(1 - \frac{\alpha_1 q}{(2\alpha_2 - \beta_2) q - \triangle c - c_{t2}}\right) + \alpha_1 q - (c_0 + c_{t1}) \doteq \overline{\Delta}_1 \end{aligned}$$

and

$$\begin{aligned} \frac{c_0 - \Delta_2}{\alpha_2 q} &\leq 1 - \frac{\Delta_2 - \Delta_1}{(2\alpha_1 - \beta_1) q - \triangle c + c_{t1}} \Longleftrightarrow \\ \Delta_1 &\geq \Delta_2 - \left(1 - \frac{c_0 - \Delta_2}{\alpha_2 q}\right) [(2\alpha_1 - \beta_1) q - \triangle c + c_{t1}] \doteq \widehat{\Delta}_1 \end{aligned}$$

then $\widehat{x}^I(s) \geq \min(x_{11}, x_{21}) \geq \max(x_{10}, x_{20})$, and the global firm's optimal strategy is $x^* = \widehat{x}^I(s)$ (because $\partial \Pi^*_{G1}/\partial x \leq 0$, for $x \geq x_{10}$, and $\partial \Pi^*_{G2}/\partial x \leq 0$, for $x \geq x_{20}$). Namely, the global firm will deter the imitator's entry.

(2) $x_{11} < x_{20}$ is not possible. Suppose it holds, i.e., $\frac{c_0 - \Delta_2}{\alpha_2 q} > 1 - \frac{\Delta_2 - \Delta_1}{(2\alpha_1 - \beta_1) q - \triangle c + c_{t1}}$. Because $(2\alpha_1 - \beta_1) q > c_0 + \triangle c, \alpha_2 q > c_0 + \triangle c + c_{t2}$, we then have

$$(c_0 - \Delta_2)(c_0 + c_{t1}) > (c_0 + c_{t1} - \Delta_2 + \Delta_1)(c_0 + \triangle c + c_{t2})$$

which does not hold because $\triangle c > c_{t1}$.

(3) $x_{21} < x_{10}$, i.e., $\Delta_1 > \overline{\Delta}_1$. If $\widehat{x}^I(s) \geq x_{10}$, the global firm's optimal strategy is $x^* = \widehat{x}^I(s)$. Otherwise, need to compare the global firm's profits at $x = \widehat{x}^I(s)$, and $x = x_{10}$.

$$\begin{aligned} \Pi^*_G\left(x = \widehat{x}^I(s)\right) &= \left(a_1 q - \triangle c \left(1 - \widehat{x}^I(s)\right) - c_0 - c_{t1} \widehat{x}^I(s)\right) N_1 \\ &\quad + \left(\alpha_2 q - (\triangle c + c_{t2}) \left(1 - \widehat{x}^I(s)\right) - c_0\right) N_2 \end{aligned}$$

$$\begin{aligned} \Pi^*_G(x = x_{10}) &= (\alpha_1 q - \triangle c (1 - x_{10}) - c_0 - c_{t1} x_{10}) N_1 \\ &\quad + \frac{[-(\triangle c + c_{t2})(1 - x) - \Delta_2 + q(1 - x_{10})(2\beta_2 - \alpha_2)]^2}{9q(1 - x_{10})} \frac{N_2}{\beta_2 - \alpha_2} \end{aligned}$$

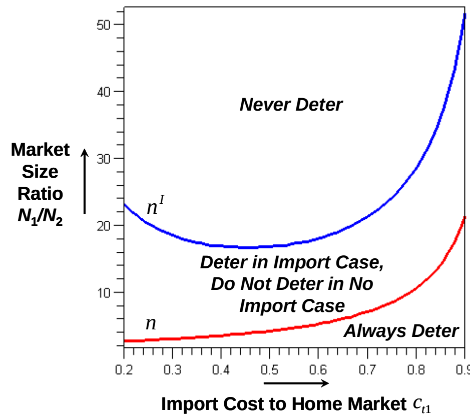


Figure 1.12: n and n^I as a Function of c_{t1}

We then have, if

$$\frac{N_1}{N_2} \leq \frac{\frac{1}{N_2}\Pi^*_{G2}(x_{10}) - \left(\alpha_2 q - (\triangle c + c_{t2})\left(1 - \widehat{x}^I(s)\right) - c_0\right)}{(c_{t1} - \triangle c)\left(x_{10} - \widehat{x}^I(s)\right)} \doteq n^I$$

the global firm's optimal strategy is $x^* = \widehat{x}^I(s)$, i.e., it deters the imitator's entry; Otherwise, $x^* = x_{10}$, i.e., the imitator enters, but only sells to emerging market. $\frac{\partial}{\partial K} n^I > 0$ immediately follows. ∎

Lemma A 4. *$\partial\overline{\Delta}_1/\partial K = 0$, $\partial\overline{\Delta}_1/\partial a_1 > 0$, $\partial\overline{\Delta}_1/\partial\Delta_2 > 0$, $\partial\overline{\Delta}_1/\partial a_2 < 0$, $\partial\overline{\Delta}_1/\partial c_{t1} \leq 0$, $\partial\overline{\Delta}_1/\partial c_{t2} \leq 0$, $\partial\overline{\Delta}_1/\partial\triangle c \leq 0$.*

Proof of Lemma A4: The properties immediately follow from the definition of $\overline{\Delta}_1$. ∎

Proof of Proposition 6: It immediately follows from Lemmas 2 and A3. ∎

Proof of Proposition 7: It immediately follows from $\Pi^*_{Lj}(x) \geq 0$ for $j = 1, 2$. ∎

1.10 Appendix B: More Comparative Studies

In the following, we study how the critical market size ratios in the two cases change with different parameters. From Figures 1 & 2, we obtain the following observations:

The impact of the import cost (c_{t1}) to home market (Figure 1.12). In the no import case, lower the import cost c_{t1} to the home market, lower is the critical market size ratio n. This means it is more likely that the global firm will not deter the imitator's entry by transferring a high amount of technology. Without threats of imitative product at home, it is intuitive that

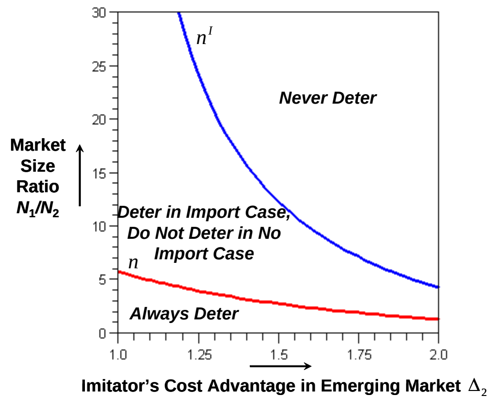


Figure 1.13: n and n^I as a Function of Δ_2

with lower import cost back to the home market, the global firm saves more costs in home market by sourcing from its foreign affiliate and thus has more incentives to transfer technology. In the import case, it is more possible for the global firm to transfer a high amount of technology for medium values of import cost c_{t1}. Reasons for reduction in n^I then increase in c_{t1} are as follows. Low import cost to the home market also means low landed cost of the imitative product, which intensifies the competition. The incentive of the global firm to transfer a high amount of technology initially increases as c_{t1} increases because the positive effect of the increasing c_{t1} on the ability of the global firm to preempt the imitative product from its home market dominates its negative effect on the diminishing cost savings of sourcing from the foreign affiliate. For high values of c_{t1}, the cost savings aspect dominates.

The impact of the imitator's cost advantage (Δ_2) in emerging market (Figure 1.13). For both cases, stronger is the imitator's cost advantage Δ_2 in emerging market, more likely the global firm will transfer a high amount of technology and switch its focus on capturing the emerging market to sourcing for its home market. In order to deter the entry of an imitator who has a strong cost advantage Δ_2, the global firm has to transfer a low amount of technology (see Lemmas 2 and A3). Many sourcing opportunities are foregone, i.e., the deterrence strategy is too costly. But in case of deterrence or non-deterrence, stronger is the imitator's cost advantage, less technology the global firm will transfer in order to limit the imitator's quality. Recall from §5.3.2, the opposite occurs when the global firm's distribution advantage Δ_1 improves.

Results regarding c_{t2}, $\triangle c$, Δ_1 and q are relatively intuitive. Our results show that in more protected economies (higher c_{t2}), or in economies with stronger comparative advantages (higher $\triangle c$), or with stronger distribution advantage in its home market (higher Δ_1), or with a lower technology product (lower q), more likely the global firm transfers a high amount of technology and the foreign affiliates are more oriented toward export markets, and technology imitations are more often.

1.11 Appendix C: A Field Study

In this section, our model is interpreted using field data obtained from a critical equipment producer in U.S.A., who faces similar choices in levels of technology transfer to its Chinese affiliate. Our model provides insights into the fundamental drivers of imitative competition that emerge in this industry.

This firm is the world's major supplier of a high-technology safety equipment. A unit of this product comprises of hundreds of components, which are assembled into nine major sub-assemblies, and then the final system. Critical process technology and labor skills of this product are mainly contained in the manufacturing of components, while assembly requires low skilled labor. This firm has transferred to its affiliate in China the technology of making about a third ($x = 1/3$ in our model) of the total components.

This product has a high value-to-weight ratio. It is thus cost-effective to transport the components or finished goods among affiliates. In addition, due to low labor rate in China, \$1.6 per hour compared with \$16 in the U.S., the total unit production cost can be reduced by about 30% ($\frac{\triangle c}{c_0+\triangle c}$) from USD\$1,000, if all components are locally made. The total labor costs account for only 4% of the total production costs, compared with 30% in the U.S. The low labor cost percentage indicates that the increase of imitator's unit production cost is marginal if it intends to improve its quality by using more skilled labor.

Currently, there is no comparable this product made by local competitors in Chinese market. An estimation by this firm of production cost advantage of the local competitors is about 40-50% ($\frac{\Delta_2}{c_0}$). However, due to strict regulations and high brand royalty of consumers peculiar to this industry in the U.S., the imitators are basically blockaded from the U.S. market (Δ_1 very high).

The total technology transfer cost of the whole unit is estimated to be \$60,000. This is negligible compared with the cost savings of serving its U.S. demand of 35,000 units in 2002. The imitation cost (K) is significant due to such complex process technology as high-level machining skills required in machined metal parts of key components, and complex testing processes performed at both sub-assembly and final assembly levels required by regulations.

The current installation base of this product in China is relatively small, 30,000 units, compared with 800,000 of the U.S. Facing no imitators' threats in its home market, the firm is aggressively transferring more technology to its Chinese affiliate in order to reduce costs for serving its U.S. market. But the risk of the potential imitators' entry into the local Chinese market exists. A critical decision managers currently face is a choice of transferring more component technology to its Chinese affiliate to take advantage of sourcing for U.S. market but giving up the emerging market to the imitators ("Export Platform"). The alternative is to maintain a low level of technology in its Chinese affiliate in order to deter the imitators' entry into the emerging market and forego sourcing advantage for home market ("Global Platform"). With an expected fast growth rate of more than 60% within next five years in the Chinese market, the managers see themselves better off to maintain current technology level in order to secure this emerging huge market, and not let imitators capitalize on getting foothold in burgeoning Chinese market.

The firm is also facing a technology transfer decision for industrial hard hats from its U.S. affiliate to its Chinese affiliate. In contrast to the above safety equipment, the imitators can easily penetrate into the U.S. market due to less regulation of this product. Foreseeing this, the managers are even more cautious in transferring technology and only limited number of components are made by its Chinese affiliate.

Both these products showcase the dilemma faced by managers regarding the appeal of sourcing in emerging markets, tapping market potential in these countries, and at the same time limiting the competitors to copy technology and pose threats in either markets. Our model is a first attempt to build a stylized model to reveal the game confronting the global and local players and assess the factors that drive the sourcing and competition dynamics.

Chapter 2

Introducing Green Products Subject to Scarce Complementary Resources

2.1 Introduction

Recently, environmental consciousness among consumers has extensively grown, in response to fast-changing climates (Maritz Research 2007, Nielsen 2007). At the same time, increasing crude oil prices are driving down the marketability of conventional petroleum fuel vehicle (*Wall Street Journal* 2007c). Vehicle manufacturers search for alternatives, for example, flex-fuel vehicles, which can be powered by either petroleum fuels or biofuels. Biofuels, such as ethanol and biodiesel, are made from renewable resources (or feedstocks), usually biological materials, such as cellulose, corn, soy bean or plant oils. The flex-fuel vehicles are environmentally-friendly because combusting biofuels reduces greenhouse gas (GHG) emission.[1] Foreseeing this opportunity, vehicle producers are ramping up production of flex-fuel vehicles (*Business Week* 2006).[2] However, the limited availability of farmland constrains the supply of biofuel feedstocks (*Business Week* 2007a). Also, vehicle manufacturers are concerned about cannibalizing conventional vehicle sales. We study these two obstacles to the development of the green vehicle market.

Manufacturers of green vehicles are usually also manufacturers of conventional vehicles.[3]

[1] Farrell et al. (2006) estimate that the fuel cycle for energy from grain ethanol requires up to 95% less petroleum than the fuel cycle for an equivalent amount of energy from gasoline, and it results in a 13% reduction in overall GHG emissions.

[2] The United States has more than 5 million flex-fuel vehicles on the road and U.S. car companies estimate that they will have sold 8 million flex-fuel vehicles by 2008 (U.S. Department of Energy 2007).

[3] Green vehicles are made by making small changes to conventional vehicles. Technically, the difference between regular vehicles and green vehicles is a small system placed in the vehicle that enables the engine to adapt to the fuel blend being used (International Atomic Energy Agency 2004).

Firms' marketing strategies of making green and conventional vehicles available influence consumer purchasing decision in the first instance. The operating cost of the vehicles (i.e., the biofuel or petroleum fuel prices) is another important economic factor that consumers will take in account when making their vehicle choice. Due to scarce feedstocks for making biofuels, high demand for biofuel can easily drive up biofuel prices (*Business Week* 2007a). As a result, the demand for green vehicles and the price of biofuel can be correlated. Consumers' vehicle choice will influence the biofuel price, and in turn their net utility from the vehicle they adopt. Firms designing their vehicle introduction strategy should take the scarce resource effect into account, and answer the question "How does the biofuel scarcity affect which vehicle(s) to offer, and at what price(s)?"

The primary goal of this paper is to provide vehicle manufacturers with guidelines for marketing green and conventional vehicles by considering the following important factors:

Green Segment. Facing the greenhouse effects, more and more consumers regard the environment as an immediate and urgent problem, and incorporate green benefits into their purchasing decision. A recent survey by the Nielsen Company (2007) suggests global warming as a major concern more than doubled around the world from October 2006 (7 percent) to April 2007 (16 percent). Another survey by Maritz Research (2007) reports that overall 47 percent of respondents would be willing to pay more for environmentally friendly services, products or brands.. This creates important incentives for companies to consider designing and marketing environmentally friendly products targeted at green consumers.

Operating Costs. The operating cost is an important economic factor that influences consumers vehicle choice. Before the introduction of flex-fuel vehicles and biofuels, petroleum fuel is the only choice for powering vehicles. The introduction of alternative fuels changes the purchasing behavior of consumers. Particularly, in recent years, increasing crude oil prices leads to a significant degree of optimism on biofuels.[4]

Scarce Green Fuel Supplies. However, the current green product strategy is not without obstacles. The scarce feedstock remains the main obstacle of promoting green vehicles. When marketing the green products, the impact of increased demand on the complementary products (biofuels) is often not taken into account (Unnasch and Pont 2004). The biofuel industry faces limited supply of feedstocks, e.g., corn and soybean, due to the scarcity in farmland, and the competing use of the feedstocks by the food industry (*Business Week* 2007a, *Business Week* 2007d, *Wall Street Journal* 2007a).[5] Given that current feedstock costs account for 70-80 percent

[4] Between 1999 and 2007, the annual average nominal price of West Texas Intermediate (WTI) crude oil price increased from \$20 to \$90 per barrel, and is expected to spike above \$100 (*Wall Street Journal* 2007c).

[5] To provide sufficient ethanol to replace all of the 130 billion gallons of gasoline used in the lightduty fleet,

of biofuel production cost, the limited supply of feedstock can easily drive up biofuel price (*McKinsey Quarterly* 2007).[6] Hence, a potential high demand for biofuels can raise the operating costs of the green vehicle, which in turn influences consumers' adoption decision. The scarce resource causes the utility of the consumers to be endogenously determined by the consumers' own choices. The scarcity of the green complementary products, compared with the ampleness of the complementary products (petroleum fuels) of conventional products, adds more dynamics to the interactions between the substitutive products.

Inferior Green Technology. Inferior green vehicle performance to conventional technologies is another main obstacle of promoting green vehicles. Although there are no additional costs for making green vehicles (Coelho and Goldemberg, 2004), some potential engine problems still exist.[7] Currently, no manufacturers guarantee their warranty services on green vehicles (Renewable Fuels Association 2006). Before the technology is improved, customers willingness to pay is low. Hence, firms need to evaluate the benefits of offering green products, by balancing growing number of green consumers and lagging green technology.

Fluctuating Petroleum Fuel Price. The crude oil price has been highly fluctuating. The resulting fluctuating petroleum fuel price creates both opportunities and risks to the vehicle manufacturers. Profitability of conventional vehicles may erode with high petroleum fuel prices. But the fuel price uncertainty can bring high values to the green vehicle adopters because of the green vehicle's fuel flexibility, which can be shared with the vehicle manufacturers.

This paper studies the optimal product strategy subject to the scarce supply of green fuels, and answers the following research questions: What is the optimal product strategy: single-product or two-product strategy? How do the petroleum fuel and biofuel prices influence the product and pricing strategy? How does the resource scarcity, or the size of green consumer segment, or the petroleum fuel price uncertainty play a role?

Our results confirm that the factors mentioned above have a significant impact on firms' product strategy, and exhibit interactions that must be well balanced. As the petroleum fuel price increases, the optimal product strategy transitions from the conventional vehicle only, to

it would be necessary to process the biomass growing on about one fourth of the 1.8-billion acre land area of the lower 48 states (Lave et al. 2001). Already worldwide, during the last decade per capita available cropland decreased 20 percent (Brown 1997). Since land is scarce, to expand outputs, either less fertile qualities of land must be cultivated, or the same qualities of land must be cultivated with processes which require less land per unit of product, but are more costly (Kurz and Salvadori 1997, Solow 1999).

[6] Corn prices have gone up 86 percent in year 2006 alone (U.S. Department of Agriculture 2007). Soybean prices has recently surged to the highest in 34 years (*FoxNews* 2007).

[7] Biodiesel is known to be linked to pre-mature engine jump failure and cold weather engine problems (U.S. Department of Agriculture 1998), while ethanol is corrosive in nature and vehicles must be operated properly (*Ethanol Producer Magazine* 2007).

both vehicles, and ultimately to the green vehicle only. However, in the case of scarce green fuel supplies, if the number of green consumers increases, the firm more likely will adopt the conventional vehicle only or two-vehicle strategies, and less likely the green vehicle only strategy, due to the potentially high green fuel price pushed up by demand. The green vehicle's fuel flexibility has its value only in the presence of uncertain petroleum fuel prices. Surprisingly, with the uncertainty, the green vehicle only strategy emerges as the optimal strategy also for low petroleum prices, due to the value generated from its fuel flexibility. Finally, different from the deterministic case, in which the green vehicle price is independent of the petroleum fuel price, the green vehicle price exhibits an interesting relationship with the petroleum fuel price.

The next section reviews relevant literature. Section 3 establishes a mathematical framework for consumer choice and firms' product strategy. In Section 4, two benchmark cases under the assumptions of ample green fuel supplies, or no fuel flexibility of the green vehicle, are analyzed. In Section 5, the assumptions are relaxed, in which a deterministic case is studied, followed by a case of fluctuating petroleum fuel prices. The impact of fuel prices and their interaction on firms' optimal product strategy is presented, and the resulting economic consequences are evaluated. Section 6 discusses contribution and limitations of the model, and suggests possible avenues for future research. Proofs are in Appendix A, and the environmental consequences are discussed in Appendix B.

2.2 Literature Review

This paper is related to four main streams of literatures: market segmentation, green marketing strategy, network externalities and ecological issues in business. Recently, researchers recognize the existence of green consumers who have new attitudes toward environmental values. Bei and Simpson (1995) suggest that, in addition to the utility obtained directly from a purchased good, green consumers also receive psychological benefits from buying an environmentally friendly product. Using conjoint analysis, Berger and Kanetkar (1995) found consumer preferences over environmental attributes by decomposing consumers' choices among multi-attributes of a product. Chen 2001, and Atasu et al. 2006 proposed green product strategies in which consumers are segmented according to the price premium the green consumers are willing to pay. Green consumers have higher valuations than conventional consumers due to a green attribute that has been embedded in the green products, i.e., the reuse of recycled inputs when the product is being produced, or the reduced waste when the product is being used. Namely, the green utility is known at the time of adoption. Our paper complements the literature by incorporating a green attribute (lower GHG emissions) that depends upon which type of complementary product is used. The green consumers' utility from the green product is partially unknown, at the time of adoption, particularly when the fuel prices are unknown.

The cannibalization effects of green products with conventional products are not widely discussed yet. Two examples are Chen 2001, and Atasu et al. 2006. Chen 2001 studies the single-product and two-product (green and ordinary) strategies, by focusing on an optimal balance between conflicting traditional and environmental attributes in designing the products. Atasu et al. 2006 consider the supply issue of the remanufacturable product - remanufacturable products are reusable returns from earlier sales. They study the impact of the existence of competitor on the profitability of remanufacturing strategy, which is shown to be more beneficial under competition. Our paper complements the literature by considering the limited supply of green resources. The limited resource causes the utility of the consumers to be endogenously determined by the consumers' own choices. The supply condition and consumers' interaction play a key role in firms' product strategy.

Thirdly, this paper is related to the literature on network externalities. The network externality arises because the utility that a user derives from a product depends upon the number of other users. The literature has mainly focused on positive externalities. Positive externality effects are present when consumers utility from using the product increases due to greater availability or variety of compatible complementary products (e.g., computer software, compact discs, digital programming, video game software) (Katz and Shapiro 1985, Cottrel and Koput 1998, Gupta et al. 1999, Gandal et al. 2000). Few studies have analyzed negative network externalities. Negative externalities arise because of the consumption of scarce resources. Asvanund et al. (2004) empirically found such negative effects of growing network size in the peer-to-peer (P2P) file sharing networks due to congestion. The scarcity of biofuels creates a similar negative externality issue in the automobile industry, along with some unique characteristics due to the presence of different consumer segments: green and conventional.

Lastly, there has been a growing body of literature addressing the ecological issues regarding natural resources, pollution, and waste. Shrivastava (1995) conceptually discusses the concept of "environmental technologies" as a growing competitive force and a tool for competitive advantage. Klassen and McLaughlin (1996) empirically show that environmental management initiatives are strongly linked to improved future financial performance, as measured by stock market performance. Several papers address the green issues in design, manufacturing and supply chains. Calcott and Walls (2000) look at the impacts of downstream waste disposal policies on upstream design for environment. King and Lenox (2001) performed a survey of the environmental impacts of just-in-time practises, and supported the idea that 'lean is green' overall. Zhu and Sarkis (2004), broke down the environmental effects into two categories – internal and external, and conclude that "Just-in-time programs with internal environmental management practices may cause further degradation of environmental performance and care". Our paper evaluates both economic and environmental consequences of firms' green product strategies.

2.3 The Model

Players and Products. We consider a monopoly manufacturer who makes a conventional vehicle and a flex-fuel vehicle. The conventional vehicle is powered by petroleum fuel, and the flex-fuel vehicle can operate on either petroleum fuel or biofuel. The conventional and flex-fuel vehicles are hereafter referred to as 'brown' and 'green' vehicles, respectively. The petroleum fuel and biofuel are hereafter referred to as 'brown' and 'green' fuels, respectively.

Fuel Supply. We consider two fuel sources.

Brown Fuel Brown fuel is a commodity. The market has ample supplies of brown fuel, and the price f_B is exogenously given.

Green Fuel Due to the limited supply of feedstocks for making green fuels, high demands can increase the green fuel price. For example, for every 100 million gallons of demand, the price of a bushel of soybeans is expected to increase by 10 cents, or a 6-cent increase in the unit production cost per gallon of biodiesel, according to National Biodiesel Board (2004). Hence, the inverse supply function is assumed to be a linearly increasing function of the demand q_G:

$$f_G = \alpha + \beta q_G \tag{2.1}$$

The intercept α is the base price before the introduction of the green fuel. The inverse price slope β is the increase of the price due to one unit increase of biofuel demand. It measures the impacts of the availability of farmland for planting biomass and the competition intensity between food and biofuel industries for feedstocks. Similar supply functions are used to model natural resource supplies (Kennedy 1974).

Demand. The consumers' willingness to pay is composed of two parts: the willingness to pay for the transport provided by the vehicle (or 'functional utility'), and the willingness to pay for the reduced green house gas (GHG) emission from biofuel combustion (or 'environmental utility').

Functional Utility Consumers have a functional utility θ for the brown vehicle, and a lower functional utility $\delta_1\theta$ for the green vehicle, where $\delta_1 < 1$, due to potential engine problems.

Environmental Utility Consumers are heterogeneous with respect to their utility from the GHG emission reduction. There are two segments of consumers: brown (denoted by segment 1) and green consumers (denoted by segment 2). The brown consumers do not value GHG emission reduction, and therefore have the same utility from combusting brown fuel and green fuels. This part of utility is normalized to zero. According to Straughan and Roberts (1999), a green consumer is a person who has a belief that individuals can play an important role in combating global warming. The green consumers thus have a positive utility, $(\delta_2 - \delta_1)\,\theta$, by combusting green fuel due to its reduced GHG emission, where $\delta_2 > 1 > \delta_1$.[8] Denote by v_B and v_G, the prices of brown vehicle and green vehicle. Given the assumptions, the consumers net utilities are obtained as shown in Table 2.1.

Table 2.1: Consumers Net Utility

	Brown Consumers	**Green Consumers**
Using Brown Vehicle with Brown Fuel	$\theta - (v_B + f_B)$	$\theta - (v_B + f_B)$
Using Green Vehicle with Brown Fuel	$\delta_1\theta - (v_G + f_B)$	$\delta_1\theta - (v_G + f_B)$
Using Green Vehicle with Green Fuel	$\delta_1\theta - (v_G + f_G)$	$\delta_2\theta - (v_G + f_G)$

The total market size is normalized to be unity. The proportion of the green consumers is $\gamma < 1$. We assume that the brown consumers are the majority: $\gamma < \frac{1}{2}$. Each consumer buys at most one unit of vehicle. We scale the number of fuel units consumed by each vehicle during its life cycle to one. Namely, each consumer buying one unit of vehicle also buys one unit of green or brown fuel.

Production Technology and Capacity. The marginal costs of making both types of vehicles are identical because green vehicles are made by making small changes to conventional vehicles. The marginal costs are normalized to zero. We assume that the manufacturer has sufficient capacity to meet the demand for both types of vehicles.

Manufacturer Decisions. The vehicle manufacturer has two decisions: which vehicle(s) to introduce, and at what prices(s).

Product Strategy The vehicle manufacturer can adopt two types of product strategies: single-product strategy and two-product strategy (or 'market-segmentation strategy'). Hereafter, the single-product strategy is referred to as 'brown-mass-marketing strategy' if the brown vehicle only, or 'green-mass-marketing strategy' if the green vehicle only; and the two-product strategy 'market-segmentation strategy'.

Pricing The manufacturer sets prices for the brown and green vehicles, v_B and v_G.

[8] US Department of Energy (www.fueleconomy.gov) provides a calculator to help users calculate the amount of GHG saved by driving a flex-fuel vehicle.

Consumers Decisions. Consumers decide which vehicle to adopt and which fuel to use.
Vehicle Choice Consumers decide whether to purchase a vehicle, and if so, in the case of the 'market-segmentation strategy', which type of vehicle to adopt: green or brown.
Fuel Choice In the case that the green vehicle is adopted, consumers decide which type of fuel to use: green or brown.
In the following, we use (V_1F_1, V_2F_2) to denote the consumers' vehicle and fuel consumption choices, in which the segment $i \in \{1, 2\}$ consumers adopt $V_i \in \{B, G\}$ type vehicle, and use $F_i \in \{B, G\}$ type fuel.
Illustration of Vehicle and Fuel Economies. We use the vehicle and fuel cost calculator at the US Department of Energy (www.fueleconomy.gov) to illustrate the model. We use Chevrolet Impala as an example, the retail price of which is about \$22,000. The retail prices of gasoline and E85 fuel are \$3.10 and \$2.60 per gallon, respectively, in 2007 November in Illinois, for example.[9] Driving 15,000 miles a year for 10 years costs \$18,900 gasoline, or \$21,000 E85, which are comparable to the vehicle prices. The lower energy content of E85, 20-30 percent fewer miles per gallon, has been taken into account in the total E85 fuel cost. The cost of E85 is about 10 percent higher than that of gasoline, which is in the range of the green consumers' willing to pay according to a recent survey by Canalys (2007).

Model parameters are summarized in Table 2.2.

Table 2.2: Model Parameters

Notations	Meanings
α	green fuel price intercept
β	green fuel inverse price slope
a	brown fuel price mean
$\frac{1}{3}b^2$	brown fuel price variance
γ	green segment size
θ	consumers utility from brown vehicle + brown fuel
δ_1	brown (green) consumers utility coefficient from green vehicle + either (brown) fuel
δ_2	green consumers utility coefficient from green vehicle + green fuel

[9] E85 is a mixture of 85 percent ethanol and 15 percent gasoline.

2.4 The Benchmark Cases

2.4.1 Case 1: No Scarcity

In this section, we study a benchmark case in which the green fuel supply is perfectly inelastic, i.e., $\beta = 0$, or the green fuel price f_G is fixed. The firm sets vehicle prices v_B and v_G such that both segments select the brown vehicle (brown-mass-marketing) or the green vehicle (green-mass-marketing), or the two segments select different vehicles (market-segmentation). The following proposition suggests which strategy arises as the optimum, depending upon the fuel prices.

Proposition 1. *The optimal product strategy:*

$$(V_1F_1, V_2F_2) = \begin{cases} (BB, BB) & \text{if } f_B \leq \underline{f}_B \\ (BB, GG) & \text{if } f_B \in \left(\underline{f}_B, \overline{f}_B\right] \\ (GG, GG) & \text{if } f_B > \overline{f}_B \end{cases}$$

where

$$\underline{f}_B = (1 - \delta_2)\,\theta + f_G,\ \overline{f}_B = \frac{1}{1-\gamma}\left[1 - \gamma - \delta_1 + \gamma\delta_2\right]\theta + f_G$$

The optimal vehicle prices are:

$$In\ \ (BB, BB) : \ v_B^{m*} = \theta - f_B \tag{2.2}$$

$$In\ \ (BB, GG) : \ \ (v_B^{s*}, v_G^{s*}) = (\theta - f_B, \delta_2\theta - f_G) \tag{2.3}$$

$$In\ \ (GG, GG) : \ v_G^{m*} = \delta_1\theta - f_G \tag{2.4}$$

Proposition 1 suggests that the relative size of the green segment and the fuel prices determine the optimal strategy as follows. When the brown fuel price f_B is low relative to green fuel price f_G, $f_B \leq \underline{f}_B$, the brown vehicle can be offered at a high price, and is therefore more profitable than the green vehicle. Hence, the firm offers the brown vehicle only, i.e., brown-mass-marketing strategy, and both segments use brown fuel, i.e., (BB, BB), as shown in Figure 2.1(a). When the brown fuel price is relatively high, $f_B > \overline{f}_B$, the green vehicle is more profitable. The firm adopts the green-mass-marketing strategy, and both segments use green fuel due to its lower price than the brown fuel, i.e., (GG, GG). When the two fuel prices are comparable, $f_B \in \left(\underline{f}_B, \overline{f}_B\right]$, the difference in consumers willingness to pay for the two vehicles plays a role. Brown consumers are willing to pay higher for the brown vehicle, while the green consumers are willing to pay higher for the green vehicle. Hence, the firm gains more profits by selling

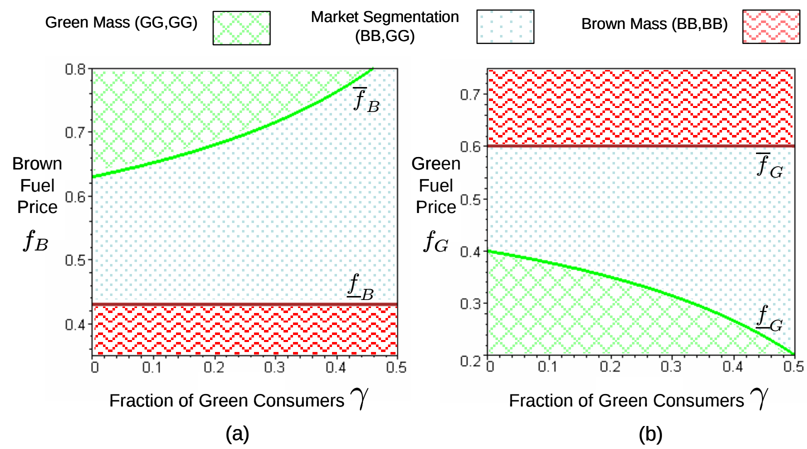


Figure 2.1: Benchmark Case 1 - Optimal Product Strategies

different vehicles to different segments, i.e., (BB, GG). In this market-segmentation strategy, hereafter referred to as 'regular market-segmentation strategy', the green vehicle is offered at a higher price, v_G^{s*}, than in the green-mass-marketing strategy, v_G^{m*}, as shown in Figure 2.2, due to the green consumers higher willingness to pay than the brown consumers. Note that, in this regular market-segmentation strategy, the green consumers do not choose brown fuel, because otherwise, the firm obtains lower profits than in the brown-mass-marketing strategy due to the green consumers lower environmental utility (see Table 2.1). The brown (or green) fuel price regions in which each of above strategies is optimal are shown in Figure 2.1(a) (or Figure 2.1(b)).

As the fraction of green consumers, γ, increases, it is more likely that the firm adopts the market-segmentation strategy, but less likely the green-mass-marketing strategy, as shown in Figure 2.1. Compared with the regular market-segmentation strategy, the green vehicle has to be offered at a lower price in the green-mass-marketing strategy, due to the brown consumers lower willingness to pay, as shown in Figure 2.2(a). The firm thus reaps higher profits from the green consumers in the market-segmentation strategy than in the green-mass-marketing strategy. This profit surplus increases with the size of green segment γ. This is why a larger green segment leads to a large region of the market-segmentation strategy. The green segment size γ, however, has no impact on the brown-mass-marketing strategy because no green vehicle is offered in this strategy.

As shown in Figure 2.2, the optimal brown (or green) vehicle prices, v_B^{m*} in brown-mass-marketing and v_B^{s*} in market-segmentation (or v_G^{m*} in green-mass-marketing and v_G^{s*} in market-segmentation), are decreasing in the brown fuel price f_B (or green fuel price f_G). The firm must reduce the vehicle prices in order to offset the impact of the fuel price increase. Because the

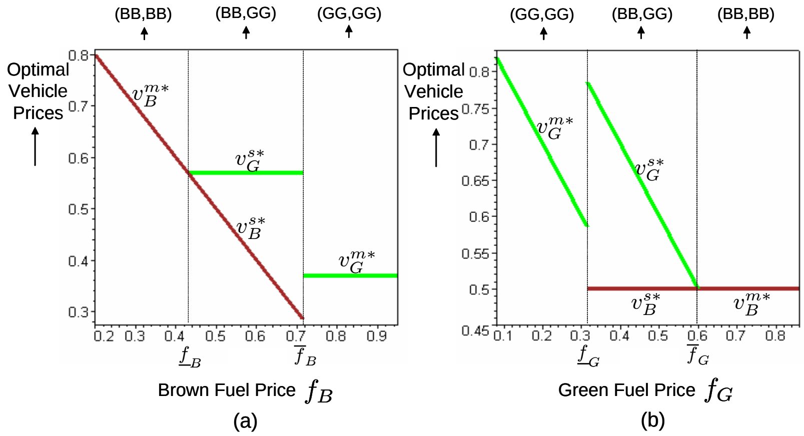


Figure 2.2: Benchmark Case 1 - Optimal Vehicle Prices

brown (or green) vehicle is powered by brown (or green) fuel, its price is independent of the other type of fuel price: green (or brown), in each strategy region.

The firm's optimal profits in green-mass-marketing, brown-mass-marketing and regular market-segmentation strategies are given by: $\Pi_G^* = v_G^{m*}$, $\Pi_B^* = v_B^{m*}$, and $\Pi_{BG}^* = (1-\gamma)\, v_B^{s*} + \gamma v_G^{s*}$, respectively. We then have the following lemma about the preference of the firm on the size of green segment:

Lemma 1. $\frac{\partial \Pi_{BG}^*}{\partial \gamma} > 0$, $\frac{\partial \Pi_G^*}{\partial \gamma} = \frac{\partial \Pi_B^*}{\partial \gamma} = 0$.

In the case of the regular market-segmentation strategy, the firm prefers the largest possible green segment size because of higher profitability of the green vehicle than the brown vehicle: $v_G^{s*} > v_B^{s*}$. In the mass-marketing strategies, the firm is indifferent.

2.4.2 Case 2: No Fuel Flexibility

In this section, we study a benchmark case in which the green fuel supply is elastic, i.e., $\beta > 0$, but the green vehicle can only be operated on the green fuel. The following proposition suggests which strategy arises as the optimum, depending upon the fuel prices.

Proposition 2. *The optimal product strategy:*
(1) If $\gamma < \frac{1}{\beta}(\delta_2 - \delta_1)\,\theta$*, or* $\gamma > \widehat{\gamma}$*:*

$$(V_1F_1, V_2F_2) = \begin{cases} (BB,BB) & \text{if } f_B \le \underline{f}_B \\ (BB,GG) & \text{if } f_B \in \left(\underline{f}_B, \overline{f}_B\right] \\ (GG,GG) & \text{if } f_B > \overline{f}_B \end{cases}$$

(2) If $\gamma \in \left[\frac{1}{\beta}\left(\delta_2 - \delta_1\right)\theta, \widehat{\gamma}\right]$:

$$\textit{if } \gamma < \widehat{\gamma} : (V_1F_1, V_2F_2) = \begin{cases} (BB, BB) & \textit{if } f_B \leq \underline{f}_B \\ (BB, GG) & f_B \in \left(\underline{f}_B, \widehat{f}_B\right] \\ (GG, BB) & \textit{if } f_B \in \left(\widehat{f}_B, \overline{\overline{f}}_B\right] \\ (GG, GG) & \textit{if } f_B > \overline{\overline{f}}_B \end{cases}$$

The optimal vehicle prices are:

$$\textit{In } (BB, BB): v_B^{m*} = \theta - f_B \tag{2.5}$$

$$\textit{In } (BB, GG): \left(v_B^{s*}, v_G^{s*}\right) = \left(\theta - f_B, \delta_2\theta - (\alpha + \beta\gamma)\right) \tag{2.6}$$

$$\textit{In } (GG, BB): \left(v_B^{s*}, v_G^{s*}\right) = \left(\theta - f_B, \delta_1\theta - (\alpha + \beta\left(1 - \gamma\right))\right) \tag{2.7}$$

$$\textit{In } (GG, GG): v_G^{m*} = \delta_1\theta - (\alpha + \beta) \tag{2.8}$$

Proposition 2 suggests that when the green segment size is large enough, $\gamma > \frac{1}{\beta}\left(\delta_2 - \delta_1\right)\theta$, another market-segmentation strategy, (GG, BB), is feasible, in which the brown consumers adopt the green vehicle, while the green consumers adopt the brown vehicle, hereafter referred to as 'irregular market-segmentation strategy'. By offering green vehicle to the brown consumers, the green fuel price, $f_G = \alpha + \beta\left(1 - \gamma\right)$, is low due to the small number of users, $1 - \gamma$. The firm can thus price vehicles such that the brown consumers have no incentive to switch to the brown vehicle due to the low green fuel price, and the green consumers have no incentive to switch to green vehicle due to the potentially high green fuel price in the case of switching of the large number of users, γ.

However, this irregular market-segmentation strategy is optimal only when the brown fuel price is not very high, $f_B \in \left(\widehat{f}_B, \overline{\overline{f}}_B\right]$, and the green segment size is not very large, $\gamma < \widehat{\gamma}$, as shown in Figure 2.3(b). At low prices f_B of the brown fuel, this strategy is dominated by the regular market-segmentation strategy (BB, GG). At low brown fuel prices, the firm is able to charge a relatively high price for its brown vehicle, $v_B^{s*} = \theta - f_B$, as shown in Figure 2.4(b). The firm therefore should exploit the higher willingness to pay of the brown consumers to the brown vehicle than to the green vehicle, and the higher willingness to pay of the green consumers to the green vehicle than to the brown vehicle, by adopting the regular market-segmentation strategy. When the brown fuel price f_B increases to a certain level $\widehat{f}_B$, the profitability of the brown vehicle erodes such that the negative effect of the high green fuel price, $f_G = \alpha + \beta\gamma$, dominates, due to the large number of users γ. The firm should then switch to the irregular market-segmentation strategy in order to mitigate the high green fuel price effect, by offering the green vehicle to the brown consumers instead. Because of the brown consumers low willingness to pay, the green vehicle price decreases, as shown in Figure 2.4(b). At very high prices f_B of the brown fuel, $f_B > \overline{\overline{f}}_B$, the profitability of the brown vehicle reduces to a very low level such that the green vehicle is more profitable, even at the highest green fuel price, $f_G = \alpha + \beta$, by offering it to all consumers. The irregular market-segmentation strategy is thus dominated by the green-mass-marketing strategy (GG, GG). The green vehicle price is further reduced to a lower level, as shown in Figure 2.4(b), because more adopters lead to a higher green fuel price. The expressions of the critical values of the brown fuel price, $\underline{f}_B$, $\overline{f}_B$, $\widehat{f}_B$,and $\overline{\overline{f}}_B$, can be found in Appendix.

When the green segment size γ is very large, $\gamma > \widehat{\gamma}$, the irregular market-segmentation strategy (GG, BB) is dominated at all possible fuel prices, by either the regular market-segmentation strategy (BB, GG) or the green-mass-marketing strategy (GG, GG), because of more adopters of the less-profitable brown vehicle (see the relatively low brown vehicle price v_B^{s*} in the (GG, BB) region in Figure 2.4(b)).

In the case of small green segment sizes, $\gamma < \frac{1}{\beta}(\delta_2 - \delta_1)\theta$, it is similar to the above benchmark case 1, as shown in Figure 2.4(a).

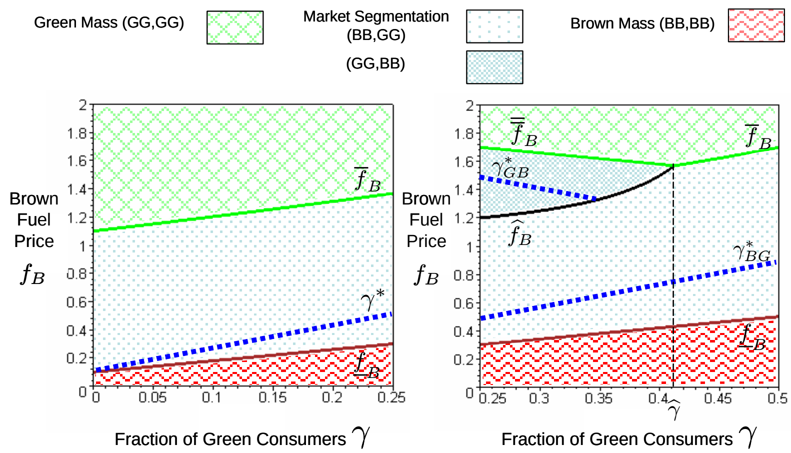
Different from the previous case, due to the green fuel supply effects, when the number of green consumers, γ, increases, it is now more likely that the firm will adopt the brown-mass-marketing (BB, BB), while less likely the regular market-segmentation strategy (BB, GG), as shown in Figure 2.3. This is due to the eroding profitability of the green vehicle because of the increasing number of adopters. The vehicle price $v_G^{s*} = \delta_2\theta - (\alpha + \beta\gamma)$ in the regular market-segmentation strategy decreases with γ.

Similar to the above benchmark case 1, the brown (or green) vehicle prices are independent of the other type of fuel price: green (or brown), within each strategy region, while decreases in brown (or green) fuel price, as shown in Figure 2.4.

The firm's optimal profits in the regular and irregular market-segmentation strategies (BB, GG) and (GG, BB) are given by: $\Pi_{BG}^* = (1-\gamma)\, v_B^{s*} + \gamma v_G^{s*}$, and $\Pi_{GB}^* = \gamma v_B^{s*} + (1-\gamma)\, v_G^{s*}$, respectively. Due to the green fuel supply effects, the firm may not prefer large green segment sizes. The following lemma suggests the preference of the firm on the green segment size γ:

Lemma 2. *(1) $\Pi_{BG}^*(\gamma)$ is concave in γ, and is maximized at*

$$\gamma_{BG}^* = \frac{1}{2\beta}\left[f_B - (1-\delta_2)\,\theta - \alpha\right]$$



(a) $\beta\gamma \leq (\delta_2 - \delta_1)\theta$ (b) $\beta\gamma > (\delta_2 - \delta_1)\theta$

Figure 2.3: Benchmark Case 2 - Optimal Product Strategies

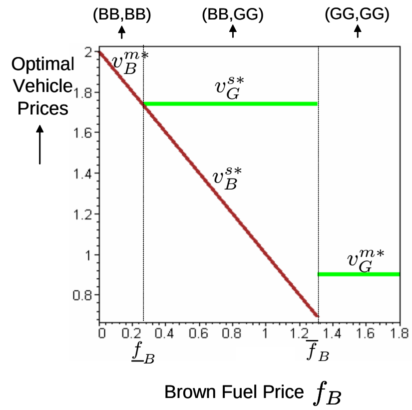
(2) $\Pi^*_{GB}(\gamma)$ *is concave in* γ*, and is maximized at*

$$\gamma^*_{GB} = \frac{1}{2\beta}\left[-f_B + (1-\delta_1)\theta + \alpha + 2\beta\right]$$

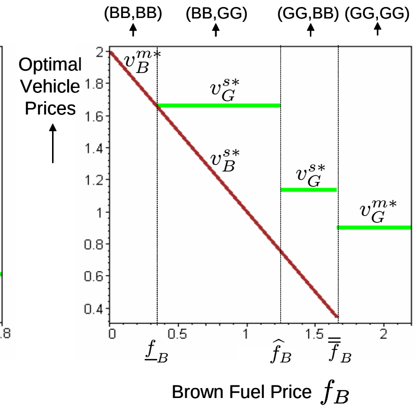
In the region where the market-segmentation strategies are optimal, the manufacturer prefers a medium green segment size γ (see γ^*_{BG} and γ^*_{GB} Figure 2.3). As the brown fuel price f_B increases, this optimal green segment size γ^*_{BG} increases in the regular market-segmentation strategy because the green consumers adopt the more profitable green vehicle. However, γ^*_{GB} decreases in the irregular market-segmentation strategy because the green consumers adopt the less profitable brown vehicle. In both strategies, the green vehicle price is higher than the brown vehicle price $v^{s*}_G > v^{s*}_B$, as shown in Figure 2.4(b). However, the firm's optimal profits at the optimal γ^*, in both strategies:

$$\begin{aligned}
\Pi^*_{BG}(\gamma^*) &= \left(1 - \frac{1}{2\beta}\left[f_B - (1-\delta_2)\theta - \alpha\right]\right)(\theta - f_B) + \frac{1}{4\beta}\left[f_B - (1-\delta_2)\theta - \alpha\right]\left[(1+\delta_2)\theta - \alpha - f_B\right] \\
\Pi^*_{GB}(\gamma^*) &= \left(1 - \frac{1}{2\beta}\left[f_B - (1-\delta_1)\theta - \alpha\right]\right)(\theta - f_B) + \frac{1}{4\beta}\left[f_B - (1-\delta_1)\theta - \alpha\right]\left[(1+\delta_1)\theta - \alpha - f_B\right]
\end{aligned}$$

decrease with the brown fuel price f_B (since $\frac{\partial \Pi^*_{BG}(\gamma^*)}{\partial f_B} = \frac{\partial \Pi^*_{GB}(\gamma^*)}{\partial f_B} = -(1-\gamma^*) < 0$). This is because the negative effect of eroding profitability of the brown vehicle dominates the positive effect of increasing number of more profitable green vehicle adopters (γ^*_{BG} in regular, and $1-\gamma^*_{GB}$ in irregular market-segmentation strategy).



(a) $\gamma \leq (\delta_2 - \delta_1)\theta/\beta$ or $\gamma > \widehat{\gamma}$



(b) $\gamma > (\delta_2 - \delta_1)\theta/\beta$

Figure 2.4: Benchmark Case 2 - Optimal Vehicle Prices

2.5 The Analysis of Scarcity and Fuel Flexibility

In this section, we relax the assumptions of the above benchmark cases, such that (1) the green fuel price is sensitive to demand, i.e., $\beta > 0$; and (2) the green vehicle can be powered by either green fuel or brown fuel.

2.5.1 Deterministic Petroleum Fuel Prices

In this section, we assume that the brown fuel price f_B is fixed. The green vehicle has a fuel flexibility. Compared with the above inflexible cases, there are other feasible strategies in which the firm prices the vehicles such that the green vehicle adopters use the brown fuel. In these cases, both brown and green consumers willingness to pay for the green vehicle, $\delta_1\theta - f_B$, is lower than that for the brown vehicle, $\theta - f_B$. Hence, these strategies must be dominated by the strategy in which the same consumers adopt the brown vehicle. It immediately follows that the firm's optimal product strategy is the same as in the above benchmark case 2, i.e., in Proposition 2. Hence, we have the following conclusions:

- Under deterministic fuel prices, the fuel flexibility of green vehicle does not bring any value to the firm. Given that the fuel prices are known at the vehicle adoption time, the green vehicle adopters always choose the green fuel.
- Under scarce green fuel supplies, when the number of green consumers increases, it is more likely that the firm will adopt the brown-mass-marketing strategy (BB, BB) because high

demand increases the green fuel price. Because of the same reason, an irregular market-segmentation strategy (GG, BB) can emerge when the green segment size is relatively large, and the brown fuel price is relatively high.

2.5.2 Uncertain Petroleum Fuel Prices

In this section, we consider that the brown fuel price f_B is uncertain. The game proceeds as follows:

- The firm decides which vehicle(s) to offer, and at what price(s): v_B and v_G;
- The consumers decide which vehicle to purchase; and
- The brown fuel price f_B is then revealed and the consumers decide which type of fuel to power their vehicles.

We consider that f_B follows a Uniform distribution over $[a-b, a+b]$, with mean a, and variance $\frac{1}{3}b^2$. The scarce green fuel supply effect must be taken into account due to limited farmland, but the effect should not be so strong that it dominates the high willingness to pay of green consumers and the vehicle manufacturers adopt the irregular market-segmentation strategy. The U.S. government is improving regulations and financial incentive programs in the biofuel industry in order to reduce the green fuel price sensitivity, as well as incentive programs for end-users.[10] The former reduces the parameter β, and the latter improves the green consumers willingness to pay, $\delta_2\theta$. Hence, in the following, we limit our analysis to the situations in which the following holds:

$$\beta\gamma \leq (\delta_2 - \delta_1)\,\theta \tag{2.9}$$

The irregular market-segmentation strategy (GG, BB) never arises as an optimal strategy. Namely, it is always more profitable to sell the green vehicle to the green consumers than to the brown consumers. In addition, we assume that

$$a + b \geq \alpha \tag{2.10}$$

[10] Government financial incentive programs support capacity expansion of ethanol production (US Department of Agriculture 2006). The Energy Policy Act (EPACT) of 2005 requires the use of 7.5 billion gallons of ethanol, or about 6% of all U.S. transportation fuels in 2012 (*Ethanol Producer Magazine* 2006). The EPACT of 2005 also offers individual consumers and businesses federal tax credits beginning in January 2006 for purchasing vehicles combusting biofuels (US Department of Energy 2005).

i.e., the highest possible brown fuel price is higher than the base price of the green fuel. Otherwise, the green vehicle is always less profitable than the brown vehicle. The green vehicle can be both less and more profitable than the brown vehicle given today's highly fluctuating brown fuel prices.

In the following, before presenting which product strategy arises as the optimum, we first study the cases in which the firm adopts only the mass-marketing strategy, or the market-segmentation strategy.

Mass-Marketing Strategies

Brown-Mass-Marketing Strategy.
When the firm adopts the brown-mass-marketing strategy by setting a price v_B, the consumers adopt if the expected utility is positive: $E\left[\theta - v_B - f_B\right] > 0$, or $\theta - v_B - a > 0$. Hence, the firm sets the optimal vehicle price such that no rents are offered to consumers:

$$v_B^{m*} = \theta - a \tag{2.11}$$

Green-Mass-Marketing Strategy.
If the firm adopts the green-mass-marketing strategy, the green vehicle users can choose either type of fuels, after they observe the brown fuel price. In the following, we first analyze the consumers equilibrium fuel choices given a realization of brown fuel price f_B. The fuel choices $k_i \in \{G, B\}$ of consumer segment $i \in \{1, 2\}$ determines the green fuel price $f_G = P_G^f\left(k_1, k_2\right)$ according to:

$$P_G^f\left(k_1, k_2\right) = \alpha + \beta q_G\left(k_1, k_2\right)$$

where $q_G\left(k_1, k_2\right)$ is the number of consumers who use the green fuel given the choices, as shown in Appendix. The green fuel price in turn determines the consumers' utility from adopting the green vehicle, and hence their vehicle purchase decision. Therefore, the green fuel supply scarcity creates externalities among consumers: when making their purchase decision, consumers take into account other consumers' fuel choice. Given the green vehicle price v_G, and the realization of the brown fuel price f_B, the consumers equilibrium fuel choices $\left(k_1^*, k_2^*\right)$ can be derived as follows:

Lemma 3. *If both segments adopt the green vehicle, the equilibrium fuel choices are:*

$$\left(k_1^*, k_2^*\right) = \begin{cases} (B, B) & \text{if } f_B \leq \alpha + \beta\gamma - \left(\delta_2 - \delta_1\right)\theta \\ (B, G) & \text{if } f_B \in \left(\alpha + \beta\gamma - \left(\delta_2 - \delta_1\right)\theta, \alpha + \beta\right] \\ (G, G) & \text{if } f_B > \alpha + \beta \end{cases} \tag{2.12}$$

When the brown fuel price is low, both segments use the brown fuel; when the brown fuel price is high, both segments use the green fuel; and when the brown fuel is medium, the brown (or green) consumers use brown (or green) fuel due to green consumers' higher willingness to pay. Given consumers equilibrium fuel choices for different realizations of the brown fuel price f_B, we can derive consumer segment i's, $i \in \{1, 2\}$, expected utilities $\widetilde{U}_G^i$ of adopting the green vehicle, as shown in Appendix. The firm then sets the optimal vehicle price $v_G^{m*} = \min\left(\widetilde{U}_G^1, \widetilde{U}_G^2\right)$, such that no rents are offered to the segment with lower expected utility. It can be shown that the brown consumers' expected utility $\widetilde{U}_G^1$ determines the optimal green vehicle price:

Lemma 4. *In the green-mass-marketing strategy, the firm's optimal green vehicle price is:*

$$v_G^{m*} = \begin{cases} \delta_1\theta - \alpha - \beta & \text{if } \alpha + \beta \leq a - b \\ \frac{[(\alpha+\beta)-(a-b)]^2}{4b} + \delta_1\theta - \alpha - \beta & \text{if } \alpha + \beta \in [a - b, a + b] \\ \delta_1\theta - a & \text{if } \alpha + \beta > a + b \end{cases} \tag{2.13}$$

The price uncertainty can increase consumers willingness to pay for green vehicle because of its fuel flexibility. The price premium that the firm can charge for its green vehicle, compared with the deterministic case ($v_G^{m*} = \delta_1\theta - (\alpha + \beta)$ in (2.8)), is referred to as the value of fuel flexibility. The value of flexibility is positive, i.e., $\frac{[(\alpha+\beta)-(a-b)]^2}{4b}$, only if the possible brown fuel prices are in a medium region such that $\alpha + \beta \in [a - b, a + b]$, i.e., the price regions of the two fuels have some overlaps. The fuel flexibility has no value if the brown fuel price is always higher than the green fuel price, i.e., $\alpha + \beta \leq a - b$, or the green fuel price is higher, i.e., $\alpha + \beta > a + b$. In the former case, the consumers always choose green fuel, and in the latter case, brown fuel. The value of flexibility, $\frac{[(\alpha+\beta)-(a-b)]^2}{4b}$, decreases with the brown fuel price mean a. Increasing brown fuel price mean reduces the likelihood of using the brown fuel, and in turn the value of flexibility stemming from the brown fuel price uncertainty. The value of flexibility increases with the brown fuel price uncertainty level, characterized by b. Higher brown fuel price uncertainty, higher possibility the consumers can switch between the two fuels.

Optimal Mass-Marketing Strategy.

Depending upon the brown fuel price parameters, and their relationship with the green fuel price, the firm chooses between green and brown-mass-marketing strategies. The firm obtains profits $\Pi_G^* = v_G^{m*}$ and $\Pi_B^* = v_B^{m*}$ in green-mass-marketing, and brown-mass-marketing strategies, respectively. Define the following critical values of a and b: when $a = a_{gb}, a_{bg}$, $\Pi_G^* = \Pi_B^*$, with $a_{gb} < a_{bg}$, and when $b = b_{bg}$, $\Pi_G^* = \Pi_B^*$. We then have the following optimal mass-marketing strategy.

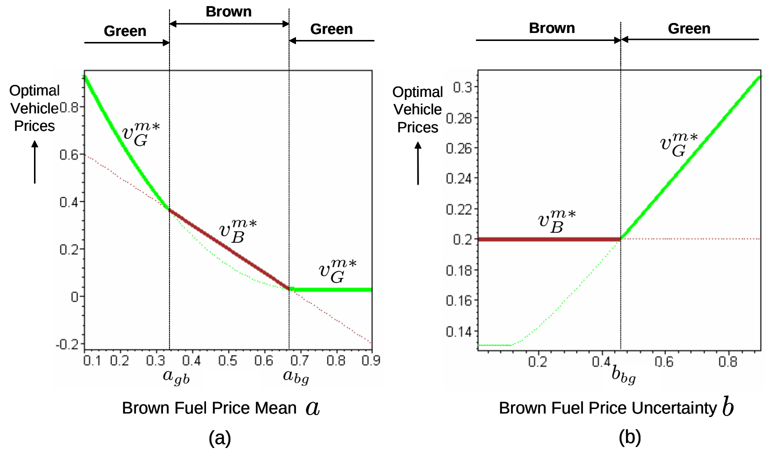


Figure 2.5: Uncertain Case - Optimal Mass Marketing Strategy and Prices as a Function of Brown Fuel Price Mean and Uncertainty

Lemma 5. *The optimal mass-marketing strategy is:*

$$\begin{cases} \textit{Brown-Mass} & \textit{if } a \in [a_{gb}, a_{bg}] \textit{ or } b < b_{bg} \\ \textit{Green-Mass} & \textit{otherwise} \end{cases}$$

As shown in Figure 2.5(a), different from the deterministic case, the green-mass-marketing strategy is optimal also for low brown fuel prices, or low means a. The green-mass-marketing strategy is optimal only for high uncertainties of brown fuel prices, b, as show in Figure 2.5(b). This is due to the value of flexibility, which increases as the mean decreases or the standard deviation increases, as explained above. In addition, different from the deterministic case (Figure 2.4), the green vehicle price v_G^{m*} is not independent of the brown fuel price parameters, due to the value of flexibility.

Market-Segmentation Strategies

Given the above small green segment size Assumption (2.9), the only possible market-segmentation strategy is that the brown and green consumers adopt the brown and green vehicles, respectively, i.e., the regular market-segmentation strategy. We then have:

Lemma 6. *In the market-segmentation strategy, the firm's optimal prices are*

$$v_B^{s*} = \theta - a$$

$$v_G^{s*} = \begin{cases} \delta_2\theta - \alpha - \beta\gamma & \text{if } \alpha + \beta\gamma - (\delta_2 - \delta_1)\,\theta \le a - b \\ \frac{[(\alpha+\beta\gamma)-\theta(\delta_2-\delta_1)-(a-b)]^2}{4b} + \delta_2\theta - \alpha - \beta\gamma & \text{if } \alpha + \beta\gamma - (\delta_2 - \delta_1)\,\theta \in [a-b, a+b] \\ \delta_1\theta - a & \text{if } \alpha + \beta\gamma - (\delta_2 - \delta_1)\,\theta > a + b \end{cases} \tag{2.14}$$

In the market-segmentation strategy, the optimal brown vehicle price is equal to the price in the deterministic case in expectation (see (2.5)). Similar to the green-mass-marketing strategy, the fuel flexibility of the green vehicle derives some value to the firm, $\frac{[(\alpha+\beta\gamma)-\theta(\delta_2-\delta_1)-(a-b)]^2}{4b}$, when the possible brown fuel prices are in a medium region. Similarly, the value of flexibility, $\frac{[(\alpha+\beta\gamma)-\theta(\delta_2-\delta_1)-(a-b)]^2}{4b}$, decreases with the brown fuel price mean a and increases with the brown fuel price uncertainty level b.

Optimal Product Strategies

The firm chooses between mass-marketing and market-segmentation strategies, depending upon the fuel prices. The firm obtains profits $\Pi_{BG}^* = (1-\gamma)\, v_B^{s*} + \gamma v_G^{s*}$, in the market-segmentation strategy. Define the following critical values of a and b: when $a = a_{bs}$ or $b = b_{bs}$, $\Pi_B^* = \Pi_{BG}^*$, and when $a = a_{gs}, a_{gs}$, or $b = b_{sg}$, $\Pi_G^* = \Pi_{BG}^*$, with $a_{gs} < a_{gs}$. Let $\gamma = \widehat{\gamma}_a$ such that $a_{gb} = a_{bs}$. Let $\gamma = \widehat{\gamma}_b$ such that $a_{bs} = 0$. We then have the following Proposition (3).

Proposition 3. *The optimal product strategy is:*

$$\text{If } \gamma \;\le\; \widehat{\gamma}_a\text{:}\;\; (V_1F_1, V_2F_2) = \begin{cases} \text{Green-Mass} & \text{if } a \le a_{gs} \\ \text{Market-Seg} & \text{if } a \in (a_{gs}, a_{sg}] \\ \text{Green-Mass} & \text{if } a > a_{sg} \end{cases}$$

$$\text{If } \gamma \;>\; \widehat{\gamma}_a\text{:}\;\; (V_1F_1, V_2F_2) = \begin{cases} \text{Green-Mass} & \text{if } a \le a_{gb} \\ \text{Brown-Mass} & \text{if } a \in (a_{gb}, a_{bs}] \\ \text{Market-Seg} & \text{if } a \in (a_{bs}, a_{sg}] \\ \text{Green-Mass} & \text{if } a > a_{sg} \end{cases}$$

Or,

$$\text{If } \gamma \le \widehat{\gamma}_b\text{:}\;\; (V_1F_1, V_2F_2) = \begin{cases} \text{Market-Seg} & \text{if } b \le b_{sg} \\ \text{Green-Mass} & \text{if } b > b_{sg} \end{cases}$$

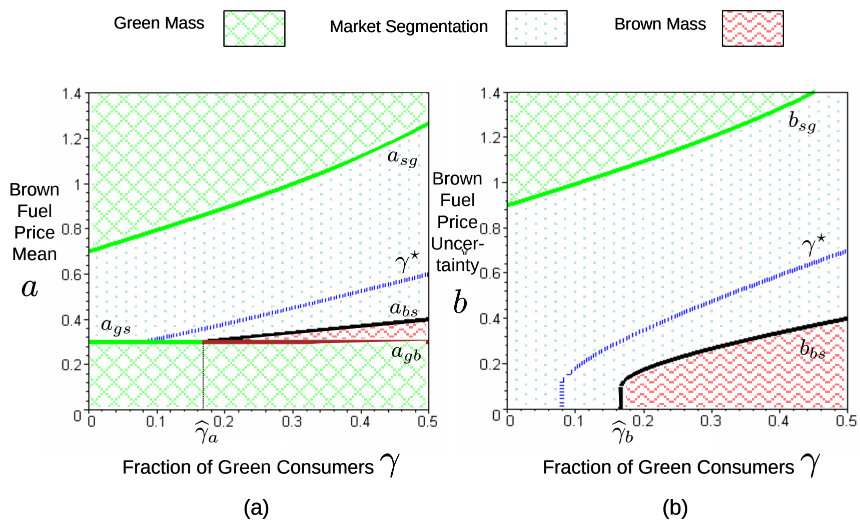


Figure 2.6: Uncertain Case - Optimal Product Strategies

$$\textit{If } \gamma > \widehat{\gamma}_b\text{: } (V_1F_1, V_2F_2) = \begin{cases} \textit{Brown-Mass} & \textit{if } b \leq b_{bs} \\ \textit{Market-Seg} & \textit{if } b \in (b_{bs}, b_{sg}] \\ \textit{Green-Mass} & \textit{if } b > b_{sg} \end{cases}$$

Different from the deterministic case, also for some low values of the brown price mean a, the green-mass-marketing strategy arises as the optimum, as shown in Figure 2.6(a). This is because of the increasing value of flexibility of green vehicle as the price mean a decreases at its low values (Lemma 4, or Figure 2.5(a)). The green-mass-marketing strategy arises as the optimum only for high uncertainties, b, as shown in Figure 2.6(b). This because of the monotonically increasing value of flexibility as the price uncertainty b increases (Lemma 4, or Figure 2.5(a)). When the size of green consumer segment is small enough, $\gamma < \widehat{\gamma}_a$ (or $\gamma < \widehat{\gamma}_b$), the brown-mass-marketing strategy is dominated by the market-segmentation strategy, and never arises as an optimal strategy, because the green vehicle is now more profitable than the brown vehicle due to the low green fuel price, $f_G = \alpha + \beta\gamma$.

The optimal vehicle prices are given in (2.11), (2.13), and (2.14). The green vehicle price v_G^{m*} can decrease with the brown fuel price mean due to decreasing value of flexibility, as shown in Figure 2.7(a), or increase with the brown fuel price uncertainty due to increasing value of flexibility, as shown in Figure 2.7(b).

We have the following observations concerning the firm's optimal profits:

The impact of brown fuel price mean and uncertainty on the optimal profits.

The firm's optimal profits generally decrease with the brown fuel price mean a, as shown in

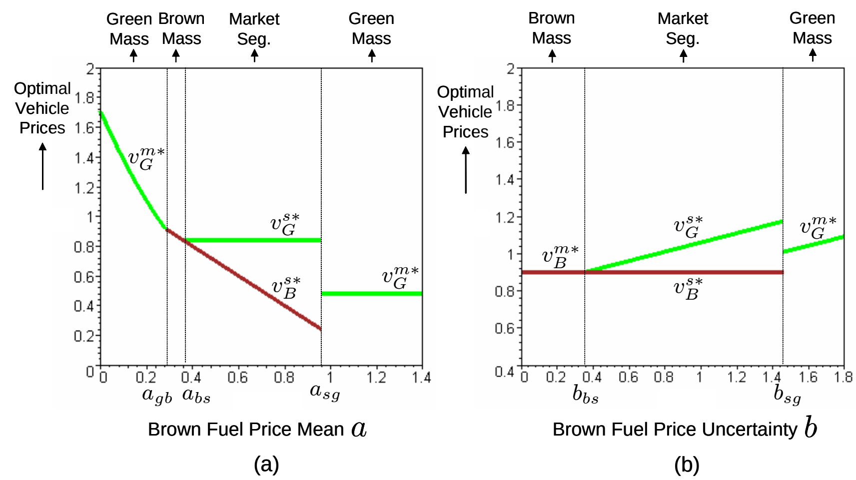


Figure 2.7: Uncertain Case - Optimal Vehicle Prices as a Function of Brown Fuel Price Mean and Uncertainty

Figure 2.8(a), and increase with the price uncertainty b, as shown in Figure 2.8(b). This is due to the value of flexibility effects of the green vehicle, and the brown fuel price effects on the brown vehicle price.

The impact of green segment size γ on the optimal profits.

In the region of market-segmentation strategy, the optimal profit Π_{BG}^* first increases then decreases with the green segment size γ. Hence, the firm prefers medium sizes of the green segment, due to the green fuel scarcity effect. As the price mean a or uncertainty b increases, the optimal segment size γ^* increases, as shown in Figure 2.6. This is because higher price mean reduces the brown vehicle price, or increases the price premium of the green vehicle relative to the brown vehicle (see Figure 2.7(a)), while higher price uncertainty increases the value of flexibility of the green vehicle (see Figure 2.7(b)). Higher profitability of the green vehicle leads to a larger green segment size preferred by the firm.

The impact of green fuel price sensitivity β on the optimal profits.

Higher green fuel price sensitivity β reduces green vehicle prices in both green-mass-marketing and market-segmentation strategies (see (2.13) and (2.14)). Hence, higher green fuel price sensitivity β leads to lower profits, as shown in Figure 2.9(a) when the optimal strategy transitions from green-mass-marketing to market-segmentation strategy, or in Figure 2.9(b) when the optimal strategy transitions from market-segmentation to brown-mass-marketing strategy. This implies that the government incentive programs in the biofuel industry will help improve the vehicle manufacturer's profits.

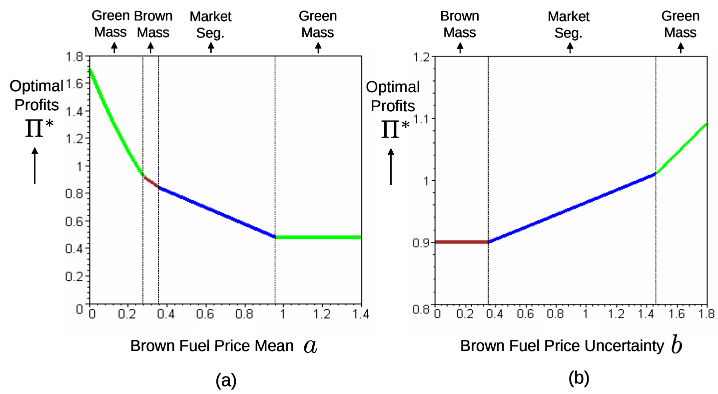


Figure 2.8: Uncertain Case - Optimal Profits as a Function of Brown Fuel Price Mean and Uncertainty

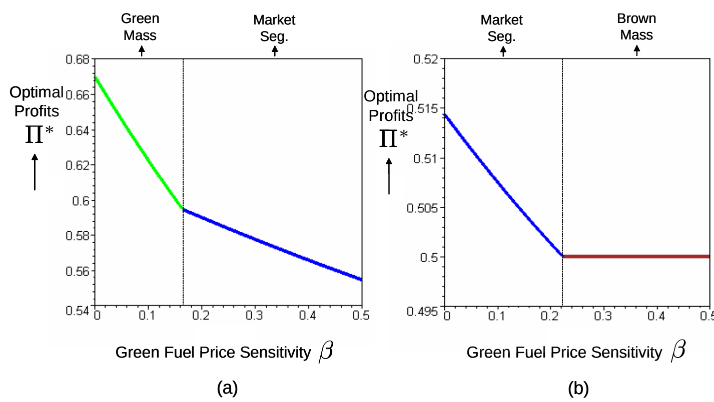


Figure 2.9: Uncertain Case - Optimal Profits as a Function of Green Fuel Price Sensitivity

2.6 Discussions

The concerns of environmental impacts coupled with high oil prices spur a trend of green vehicles powered by biofuels. The scarce biofuel supply remains a major obstacle to the development of the green product market. The scarcity causes the utility of the consumers to be endogenously determined by the consumers own vehicle choices, and therefore it plays a key role in determining firms optimal product strategy. Due to the scarcity, the manufacturer may prefer medium green segment sizes because large green segment sizes may push up the green fuel price. Due to the same reason, it is less likely that the firm will offer the green vehicle when the green segment size increases. In the case of fluctuating petroleum fuel prices, the green vehicle only strategy emerges as an optimal strategy also for low petroleum prices, due to the value generated from its fuel flexibility. Due to the fuel flexibility, the optimal green vehicle price exhibits a counter-intuitive relationship with the petroleum fuel price parameters.

The model can be extended in a few directions. One promising avenue for future research is to consider a collaboration between the vehicle manufacturer and the biofuel producers in reducing biofuel costs or increasing green awareness, e.g., General Motors and Ford's partnership with ethanol producers (VeraSun 2006). Reducing biofuel costs will improve the profitability of the green vehicle, but increasing green segment size may not, as shown in the paper. The latter however may benefit the ethanol producers or the partnership. The answers are not obvious, and will require more research building on models such as those attempted in this paper. The second promising path is to incorporate the supply elasticity of petroleum fuel. As UBS's Shaw (*Business Week* 2007b) pointed out, the success of biofuel depends upon high oil prices - which make biofuels more attractive - but its own success lowers demand for oil which in turn trims oil prices. Another path is to incorporate government's environmental regulations. Inevitably, the automakers will face stricter fleet average carbon standards (*Business Week* 2007c, *Wall Street Journal* 2007b).[11] Companies such as General Motors, and Ford, have been investing efforts in developing fuel-efficient vehicles, the manufacturing costs of which are however higher than the conventional and flex-fuel vehicles (*Business Week* 2007e). With the advance of fuel efficient technology, such issues have come to the forefront: How will the introduction of the fuel-efficient technology affect the automakers' product strategy? How should the automakers balance the fuel-efficient vehicles' high production costs and the scarce green fuel supply issues associated with the flex-fuel vehicle? Will the overall GHG emission increase or decrease with the advent of the alternative green technology? Further research is required, building on models such as those attempted in this paper.

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[11] Manufacturers of all 2009 and later model year vehicles will be required to meet a fleet average standard and that becomes more stringent each year through 2016 (New York State Department of Environmental Conservation 2005). The Senate will vote on a bill that would require automakers to raise fuel economy 40% to a fleet-wide average of 35 miles per gallon by 2020 (*Business Week* 2007c).

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2.8 Appendix A: Proofs

Lemma A 1. *In the benchmark case 1, the optimal mass-marketing strategy is:*

$$(V_1F_1, V_2F_2) = \begin{cases} (BB, BB) & \text{if } f_B < (1-\delta_1)\,\theta + f_G \\ (GG, GG) & \text{if } f_B \geq (1-\delta_1)\,\theta + f_G \end{cases}$$

The optimal prices are: $v_B^{m*} = \theta - f_B$ *and* $v_G^{m*} = \delta_1\theta - f_G$.

Proof of Lemma A1. In brown-mass, the firm offers no rents to all consumers by setting the optimal price: $v_B^{m*} = \theta - f_B$. In green-mass, the firm offers no rents to the brown consumers by setting the optimal price: $v_G^{m*} = \max(\delta_1\theta - f_B, \delta_1\theta - f_G)$. ■

Lemma A 2. *In the benchmark case 1, the optimal market-segmentation strategy is:*

$$(V_1F_1, V_2F_2) = \begin{cases} (BB, GB) & \text{if } f_B \leq -(\delta_2 - \delta_1)\,\theta + f_G \\ (BB, GG) & \text{if } f_B > -(\delta_2 - \delta_1)\,\theta + f_G \end{cases}$$

The optimal vehicle prices are: $(v_B^{s*}, v_G^{s*}) = \begin{cases} (\theta - f_B, \delta_1\theta - f_B) & \text{for } (BB, GB) \\ (\theta - f_B, \delta_2\theta - f_G) & \text{for } (BB, GG) \end{cases}$.

Proof of Lemma A2. In a market-segmentation strategy, the firm introduces different vehicles to different segments. The prices are set such that the two segments self-select between themselves. If the green vehicle is offered, consumers need to consider which type of fuel to use. Hence, there are four possible market-segmentation strategies: (BB, GG), (BB, GB), (GG, BB), and (GB, BB). We solve for each possible strategy the optimal vehicle prices (v_B^*, v_G^*).
(1) (BB, GG),

$$\max_{v_B, v_G \geq 0} \Pi^s = (1-\gamma)\,v_B + \gamma v_G$$

subject to participation constraints:

$$\begin{aligned} \theta - f_B - v_B &\geq 0 \\ \delta_2\theta - f_G - v_G &\geq 0 \end{aligned}$$

and the self-selection constraints:

$$\begin{aligned}\theta - f_B - v_B &\geq \delta_1\theta - \min\left(f_B, f_G\right) - v_G \\ \delta_2\theta - f_G - v_G &\geq \theta - f_B - v_B\end{aligned}$$

The optimal solution is such that the second self-selection and the participation conditions are binding:

$$\left(v_B^*, v_G^*\right) = \begin{cases} \left(\theta - f_B, \delta_2\theta - f_G\right) & \text{If } f_B \geq f_G - \left(\delta_2 - \delta_1\right)\theta \\ \text{no solution} & \text{o/w} \end{cases}$$

(1) (BB, GB),

Objective Function	$\Pi_{II} = \left(1-\gamma\right)v_B + \gamma v_G$
Constraints	$\theta - f_B - v_B \geq \delta_1\theta - \min\left(f_B, f_G\right) - v_G$ $\delta_1\theta - f_B - v_G \geq \theta - f_B - v_B$ $\theta - f_B - v_B \geq 0$ $\delta_1\theta - f_B - v_G \geq 0$
Optimal Solution	$\begin{cases} \left(\theta - f_B, \delta_1\theta - f_B\right) & \text{If } f_B < f_G \\ \text{no solution} & \text{o/w} \end{cases}$

(2) (GB, BB),

Objective Function	$\Pi_{III} = \gamma v_B + \left(1-\gamma\right)v_G$
Constraints	$\delta_1\theta - f_B - v_G \geq \theta - f_B - v_B$ $\theta - f_B - v_B \geq \max\left[\delta_2\theta - f_G - v_G, \delta_1\theta - f_B - v_G\right]$ $\delta_1\theta - f_B - v_G \geq 0$ $\theta - f_B - v_B \geq 0$
Optimal Solution	$\begin{cases} \left(\theta - f_B, \delta_1\theta - f_B\right) & \text{If } f_B < f_G - \left(\delta_2 - \delta_1\right)\theta \\ \text{no solution} & \text{o/w} \end{cases}$

(3) (GG, BB),

Objective Function	$\Pi_{IV} = \gamma v_B + (1-\gamma) v_G$
Constraints	$\delta_1\theta - f_G - v_G \geq \theta - f_B - v_B$ $\theta - f_B - v_B \geq \max[\delta_2\theta - f_G - v_G, \delta_1\theta - f_B - v_G]$ $\delta_1\theta - f_G - v_G \geq 0$ $\theta - f_B - v_B \geq 0$
Optimal Solution	no solution

By maximizing profits $\Pi^* = \max_{j=I,II,III,IV} \Pi_j$, we obtain the above results. ■

Proof of Proposition 1. It immediately follows from Lemmas A(1) and A(2). ■

Lemma A 3. *In the benchmark case 2, the optimal mass-marketing strategy is:*

$$(V_1F_1, V_2F_2) = \begin{cases} (BB, BB) & \text{if } f_B < (1-\delta_1)\theta + (\alpha+\beta) \\ (GG, GG) & \text{if } f_B \geq (1-\delta_1)\theta + (\alpha+\beta) \end{cases}$$

The optimal prices are: $v_B^{m*} = \theta - f_B, v_G^{m*} = \delta_1\theta - (\alpha+\beta)$.

Proof of Lemma A3. In brown-mass: $v_B^{m*} = \theta - f_B$. In green-mass: $v_G^{m*} = \delta_1\theta - (\alpha+\beta)$. ■

Lemma A 4. *In the benchmark case 2, the optimal marke-segmentation strategy is:*
(1) If $\beta\gamma < (\delta_2 - \delta_1)\theta$,

$$(V_1F_1, V_2F_2) = (BB, GG)$$

(2) If $\beta\gamma \geq (\delta_2 - \delta_1)\theta$,

$$(V_1F_1, V_2F_2) = \begin{cases} (BB, GG) & \text{if } f_B \leq \widehat{f}_B \\ (GG, BB) & \text{if } f_B > \widehat{f}_B \end{cases}$$

where, $\widehat{f}_B = \theta - \frac{1}{1-2\gamma}\{[\delta_1\theta - (\alpha+\beta(1-\gamma))](1-\gamma) - [\delta_2\theta - (\alpha+\beta\gamma)]\gamma\}$.
The optimal vehicle prices are: $(v_B^{s*}, v_G^{s*}) = \begin{cases} (\theta - f_B, \delta_2\theta - (\alpha+\beta\gamma)) & \text{for } (BB, GG) \\ (\theta - f_B, \delta_1\theta - (\alpha+\beta(1-\gamma))) & \text{for } (GG, BB) \end{cases}$.

Proof of Lemma A4. There are two possible market-segmentation strategies: (BB, GG) and (GG, BB). We solve for each possible strategy the optimal vehicle prices (v_B^*, v_G^*):

(1) (BB, GG),

Objective Function	$\Pi_I = (1-\gamma) v_B + \gamma v_G$
Constraints	$\theta - f_B - v_B \geq \delta_1\theta - (\alpha+\beta) - v_G$ $\delta_2\theta - (\alpha+\beta\gamma) - v_G \geq \theta - f_B - v_B$ $\theta - f_B - v_B \geq 0$ $\delta_2\theta - (\alpha+\beta\gamma) - v_G \geq 0$
Optimal Solution	$(\theta - f_B, \delta_2\theta - (\alpha+\beta\gamma))$

(2) (GG, BB),

Objective Function	$\Pi_{II} = \gamma v_B + (1-\gamma) v_G$
Constraints	$\delta_1\theta - (\alpha+\beta(1-\gamma)) - v_G \geq \theta - f_B - v_B$ $\theta - f_B - v_B \geq \delta_2\theta - (\alpha+\beta) - v_G$ $\delta_1\theta - (\alpha+\beta(1-\gamma)) - v_G \geq 0$ $\theta - f_B - v_B \geq 0$
Optimal Solution	$\begin{cases} (\theta - f_B, \delta_1\theta - (\alpha+\beta(1-\gamma))) & \text{if } \beta\gamma \geq (\delta_2-\delta_1)\theta \\ \text{no solution} & \text{o/w} \end{cases}$

By maximizing profits $\Pi^* = \max\limits_{j=I,II} \Pi_j$, we obtain the above results, under the assumption $\gamma < 1/2$.■

Proof of Proposition 2. It immediately follows from Lemmas A(3) and A(4). The critical brown fuel prices are:

$$
\begin{aligned}
\underline{f}_B &= (1-\delta_2)\theta + \alpha + \beta\gamma \\
\overline{f}_B &= \frac{1}{1-\gamma}[1-\gamma-\delta_1+\gamma\delta_2]\theta + \alpha + \beta(1+\gamma) \\
\widehat{f}_B &= \theta - \frac{1}{1-2\gamma}\{[\delta_1\theta - (\alpha+\beta(1-\gamma))](1-\gamma) - [\delta_2\theta - (\alpha+\beta\gamma)]\gamma\} \\
\overline{\overline{f}}_B &= (1-\delta_1)\theta + \alpha + (2-\gamma)\beta \\
\gamma &= \widehat{\gamma} \text{ such that } \widehat{f}_B = \overline{\overline{f}}_B
\end{aligned}
$$

■

Proof of Lemma 3. Given segment $-i \in \{1,2\}$ consumers' fuel choice $k_{-i} \in \{G, B\}$, the segment i consumers' utility from adopting the green vehicle at price v_G and choosing fuel

$k_i \in \{G, B\}$ is given by

$$U_G^i(k_i, k_{-i}) = \begin{cases} \begin{cases} \delta_1\theta - f_G(k_i, k_{-i}) - v_G & \text{if } k_i = G \\ \delta_1\theta - f_B - v_G & \text{if } k_i = B \end{cases} & \text{for } i = 1 \\ \begin{cases} \delta_2\theta - f_G(k_i, k_{-i}) - v_G & \text{if } k_i = G \\ \delta_1\theta - f_B - v_G & \text{if } k_i = B \end{cases} & \text{for } i = 2 \end{cases}$$

where the green fuel price is given by $f_G(k_i, k_{-i}) = \alpha + \beta q_G(k_i, k_{-i})$, and $q_G(k_i, k_{-i})$ is the number of consumers who use the green fuel:

$$q_G(k_i, k_{-i}) = \begin{cases} 0 & (k_1^*, k_2^*) = (B, B) \\ \gamma & (k_1^*, k_2^*) = (B, G) \\ 1-\gamma & (k_1^*, k_2^*) = (G, B) \\ 1 & (k_1^*, k_2^*) = (G, G) \end{cases}$$

The consumers equilibrium fuel choices are then given by:

$$\begin{cases} k_i^* \in \underset{k_i \in \{G,B\}}{\arg\max}\, U_2^i\left(k_i, k_{-i}^*\right) \\ k_{-i}^* \in \underset{k_{-i} \in \{G,B\}}{\arg\max}\, U_2^i\left(k_{-i}, k_i^*\right) \end{cases}$$

and follow as above. ■

Proof of Lemma 4. The consumers' expected utilities are:
(1) $a - b < \alpha + \beta\gamma - (\delta_2 - \delta_1)\theta$,

$$\begin{aligned} \widetilde{U}_G^1 &= -v_G + \int_{\alpha+\beta}^{a+b} \frac{\delta_1\theta - (\alpha+\beta)}{2b} df_B + \int_{\alpha+\beta\gamma-(\delta_2-\delta_1)\theta}^{\alpha+\beta} \frac{\delta_1\theta - f_B}{2b} df_B \\ &\quad + \int_{a-b}^{\alpha+\beta\gamma-(\delta_2-\delta_1)\theta} \frac{\delta_1\theta - f_B}{2b} df_B \\ &= -v_G + \frac{\left[(\alpha+\beta) - (a-b)\right]^2}{4b} + \delta_1\theta - \alpha - \beta \end{aligned}$$

$$
\begin{aligned}
\widetilde{U}_G^2 &= -v_G + \int_{\alpha+\beta}^{a+b} \frac{\delta_2\theta - (\alpha+\beta)}{2b} df_B + \int_{\alpha+\beta\gamma-(\delta_2-\delta_1)\theta}^{\alpha+\beta} \frac{\delta_2\theta - (\alpha+\beta\gamma)}{2b} df_B \\
&\quad + \int_{a-b}^{\alpha+\beta\gamma-(\delta_2-\delta_1)\theta} \frac{\delta_1\theta - f_B}{2b} df_B \\
&= -v_G + \frac{2\theta(\delta_2-\delta_1)[(a+b)-\alpha] + \beta^2(1-2\gamma)}{4b} + \frac{[\beta\gamma - \theta(\delta_2-\delta_1)]^2}{4b} \\
&\quad + \frac{[(\alpha+\beta)-(a-b)]^2}{4b} + \delta_1\theta - \alpha - \beta
\end{aligned}
$$

Then, $\widetilde{U}_G^1 - \widetilde{U}_G^2 = -\frac{1}{4b}\left[2\theta(\delta_2-\delta_1)[(a+b)-\alpha] + \beta^2(1-2\gamma) + [\theta(\delta_2-\delta_1)-\beta\gamma]^2\right] < 0$ due to the Assumption (2.10). In addition, the following holds

$$
\begin{aligned}
\frac{\partial}{\partial b}\frac{[(\alpha+\beta)-(a-b)]^2}{4b} &= \frac{[(a+b)-(\alpha+\beta)][(\alpha+\beta)-(a-b)]}{4b^2} \\
\frac{\partial}{\partial a}\frac{[(\alpha+\beta)-(a-b)]^2}{4b} &= \frac{-2[(\alpha+\beta)-(a-b)]}{4b}
\end{aligned}
$$

Other cases: (2) $a-b \in [\alpha+\beta\gamma-(\delta_2-\delta_1)\theta, \alpha+\beta]$, and (3) $a-b > \alpha+\beta$, are similar. ∎

Proof of Lemma 5. Since

$$
\Pi_B = \theta - a, \Pi_G = v_G
$$

we have,

$$
\begin{aligned}
\Pi_B &> \Pi_G \Leftrightarrow \\
\theta - a &> \frac{[(\alpha+\beta)-(a-b)]^2}{4b} + \delta_1\theta - \alpha - \beta \Leftrightarrow \\
0 &> b^2 - [4(1-\delta_1)\theta + 2(\alpha+\beta-a)]b + (\alpha+\beta-a)^2 \Leftrightarrow b \in [a_{gb}, a_{bg}] \\
\text{or } 0 &> a^2 + [4b - 2(\alpha+\beta+b)]a + (\alpha+\beta+b)^2 - 4[(1-\delta_1)\theta + \alpha + \beta]b \Leftrightarrow a \in [b_{gb}, b_{bg}]
\end{aligned}
$$

∎

Proof of Lemma 6.The firm solves the following problem:

$$
\max \ \Pi = (1-\gamma)v_B + \gamma v_G
$$

subject to participation constraints:

$$
\underset{f_B}{E}[\theta - f_B - v_B] \geq 0
$$

$$\underset{f_B}{E}\max\left[\delta_1\theta - f_B - v_G, \delta_2\theta - (\alpha+\beta\gamma) - v_G\right] \geq 0$$

self-selection constraints:

$$\underset{f_B}{E}\left[\theta - f_B - v_B\right] \geq \widetilde{U}_G^1$$

$$\underset{f_B}{E}\max\left[\delta_1\theta - f_B - v_G, \delta_2\theta - (\alpha+\beta\gamma) - v_G\right] \geq \underset{f_B}{E}\left[\theta - f_B - v_B\right]$$

where $\widetilde{U}_G^1$ is the expected utility of the brown consumers if they switch to the green vehicle, which is the same as in the above green-mass-marketing strategy. And,

$$\begin{aligned}
& \underset{f_B}{E}\max\left[\delta_1\theta - f_B - v_G, \delta_2\theta - (\alpha+\beta\gamma) - v_G\right] \\
= & \int_{a-b}^{(\delta_1-\delta_2)\theta+(\alpha+\beta\gamma)} \frac{\delta_1\theta - f_B}{2b} df_B + \int_{(\delta_1-\delta_2)\theta+(\alpha+\beta\gamma)}^{a+b} \frac{\delta_2\theta - (\alpha+\beta\gamma)}{2b} df_B - v_G \\
= & \frac{1}{4b}\left[(\alpha+\beta\gamma) - (\delta_2-\delta_1)\theta\right]^2 - \frac{1}{2b}\delta_1\theta(a-b) + \frac{1}{4b}(a-b)^2 + \frac{a+b}{2b}\left[\delta_2\theta - (\alpha+\beta\gamma)\right] - v_G
\end{aligned}$$

The participation and the second (green consumers) self-selection conditions must be binding. Hence,

$$\begin{aligned}
v_B^* &= \theta - a \\
v_G^* &= \frac{\left[\theta(\delta_2-\delta_1)\right]^2 + 2\left[(a+b) - (\alpha+\beta\gamma)\right](\delta_2-\delta_1)\theta}{4b} + \frac{\left[(\alpha+\beta\gamma) - (a-b)\right]^2}{4b} + \delta_1\theta - \alpha - \beta\gamma
\end{aligned}$$

■

Proof of Proposition 3. It immediately follows from Lemmas 5 and 6. ■

2.9 Appendix B: Environmental Consequences

Lemma A 5. ***A*** *The number of consumers who use the green fuel:*
(1) increases as the brown fuel price f_B increases in the deterministic case, but may decrease as the brown fuel price mean increases in the uncertain case.
(2) may decrease as the green segment size γ increases in both cases.

For a given green segment size γ, as the brown fuel price f_B increases, the fraction of consumers who use the green fuel increases from 0 to γ to 1, as shown in Figure 2.3. In the uncertain case, however, the percentage decreases from 1 to 0 or γ, at low brown fuel price means, because the firm switches from green-mass to brown-mass or market-segmentation strategies. For a given brown fuel price f_B or mean a, in both cases, as the green segment size increases, the percentage of consumers who use the green fuel increases only when the firm adopts a market-segmentation strategy. When the segment size increases such that the firm switches from the green-mass-marketing to market-segmentation or from the market-segmentation to brown-mass-marketing, the number of consumers decreases from 1 to γ, or from γ to 0.

Chapter 3

Repeatedly Selling to A Newsvendor in Fluctuating Markets

3.1 Introduction

An important and often recurring question addressed in the supply chain management literature is how firms in a decentralized supply chain, each having their own, interdependent objective functions, can be motivated to make decisions that optimize the objective function of the whole supply chain (i.e., the sum of the participating firms' profits, see Tayur et al., 1999, Cachon, 2003). The supply chain management literature discusses how elaborate contracts can be designed so that the participants have an incentive to take the decisions that optimize the supply chain's total profits (see, e.g., Pasternack 1985, Lee and Whang, 1997, Barnes-Schuster et al., 1998). In practice, the actual implementation may differ from what is stipulated in the contract (Neuville, 1997). Managers in different firms that operate in the same supply chain interact repeatedly with each other. Therefore, trust and social pressure become important elements that govern the supply chain relationship, complementary to elaborated contracts.

A typical supply chain game is the seller-newsvendor game. In this game, a seller (manufacturer or supplier) produces and sells a product to a newsvendor (retailer or buyer), who faces an uncertain market. Porteus and Lariviere (2001) have shown that a supply chain governed by a wholesale price contract cannot be coordinated (i.e., joint maximum payoffs cannot be achieved) in a single-shot interaction. A more elaborate contract with a buyback option for the retailer is needed in order to achieve coordination. In this paper, we study coordination with a wholesale price contract when a manufacturer and retailer repeatedly interact with each other. Players may be motivated to cooperate with each other if the gains from cooperation over the long run exceed the short run gains that they would obtain from not cooperating. During an economic boom, attractive short run gains may make deviation from cooperation more tempting. We may thus expect that market fluctuations adversely impact the ability to coordinate a supply chain through repeated interaction. We develop in this paper a model that allows us to address the following questions: Under which circumstances (cost, revenues, market uncertainty and discount factor) will the jointly maximal payoffs be achieved through repeated interaction? How will the jointly maximal profits be divided and what will the cooperating wholesale price be? What will the impact be of fluctuating demand on the ability to coordinate the supply chain? Who benefits from the information about market fluctuations?

In the next section, related literature will be discussed briefly, then the one-shot constituent game (the stage game) will be elaborated. In the section following, the stage game will be played repeatedly and the conditions under which coordination can be achieved will be determined. In the last two sections, points for further research are developed and conclusions are drawn.

3.2 Related Literature

Japanese techniques like Total Quality Management or Just In Time production techniques triggered the interest in supplier-manufacturer relationships. The traditional strategy literature was mainly based on exploitation of bargaining power where possible (Porter, 1980). The quality management practitioners, however, argued that the cost of close coordination with manufacturers is less than the added benefit of better quality, reduced inventories, etc. (Deming, 1986). Kahn et al. (1986) identified the impact of adversarial manufacturer relations on the purchasing costs. Ali et al. (1997), for example, strongly advocate the adoption of partnership relationships with manufacturers. A number of authors compare the advantages and disadvantages of partnership sourcing versus competitive sourcing. Richardson and Roumasset (1995) compare sole sourcing, competitive sourcing and parallel sourcing (sole sourcing, but limited to a particular product category) and find the optimal sourcing arrangement in different environments. Taylor and Wiggins (1997) compare the cost performance of the American system, which involves competitive bidding, large batches and quality inspection of an incoming order, to the Japanese system with repeat purchases from one manufacturer, small batches and no inspection. They conclude that when using flexible manufacturing technology and having complex products, the Japanese system performs better. Parker and Hartley (1997) critique the partnership-sourcing approach by adopting a transaction cost framework and point out the existence of a continuum of relationships between adversarial and partner relationships.

In the Operations Management literature, Porteus (1990) describes the classical newsvendor problem. It is one of the most simple inventory models in which a newsvendor needs to determine the optimal order quantity before the market demand is realized. Ordering too much may leave the newsvendor with excess stock. Not ordering enough may result in lost sales and goodwill. The newsvendor problem is a single period, single actor problem. Lippman and McCardle (1997) consider competition between several newsvendors. Lariviere and Porteus (2001) analyze a wholesale price manufacturer-newsvendor contract with a Stackelberg game and study the impact of the demand distribution functions on the equilibrium wholesale prices, order quantities and profits. Other authors extended the wholesale price and buy-back contracts by incorporating asymmetric information (Ha, 1998), subcontracting (Van Mieghem, 1999), options (Barnes-Shuster et al., 2002) and substitute products (Narayanan and Raman, 1997). Tsay (1999) provides a general framework for contracting issues between a buyer and a manufacturer in the same supply chain. Lariviere (1999) surveys a special class of supply chain contracts in which the buyer faces a newsvendor problem. Tayur et al. (1999) and Cachon (2003) provide reviews of the literature of quantitative models for supply chain management. In a single-stage game with a wholesale price as the only contract parameter that is determined by the manufacturer and the order quantity by the retailer, supply chain coordination cannot be achieved (i.e., the sum of the profits of the retailer and manufacturer can be increased). This is due to the double marginalization effect: In order to make positive profits, the manufacturer sets the wholesale price above the marginal costs. From a supply chain point of view, the retailer faces too high costs and orders too few items. In the economics, marketing and operations management literature, more elaborate contracts that do allow for supply chain coordination are studied. One such contract is a franchising contract (Tirole, 1996): The manufacturer charges a fixed fee upfront to the retailer and subsequently delivers all products at marginal costs. As long as the franchising fee is less than the expected profits for the retailer, he will accept it and determine the order quantity on the marginal costs. This corresponds to the optimal order quantity from the supply chain point of view. Another contract is a buy-back contract (Pasternack 1985) in which the manufacturer buys back a fraction of the unsold items at a discount price. Pasternack determines the contract parameters (wholesale price, fraction that can be bought back and take-back discount) that create an incentive for the newsvendor to order the jointly optimal order quantity. The revenues for the retailer that are generated by the buy-back induces the retailer to increase his order quantity. When carefully set, the buy-back price may also induce the retailer to order the supply chain optimal quantity. Most research in the supply chain literature considers single-stage games. Taylor and Plambeck (2005) and Atkins et al. (2005) study supply chain coordination with repeated interaction through "relational contracts". These contracts specify the interaction between an upstream and a downstream player after each possible history interaction. A relational contract is self-enforcing; i.e., no player may have an incentive to deviate from the contract. Taylor and Plambeck study how relational contracts can be used to govern a supplier's capacity investment for a downstream manufacturer. Atkins et al. study how relational contracts can be used to govern a manufacturer's order quantity to a downstream retailer.

In the economics literature, Fudenberg and Tirole (1991) make a distinction between finitely and infinitely repeated games, games with the same and with varying players, games with observable actions and imperfect signals of the opponent's play. Tirole (1986) and Fudenberg and Tirole (1989) provide a review of applications of infinitely repeated games in economic theory, with special attention to collusion between oligopolists. Rotemberg and Saloner (1986) study collusion in an environment with a fluctuating market. They show that in periods of high demand (booming markets), full collusion is not sustainable in equilibrium. Similarly, as Rotemberg, we are interested in understanding how market fluctuations impact the use of relational contracts in a manufacturer-retailer supply chain, as in Atkins et al. (2005).

3.3 The Single Period Game

In this section, we discuss the interaction between a retailer and a manufacturer in a single period (the 'stage game'). We first analyze the integrated supply chain, which is owned by a single agent. Next, we analyze the decentralized supply chain, where the upstream manufacturing operations and the downstream sales operations are owned by the manufacturer and the retailer, respectively.

The market demand and production structure. We consider a supply chain with a downstream market to which a product can be sold at unit retail price, r. The market demand, ξ, is uncertain, but can be characterized by means of a density function, $\phi(\xi)$, with $\xi \in \left[\underline{\xi}, \overline{\xi}\right]$, $0 < \underline{\xi} < \overline{\xi} < \infty$. The product is produced by the manufacturer at a unit cost of c. Production needs to start before the actual demand realization is observed. If the realized demand is less than produced quantity, y, demand is completely satisfied and the remaining items are salvaged. If the realized demand is more than y, then all y items are sold and the excess demand is lost. Without loss of generality, we set the salvage value equal to zero. We assume that the demand distribution is independent of the retail price, r, and the order quantity, y. In order to avoid trivial solutions, we impose $r \geq c \geq 0$.

The integrated supply chain. In the case that the supply chain is owned and operated by a single agent (the 'newsvendor'), the agent needs to determine the optimal production quantity. The newsvendor's profit as a function of y is given by:

$$\Pi_I(y) \doteq rD(y) - cy \tag{3.1}$$

where, $D(y) = \mathbb{E}_\xi(\min(\xi, y)) = \int_{\underline{\xi}}^{y} \xi\phi(\xi)\,d\xi + y\overline{\Phi}(y)$ with $\Phi(y) \doteq \int_{\underline{\xi}}^{y} \phi(\xi)\,d\xi$ and $\overline{\Phi}(y) \doteq 1 - \Phi(y)$ is the expected demand that will be satisfied from the produced quantity y (Porteus and Lariviere, 1999). The production quantity that maximizes the total profit is:

$$y^I \doteq \overline{\Phi}^{-1}\left(\frac{c}{r}\right). \tag{3.2}$$

The well-known newsvendor result is that y has to be optimally set so that all demand is satisfied with probability $1-\frac{c}{r}$. Note that the optimal production quantity, y^I, decreases as the production cost, c, increases. We denote integrated supply chain profits, $rD\left(y^I\right) - cy^I$, as Π_I. These profits will be used as a benchmark for the Stackelberg game, which we describe in the next section.

The decentralized supply chain. Consider now a supply chain in which a retailer purchases items from a manufacturer at a wholesale price w. We focus on a wholesale price-only contract: After observing w, the retailer decides on the number of items that he will order from the manufacturer, y, before the demand is realized. This situation can be modelled as a Stackelberg game in which the manufacturer is the leader. Without loss of generality, we can determine the action and action spaces of the manufacturer and retailer as $w \in [c, r]$ and $y \in \left[\underline{\xi}, \overline{\xi}\right]$, respectively. We determine the subgame perfect Nash equilibrium of this game by backward induction: For a given w, the retailer's profit as a function of w and y is similar to (3.1), but with c substituted by w: $\Pi_R(w, y) \doteq rD(y) - wy$. The optimal order quantity is $y(w) \doteq \overline{\Phi}^{-1}\left(\frac{w}{r}\right)$. The manufacturer's profit as a function of w and y is:

$$\Pi_M(w, y) \doteq (w - c)\,y \tag{3.3}$$

The equilibrium wholesale price, w, can be determined by maximizing the manufacturer's profits with $y(w)$ as the manufacturer's demand function. However, it turns out that it is more convenient to use the inverse demand function, $w(y)$, defined as:

$$w(y) = r\overline{\Phi}(y) \tag{3.4}$$

and maximize the manufacturer's profit with respect to the order quantity: $y^* = \arg\max_y$

$\Pi_M(w(y), y)$. As a notational convention, we use superscript * to refer to equilibrium quantities of the Stackelberg game. Then, y^* is the equilibrium order quantity and $w^* = r\overline{\Phi}(y^*)$ is the equilibrium wholesale price (Porteus and Lariviere, 2001). We assume that $\phi(y)$ satisfies the increasing general failure rate (IGFR) property (i.e., $y\frac{\phi(y)}{\overline{\Phi}(y)}$ is increasing), then, y^* is uniquely determined by:

$$\frac{c}{r} = \overline{\Phi}(y)\left(1 - \frac{\phi(y)\,y}{\overline{\Phi}(y)}\right) \tag{3.5}$$

If $y^* \notin [\underline{\xi}, \overline{\xi}]$, then it is set to the closest boundary ($\underline{\xi}$ or $\overline{\xi}$) (Lariviere and Porteus, 2001).

Proposition 1. *The order quantity in the Stackelberg game, y^*, is less than the jointly optimal order quantity, y^I.*

According to Proposition 1, too few items are ordered by the retailer in the stage game with a wholesale price contract. This is due to the double-marginalization principle (Spengler, 1950). Note that the retailer's unit cost is w. In order to make positive profits, the manufacturer sets w strictly higher than c. Remember that the optimal order quantity decreases as its cost increases. Therefore, in the Stackelberg game, the retailer orders less than the system optimal quantity. In a single stage game, a contract with more parameters than the wholesale price is necessary in order to achieve supply chain coordination (see Cachon, 2003). As the equilibrium order quantity is lower than the integrated order quantity, it follows that the supply chain profits $\Pi_R^* + \Pi_M^*$ with $\Pi_i^* = \Pi_i(w^*, y^*)$, for $i \in \{R, M\}$ are less than the integrated supply chain profits, Π_I. In the next section, we discuss how the supply chain can be coordinated with a wholesale price contract in a repeated game context.

3.4 The Infinitely Repeated Game

In this section, we consider the Stackelberg game of the previous section as the stage game of an infinitely repeated game. We first set up the game, describe the strategies (trigger strategies) and discuss the main result for repeated games (the Folk Theorem). In the first subsection, we analyze the repeated game for the case of identical demand distributions in each period. In the second subsection, we analyze the repeated game for the case with fluctuating distributions.

The infinitely repeated game. We embed the single period Stackelberg game in an infinitely repeated game. We focus on perishable good, or on high tech products with a short product life cycle which corresponds to one period in the repeated game. In both cases, no left-over inventory can be carried over from period to period. Furthermore, we assume that the market demand in a period is independent of the market demand in any other period. In each period

t, the complete history of interactions, $h_t = ((w_0, y_0), (w_1, y_1), ..., (w_{t-1}, y_{t-1}))$ is observable to both players. Let H_t be the set of all possible period t histories. A strategy consists of a mapping from every possible history of actions, h_t, to the player's action space; $H_t \to (w_t(h_t), y_t(h_t)) \in [c, r] \times [\underline{\xi}, \overline{\xi}]$. The payoffs of the both players are determined by the normalized discounted revenue stream over an infinite horizon; $V_M = (1-\delta)\sum_{t=0}^{\infty} \delta^t \Pi_M (w_t(h_t), y_t(h_t))$ and $V_R = (1-\delta)\sum_{t=0}^{\infty} \delta^t \Pi_R (w_t(h_t), y_t(h_t))$, respectively, with discount factor $\delta \in (0,1)$.

The Nash-threats folk theorem. Infinitely repeated games have typically many equilibria (Fudenberg and Tirole, 1991). We focus on subgame perfect equilibria. Friedman (1971) showed that a minimum discount factor $\underline{\delta}$ exists, so that any payoff profile may be realized by means of a subgame perfect equilibrium that Pareto dominates the stage game equilibrium payoff for $\delta \geq \underline{\delta}$; i.e., $V_i \geq \Pi_i^*$ with $i \in \{R, M\}$. Consider the following 'Grim trigger strategy' characterized by (w, y):

In the first period, the manufacturer sets the wholesale price to w. In the following periods, if (w, y) was played in all previous periods, then the manufacturer sets the price to w. If in one of the previous periods (w, y) was not played, then the manufacturer sets the wholesale price to w^*. In the first period, the retailer orders y. In the following periods, if (w, y) was played in all previous periods and the manufacturer sets w in this period, then the retailer orders y. If in all previous periods (w, y) was played and the manufacturer does not set w (but w') in this period, then the retailer orders $y(w')$. If in one of the previous periods (w, y) was not played, then the retailer orders y^*.

It can be proven (see, e.g., Laffont and Tirole 1991, or, Gibbons 1992) that a trigger strategy is a subgame perfect equilibrium if *during a single period, no player may have an incentive to deviate from* (w, y).

Note that other versions of the folk theorem with a larger space of possible payoffs exist. The strategies necessary to realize these payoff profiles are more complicated. As our objective is to obtain insight in supply chain coordination, we focus on Grim trigger strategies. As a notational convention, we use superscript † to refer to equilibrium trigger strategy of the repeated game. In the following subsection, we determine the values of $(w^\dagger, y^\dagger)$ that are supported in equilibrium as a function of δ, the cost and demand parameters.

3.4.1 Repeated Games with Independent and Identically Distributed Demand for Each Period

Analysis

The equilibrium condition that no player may have an incentive to deviate from (y, w) can be stated for the retailer as:

$$\underset{y_d}{Max}\left\{\Pi_R\left(w, y_d\right)\right\} + \frac{\delta}{1-\delta}\Pi_R^* \leq \frac{1}{1-\delta}\Pi_R\left(w, y\right) \tag{3.6}$$

or, for a given w, sum of the maximum profit attainable during this period by deviating and the discounted punishment payoffs from the next period on, must be less than the discounted payoffs of not deviating from trigger strategy. Similarly, for the manufacturer, the equilibrium condition can be stated as:

$$\underset{w_d}{Max}\left\{\Pi_M\left(w_d, y\left(w_d\right)\right)\right\} + \frac{\delta}{1-\delta}\Pi_M^* \leq \frac{1}{1-\delta}\Pi_M\left(w, y\right) \tag{3.7}$$

$\left(w^{\dagger}, y^{\dagger}\right)$ characterizes an equilibrium trigger strategy satisfying (3.6) and (3.7). Note that the optimal deviation price of the manufacturer is the wholesale price of the stage game: $w_d^* = w^*$, and (3.7) reduces to:

$$\Pi_M^* \leq \Pi_M\left(w, y\right). \tag{3.8}$$

Furthermore, $\underset{y_d}{Max}\left\{\Pi_R\left(w, y_d\right)\right\}$ in (3.7) reduces to $\Pi_R\left(w, y\left(w\right)\right)$. In order to gain insight in the equilibrium strategies defined by (3.6) and (3.8), we characterize the equilibrium strategies $\left(w^{\dagger}, y^{\dagger}\right)$ that maximize the supply chain profits. Define Δ_δ as the set of y such that $\exists$ w such that (w, y) satisfies equilibrium conditions (3.6) and (3.8). Full coordination (i.e., $\Pi^{\dagger} = \Pi_I$) is possible if and only if $y^I \in \Delta_\delta$. If full coordination is possible for a particular δ, then it follows from the Folk Theorem that for any $\delta \leq \delta' < 1$, full coordination is also possible. The following Proposition characterizes the minimum discount factor above which full coordination is possible:

Proposition 2. *The minimum discount factor above which the supply chain can fully coordinate is:*

$$\underline{\delta} = \frac{\frac{\Psi_R}{\Lambda_R}}{1 + \frac{\Psi_R}{\Lambda_R}}$$

where, $\Psi_R = \Pi_R^d - \Pi_R$*,* $\Lambda_R = \Pi_R - \Pi_R^*$*,* $\Pi_R^d = \Pi_R\left(\widehat{w}, y\left(\widehat{w}\right)\right)$ *with* $\widehat{w} = c + \frac{\Pi_M^*}{y^I}$ $\Pi_R = \Pi_I - \Pi_M^*$*, and* $\Pi_M = \Pi_M^*$*.*

The minimum discount factor is determined by the ratio $\frac{\Psi_R}{\Lambda_R}$. Ψ_R is the increase in profits that the retailer would obtain in the case that he would deviate from the coordinated supply chain order quantity. Λ_R is the increase in profits of the retailer that may be achieved by coordination. In other words, the former measures the temptation for the retailer to deviate from coordiation, and the latter mesaures the ability of the supply chain to punish a deviating retailer. $\frac{\Psi_R}{\Lambda_R}$ can thus be thought of as a relative measure of temptation for the retailer to deviate. The larger his temptation, or the more lenient his punishment, the higher the minimum discount factor for which the coordination is possible. Furthermore, at the lowest discount factor, the coordination does not increase the manufacturer's profit and all gains flow to the retailer.

Proposition 3. *When $\underline{\delta} \leq \delta < 1$, full coordination is possible. A range of price schedules is possible in equilibria: $w^\dagger \in [\underline{w}, \overline{w}]$, where $\underline{w}$ and $\overline{w}$ are determined by:*

$$\underline{w} : \Pi_M^* = \Pi_M \left(w, y^I\right), \ \overline{w} : \Pi_R \left(w, y\left(w\right)\right) + \frac{\delta}{1-\delta}\Pi_R^* = \frac{1}{1-\delta}\Pi_R\left(w, y^I\right)$$

A range of profit divisions is possible in equilibria:
1) The upper bound (resp., lower bound) of the retailer's (resp., manufacturer's) profit is $\Pi_I - \Pi_M^*$ (resp., Π_M^*).
2) The lower bound (resp., upper bound) of the retailer's (resp., manufacturer's) profit is decreasing (resp., increasing) in δ. When δ goes to 1, the lower bound (resp., upper bound) of the retailer's (resp., manufacturer's) profit goes to Π_R^* (resp., $\Pi_I - \Pi_R^*$).

When $\delta > \underline{\delta}$, full coordination can be achieved; i.e., $y^I \in \Delta_\delta$. Proposition 3 gives bounds on the wholesale price: $\underline{w}$ ($\overline{w}$) is the lowest (highest) possible wholesale price, as the manufacturer's (retailer's) profits with this wholesale price in the repeated game are exactly equal to the manufacturer's (retailer's) profits in the single-period game. $\overline{w}$ ($\underline{w}$) is the wholesale price that makes the retailer (manufacturer) indifferent to deviating or not. Proposition 3 states that full supply chain coordination by repeated interaction is possible for high discount factors. Compared to the single-period Stackelberg interaction, full cooperation is made feasible by a wholesale price decrease, as $w^\dagger \leq \overline{w} < w^*$. This is beneficial for the retailer. In exchange, the retailer orders the jointly optimal order quantity allowing for supply chain coordination. However, the retailer faces strong incentives in each period to order less ($y^I > y\left(w^\dagger\right)$, as $y\left(w\right)$ is decreasing in w, $w^\dagger > c$ and $y^I = y\left(c\right)$). Taking the future interaction with the manufacturer into account, the retailer does not want to deviate from the joint optimal order quantity because the net gains of deviation in the current period are less than the profit loss of entering the punishment phase. Similarly, the manufacturer has no incentive to increase the low wholesale price, as the potential gains are greater than the profit loss caused by the immediate reaction of the retailer (who will order less) and the subsequent punishment phase. For $\delta = \underline{\delta}$, the (coordinated) supply chain profits are split in a unique way. For $\underline{\delta} < \delta < 1$, the manufacturer's profits may range from Π_M^* (which are the profits at $\underline{\delta}$) to some value greater than Π_M^* (but less than $\Pi_I - \Pi_R^*$).

Markets with Uniform Demand Distribution.

Specializing for the uniform distribution, we have that:

Corollary 1. *For the uniform distribution,* $\phi(\xi) = \frac{1}{\overline{\xi} - \underline{\xi}}$ *for* $\xi \in [\underline{\xi}, \overline{\xi}]$. *Let* $\gamma = \frac{\overline{\xi}}{\underline{\xi}}$. *If* $\frac{r-c}{r} > \frac{1}{\gamma - 1}$, *then, we have that:* $\underline{\delta} = \frac{1}{5}$. *Otherwise,*

$$\underline{\delta} = \frac{1}{1 + \left(1 + (\gamma - 1)\frac{r-c}{r}\right)^2}$$

It is interesting to note that, when the product margin (measured by $\frac{r-c}{r}$) is high and/or the demand variance (measured by γ) is high, the minimum discount factor does not depend on the cost or revenue structure, nor on the expected value and standard deviation of demand. For low product margins or low market variance, the minimum discount factor decreases as the market variance increases or as the product margin increases.

3.4.2 Repeated Games with Fluctuating Demand

In the previous subsection, the demand distribution in each period was the same and the demand realization is independent of all previous realizations. It is possible that the demand distribution changes from one period to another. In the setting of the newsvendor problem, this would correspond to periods of high demand for newspaper (e.g., when a major sport or political event takes place), followed by periods of lower demand. In periods with high demand, more profits may be made. It may then be more tempting to deviate from the equilibrium strategy. We analyze the impact of demand fluctuation on the retailer and manufacturer's incentive to coordinate. We model exogenous demand fluctuation in the same spirit as Rotemberg and Saloner (1986). In each period, the demand distribution will depend on the realization of a stochastic variable, κ, with density $\phi_\kappa(\xi)$ and CDF $\Phi_\kappa(\xi)$ over $[\underline{\xi}, \overline{\xi}]$. For our analysis, κ has density $\theta(\kappa)$ and distribution $\Theta(\kappa) \doteq \int_{\underline{\kappa}}^{\kappa} \theta(\kappa)\, d\kappa$ over $[\underline{\kappa}, \overline{\kappa}]$. In the beginning of each period, the Nature draws a realization of $\widetilde{\kappa}$ independently from the previous periods. $\widetilde{\kappa}$ is observable to both the retailer and the manufacturer. The stage game then proceeds as in the previous subsection: the manufacturer sets the wholesale price, communicates it to the retailer, the retailer determines the order quantity, and finally, the Nature draws the demand realization from the distribution $\phi_{\widetilde{\kappa}}(\xi)$. With fluctuating demand, the trigger strategy for the retailer and manufacturer depends on the realization of κ and is thus determined by a price and production *schedule*: $(w(\kappa), y(\kappa))$. For notational convenience, we use the operator $\mathbb{E}_{\kappa}[\bullet]$ to indicate $\int_{\underline{\kappa}}^{\kappa} \bullet d\Theta(\kappa)$.

Analysis

Conditional on the realization of a signal κ, denote the integrated (stage game) the order quantity as: $y^I(\kappa)$ $(y^*(\kappa))$ and, for a given wholesale price, w, denote the optimal order quantity as: $y(w,\kappa)$. Denote $\widetilde{\Pi}_R^* = \mathbb{E}_{\kappa}[\Pi_R^*(\kappa)]$, and $\widetilde{\Pi}_M^* = \mathbb{E}_{\kappa}[\Pi_M^*(\kappa)]$, which are the expected stage game profits. For each signal realization, equilibrium conditions have to be determined. For the retailer, the equilibrium condition can be stated as:

$$\begin{aligned} &\underset{y_d}{Max}\{\Pi_R(w(\kappa), y_d, \kappa)\} + \frac{\delta}{1-\delta}\widetilde{\Pi}_R^* \\ \leq\ & \Pi_R(w(\kappa), y(\kappa), \kappa) + \frac{\delta}{1-\delta}\mathbb{E}_{\kappa}[\Pi_R(w(\kappa), y(\kappa), \kappa)] \text{ for } \kappa \in [\underline{\kappa}, \overline{\kappa}] \end{aligned} \tag{3.9}$$

and for the manufacturer:

$$\begin{aligned} &\underset{w_d}{Max}\{\Pi_M(w_d, y(w_d, \kappa), \kappa)\} + \frac{\delta}{1-\delta}\widetilde{\Pi}_M^* \\ \leq\ & \Pi_M(w(\kappa), y(\kappa), \kappa) + \frac{\delta}{1-\delta}\mathbb{E}_{\kappa}[\Pi_M(w(\kappa), y(\kappa), \kappa)] \text{ for } \kappa \in [\underline{\kappa}, \overline{\kappa}] \end{aligned} \tag{3.10}$$

$\left(w^{\dagger}(\kappa), y^{\dagger}(\kappa)\right)$ characterizes an equilibrium trigger strategy and satisfies (3.9) and (3.10) for all $\kappa \in [\underline{\kappa}, \overline{\kappa}]$. Similarly, as in the stationary demand case, the optimal deviation price of the manufacturer is the wholesale price of the stage game; $w_d^*(\kappa) = w^*(\kappa)$. In each period, the profits and temptation to deviate depend on κ. As punishment for the manufacturer only can start in the period following the deviation, the punishment ability does not depend on κ, but on the expectation of punishment ability in the next periods.

Define Ω_δ as the set of functions $y(\kappa)$ defined over $[\underline{\kappa}, \overline{\kappa}]$ such that $\exists\ w(\kappa) \geq 0$ such that $(w(\kappa), y(\kappa))$ satisfy (3.9) and (3.10) for all $\kappa \in [\underline{\kappa}, \overline{\kappa}]$. Full coordination (i.e., $\widetilde{\Pi}^{\dagger} = \widetilde{\Pi}_I$) is possible if and only if $y^I(\kappa) \in \Omega_\delta$. If full coordination is possible for a particular δ, then, it follows from the Folk Theorem that for any $\delta \leq \delta' < 1$, full coordination is also possible. Denote $\Sigma_\delta\left(\widetilde{\Pi}_R\right)$ as the class of price schedules defined over $[\underline{\kappa}, \overline{\kappa}]$ such that (3.9) and (3.10) are satisfied, given the expected profits of the retailer in equilibrium $\widetilde{\Pi}_R \in \left[\widetilde{\Pi}_R^*, \widetilde{\Pi}_I - \widetilde{\Pi}_M^*\right]$. Then, for any

$w(\kappa) \in \Sigma_\delta\left(\widetilde{\Pi}_R\right)$, (3.9) reduces to:

$$C_R\left(w(\kappa), \widetilde{\Pi}_R, \kappa\right) \geq 0 \text{ for } \kappa \in [\underline{\kappa}, \overline{\kappa}] \tag{3.11}$$

with $C_R\left(w, \widetilde{\Pi}_R, \kappa\right) \doteq \Pi_R\left(w, y^I(\kappa), \kappa\right) + \frac{\delta}{1-\delta}\widetilde{\Pi}_R - \Pi_R\left(w, y(w,\kappa), \kappa\right) - \frac{\delta}{1-\delta}\widetilde{\Pi}_R^*$ and (3.10) reduces to:

$$C_M\left(w(\kappa), \widetilde{\Pi}_R, \kappa\right) \geq 0 \text{ for } \kappa \in [\underline{\kappa}, \overline{\kappa}] \tag{3.12}$$

with $C_M\left(w, \widetilde{\Pi}_R, \kappa\right) \doteq \Pi_M\left(w, y^I(\kappa), \kappa\right) + \frac{\delta}{1-\delta}\left(\widetilde{\Pi}_I - \widetilde{\Pi}_R\right) - \widetilde{\Pi}_M^*(\kappa) - \frac{\delta}{1-\delta}\widetilde{\Pi}_M^*$. Conditions (3.11) and (3.12) depend only on $\left(\kappa, \widetilde{\Pi}_R\right)$. We can denote for each $\left(\kappa, \widetilde{\Pi}_R\right)$, the highest (resp., the lowest) wholesale price that the retailer (resp., the manufacturer) is willing to pay as $\overline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right)$ (resp., $\underline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right)$), i.e.,

$$\forall c \leq w \leq \overline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right) : C_R\left(w, \widetilde{\Pi}_R, \kappa\right) \geq 0 \text{ and } \forall \underline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right) \leq w \leq r : C_M\left(w, \widetilde{\Pi}_R, \kappa\right) \geq 0$$

Before stating a Proposition that determines the profit division, we find equivalent conditions of (3.11) and (3.12):

Lemma 1. *Given a discount factor δ, a necessary and sufficient condition for $y^I(\kappa) \in \Omega_\delta$, $\forall \kappa$, is as follows: $\exists\, \widetilde{\Pi}_R \in \left[\widetilde{\Pi}_R^*, \widetilde{\Pi}_I - \widetilde{\Pi}_M^*\right]$, s.t.,*

$$\begin{aligned} \forall \kappa &\in [\underline{\kappa}, \overline{\kappa}] : \underline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right) \leq \overline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right) \text{ and} &(3.13)\\ \mathbb{E}_\kappa[rD\left(y^I(\kappa), \kappa\right) - y^I(\kappa)\,\overline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right)] &\leq \widetilde{\Pi}_R \leq \mathbb{E}_\kappa[rD\left(y^I(\kappa), \kappa\right) - y^I(\kappa)\,\underline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right)] &(3.14)\end{aligned}$$

then conditions for (3.11) and (3.12) are also satisfied.

Lemma 1 allows determining, for any given $\widetilde{\Pi}_R$, whether it is possible to find a wholesale price schedule that satisfies the equilibrium conditions and results in $\widetilde{\Pi}_R$ and $\widetilde{\Pi}_I - \widetilde{\Pi}_R$ profits for the retailer and manufacturer, respectively. Condition (3.13) is obvious, within the class of price schedules $\Sigma_\delta\left(\widetilde{\Pi}_R\right)$, that for each signal realization, the highest wholesale price that the retailer is willing to pay has to be higher than the lowest wholesale price that the manufacturer is willing to offer. If that is not the case, no price schedule can be found that satisfies the equilibrium conditions and results in a split of profits $\left(\widetilde{\Pi}_R, \widetilde{\Pi}_I - \widetilde{\Pi}_R\right)$ for the retailer and manufacturer, respectively. Any price schedule $w(\kappa) \in \Sigma_\delta\left(\widetilde{\Pi}_R\right)$ is thus bounded by $\underline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right)$ and $\overline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right)$.

However, condition (3.13) is not sufficient. Even if (3.13) is satisfied, it may be possible that there does not exist any price schedule $w(\kappa)$ that results in a split of profits of $\left(\widetilde{\Pi}_R, \widetilde{\Pi}_I - \widetilde{\Pi}_R\right)$. Condition (3.14) guarantees the latter: it garantees that $\widetilde{\Pi}_R$ is higher than the minimum profits the retailer expects to obtain and lower than the maximum profits the manufacturer allows for the retailer. The following Proposition characterizes the minimum discount factor above which the full coordination is possible, the equilibrium order quantities and wholesale price:

Proposition 4. *The minimum discount factor above which the supply chain can coordinate is also determined by:*

$$\underline{\delta} = \frac{\frac{\Psi_R}{\Lambda_R}}{1 + \frac{\Psi_R}{\Lambda_R}}$$

Here, $\Psi_R = \max_\kappa \Psi_R(\kappa) = \max_\kappa \left[\Pi_R^d(\kappa) - \Pi_R(\kappa)\right]$, *and* $\Lambda_R = \widetilde{\Pi}_R - \widetilde{\Pi}_R^*$, *where* $\Pi_R^d(\kappa) = \Pi_R(w(\kappa), y(w(\kappa), \kappa), \kappa)$, $\Pi_R(\kappa) = \Pi_R\left(w(\kappa), y^I(\kappa), \kappa\right)$ *with* $w(\kappa) = c + \frac{\Pi_M^*(\kappa)}{y^I(\kappa)}$, $\widetilde{\Pi}_R = \widetilde{\Pi}_I - \widetilde{\Pi}_M^*$ *and* $\widetilde{\Pi}_M = \widetilde{\Pi}_M^*$.

As in the case with no demand fluctuation, supply chain coordination is obtained by a decrease in the wholesale price and an increase in the order quantity (compared with the stage game price and quantity). Also, the minimum discount factor is determined by the retailer's temptation to deviate and his punishment for deviation. The larger his temptation, or the more lenient his punishment, the higher the minimum discount factor above which the coordination is possible. In the fluctuation case, however, the incentives to deviate in each period depend on the market signal, κ, which is observable to both players. Therefore, there will exist a market signal, to which we refer as κ_0, for which the deviation temptation Ψ_R is the highest, or the relative temptation $\frac{\Psi_R}{\Lambda_R}$ is the highest. The highest temptation determines the lowest possible discount factor for cooperation. Furthermore, at the lowest discount factor, the coordination does not increase the manufacturer's profit and all gains flow to the retailer.

When $\delta > \underline{\delta}$, full coordination can be achieved. Now, we can determine bounds on the equilibrium profits:

Proposition 5. *When* $\underline{\delta} \leq \delta < 1$, *full coordination is possible, and a range of profit divisions is possible in equilibria:*
1) The upper bound (resp., lower bound) of the retailer's (resp., manufacturer's) profit is $\widetilde{\Pi}_I - \widetilde{\Pi}_M^*$ *(resp.,* $\widetilde{\Pi}_M^*$*).*
2) The lower bound (resp., upper bound) of the retailer's (resp., manufacturer's) profit is decreasing (resp., increasing) in δ*. When* δ *goes to* 1*, the lower bound (resp., upper bound) of the retailer's (resp., manufacturer's) profit goes to* $\widetilde{\Pi}_R^*$ *(resp.,* $\widetilde{\Pi}_I - \widetilde{\Pi}_R^*$*). There exists* $(\underline{\delta} <)\, \overline{\delta} < 1$

such that: When $\underline{\delta} < \delta < \overline{\delta}$, the minimum equilibrium profits for the retailer are such that there exist a $\kappa_1 \in [\underline{\kappa}, \overline{\kappa}]$ for which (3.13) is binding; and when $\overline{\delta} \leq \delta < 1$, the minimum equilibrium profits for the retailer are such that (3.14) is binding.

For $\delta = \underline{\delta}$, the (coordinated) supply chain profits are split in a unique way. When $\underline{\delta} < \delta < 1$, a continuum of strategies become sustainable in equilibrium, and there are different possible profit divisions between the two players. The maximum profit that the retailer can get is the same as his profit at $\underline{\delta}$, while the minimum profit is decreasing in δ. When δ is close to 1, the stage game equilibrium profit of the retailer is again sustainable in equilibrium, and the maximum profit that the manufacturer can get is $\widetilde{\Pi}_I - \widetilde{\Pi}_R^*$. The range of their profits decreases as δ decreases and collapses at $\underline{\delta}$. Being the leader of this game, the manufacturer is able to choose a wholesale price that leads to her maximum profit. Thus, the retailer is best off with a discount factor just above $\underline{\delta}$, and the manufacturer is better off with high values of the discount factor. Figure 3.1 shows a possible region of $\widetilde{\Pi}_R$ when the system is fully coordinated, denoted by 'Coordinated Area'. As illustrated, the minimum profit that the retailer can get is decreasing in δ, and defined by two curves. On the first curve (for $\underline{\delta} < \delta < \overline{\delta}$), there exists a strong market signal κ^* such that the retailer and the manufacturer are indifferent in cooperating or not, in other words, below this curve there does not exist a price schedule such that for all market singals neither of them will deviate. The second curve (for $\underline{\delta} < \delta < \overline{\delta}$) is the boundary below which all $\widetilde{\Pi}_R$'s are lower than the lowest acceptable profits for the retailer.

Minimum Discount Factor - Markets with Uniform Demand Distribution with Fluctuation of Mean or Variance

In this section, we assume that both κ and demand ξ follow Uniform distributions.

Fluctuation of the market demand variance. First we assume that the market signal κ is the standard deviation of the demand distribution, i.e., $Var\left[\xi\right] = \kappa^2$. Suppose $E\left[\xi\right] = \mu$. Then, $\phi_\kappa\left(\xi\right) = \frac{1}{2\sqrt{3}\kappa}$ over $\left[\mu - \sqrt{3}\kappa, \mu + \sqrt{3}\kappa\right]$, and $\theta\left(\kappa\right) = \frac{1}{\overline{\kappa} - \underline{\kappa}}$ over $[\underline{\kappa}, \overline{\kappa}]$. We consider two scenarios: One that the market signal κ is observable and one that the market signal is not observable. In the case that the market signal κ is not observable, let $\Phi\left(\xi\right) = \mathbb{E}_\kappa\left(\Phi_\kappa\left(\xi\right)\right)$ be the expected demand distribution. The expected value of ξ is μ (for any value of $\underline{\kappa}$ and $\overline{\kappa}$). The standard deviation is denoted by σ_ξ and is a function of $\underline{\kappa}$ and $\overline{\kappa}$. Note that the expected standard deviation of the market demand is $\sigma_{\xi|\kappa} = \frac{\overline{\kappa} + \underline{\kappa}}{2}$. Then, $\frac{\sigma_\xi}{\sigma_{\xi|\kappa}}$ is a measure of the informativeness of the signal. If $\frac{\sigma_\xi}{\sigma_{\xi|\kappa}} = 1$, then the signal does not contain any information. Higher values of $\frac{\sigma_\xi}{\sigma_{\xi|\kappa}}$ indicate a higher variance reduction by the signal. We denote the minimum discount factor $\underline{\delta}$ ($\underline{\delta}'$) without (with) observable market signals. Table 3.1 shows all these values under different

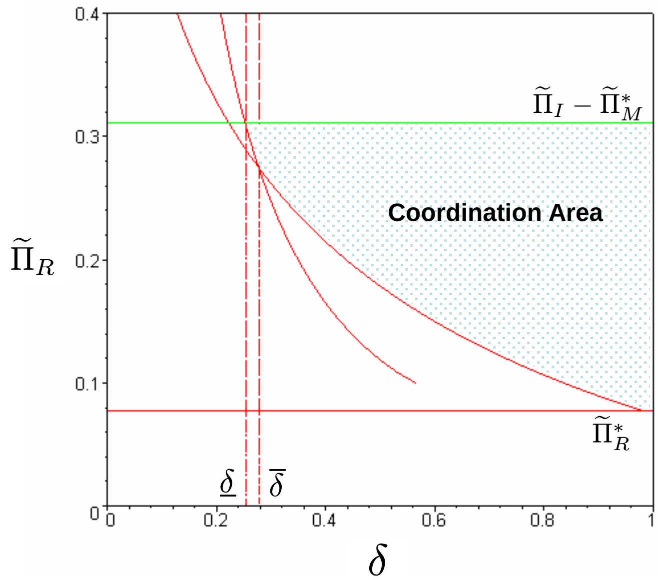

Figure 3.1: *Illustration of the retailer's expected profit range as a function of* δ*, and the area where the supply chain can coordinate (*$\delta = \underline{\delta}$*). In this example,* $\underline{\delta} = 0.2527$*,* $\frac{c}{r} = 0.1, \mu = 1, \underline{\kappa} = 0.1$ *and* $\overline{\kappa} = 0.4$*.*

parameter settings, with $c/r = 0.1$ and $\mu = 1$ for a series of $\underline{\kappa}$ and $\overline{\kappa}$ such that $\frac{\underline{\kappa}+\overline{\kappa}}{2} = 0.25$. Note that for $\underline{\kappa} = \overline{\kappa} = 0.25$, the signal does not contain any information ($\frac{\sigma_\xi}{\sigma_{\xi|\kappa}} = 1$), and we have that $\gamma = 2.527$ and $1 - \frac{c}{r} = 0.9 > \frac{1}{\gamma - 1} = 0.6547$ such that from Corollary 1 we obtain that $\underline{\delta} = 0.2$.

Table 3.1: Supply chain performance with $Var\left[\xi\right] = \kappa^2$, $\mu = 1$, $\sigma_{\xi|\kappa} = 0.25$ and $c/r = 0.1$.

Δ_κ	$\underline{\delta}$	$\underline{\delta}'$	$\frac{\kappa_0 - \underline{\kappa}}{\overline{\kappa} - \underline{\kappa}}$	$\frac{\sigma_\xi}{\sigma_{\xi\|\kappa}}$	$\widetilde{\Pi}_I - \Pi_I$	$\widetilde{\Pi}_R - \Pi_R$	$\widetilde{\Pi}_M - \Pi_M$
0.40	0.3174	0.2686	0.23	1.101	1.040E-2	-0.971E-2	2.011E-2
0.35	0.2949	0.2603	0.19	1.078	0.858E-2	-0.649E-2	0.150E-1
0.30	0.2726	0.2527	0.14	1.058	0.681E-2	-0.367E-2	1.049E-2
0.25	0.2510	0.2456	0.07	1.040	0.511E-2	-0.135E-2	0.647E-2
0.20	0.2303	0.2391	0.00	1.026	0.352E-2	0.029E-2	0.323E-2
0.15	0.2111	0.2298	0.00	1.014	0.208E-2	0.1003E-2	0.108E-2
0.10	0.2000	0.2182	0.00	1.006	0.093E-2	0.047E-2	0.046E-2
0.05	0.2000	0.2083	0.00	1.001	0.023E-2	0.011E-2	0.011E-2
0.00	0.2000	0.2000	0.00	1.000	0	0	0

From Table 3.1, we have the following observations:

The impact of market demand variance fluctuation on supply chain coordination. When the information about market fluctuation is observable to both players, supply chain coordination may either be restricted ($\underline{\delta} < \underline{\delta}'$) or enhanced ($\underline{\delta} > \underline{\delta}'$). If the signal is less informative ($\frac{\sigma_\xi}{\sigma_{\xi|\kappa}} \leq 1.026$), then market fluctuation decreases the range of discount factors for which supply chain coordination is possible. Here, the critical market signal is $\kappa_0 = \underline{\kappa}$. As κ is the market uncertainty variance, supply chain profits decrease as a function of κ. Thus, it is expected that temptation to deviate will be the highest for $\kappa_0 = \underline{\kappa}$. However, if the signal is informative ($\frac{\sigma_\xi}{\sigma_{\xi|\kappa}} \geq 1.040$), then observed market fluctuation increases the range of discount factors for which supply chain coordination is possible. Here, the critical market signal, κ_0, is interior in $[\underline{\kappa}, \overline{\kappa}]$.

The impact of market demand variance fluctuation and signal information on supply chain coordination. The higher the information content of the market signal (higher $\frac{\sigma_\xi}{\sigma_{\xi|\kappa}}$), the more difficult it is to achieve supply chain coordination: $\underline{\delta}'$ increases as Δ_κ increases.

When the market signal is not observable, the higher the market uncertainty (σ_ξ), the more difficult it is to achieve supply chain coordination. Remember from Corollary 1 that the opposite is true for the uniform distribution for which $\left(1 - \frac{c}{r}\right)(\gamma - 1) < 1$. Thus, without fluctuating demand, market uncertainty may have an ambiguous role for supply chain coordination.

The impact of market demand variance fluctuation and signal information the players' profits. The availability of a market signal increases the system profit $\widetilde{\Pi}_I - \Pi_I \geq 0$. Furthermore, as the information content of the signal increases (higher $\frac{\sigma_\xi}{\sigma_{\xi|\kappa}}$), the system profit gain increases. The availability of a market signal increases the manufacturer's profit. Furthermore, as the information content of the signal increases (higher $\frac{\sigma_\xi}{\sigma_{\xi|\kappa}}$), the manufacturer's profit gain increases. However, the availability of a market signal may decrease the retailer's profit. When the market signal is very informative (high $\frac{\sigma_\xi}{\sigma_{\xi|\kappa}}$), the retailer may have lower expected profits with a market signal than without a market signal. In that case, the manufacturer's profit gains are not only due to the system efficiency improvement, but, also due to a better strategic position with respect to the retailer. Only with moderately informative signals can the manufacturer share the increase in system profits with the retailer. Obviously, the profit gains due to market information decrease as the signal becomes less informative.

Markets with fluctuation of the mean demand. In the following, we assume that the market signal κ is the average of the demand distribution, i.e., $E[\xi] = \kappa$. Suppose $Var[\xi] = \sigma^2$. Then, $\phi_\kappa(\xi) = \frac{1}{2\sqrt{3}\sigma}$ over $\left[\kappa - \sqrt{3}\sigma, \kappa + \sqrt{3}\sigma\right]$, and $\theta(\kappa) = \frac{1}{\overline{\kappa} - \underline{\kappa}}$ over $[\underline{\kappa}, \overline{\kappa}]$. We still consider two scenarios as above. In the case that the market signal κ is not observable, let the standard deviation be denoted by σ_ξ. $\frac{\sigma_\xi}{\sigma}$ is a measure of the informativeness of the signal. Table 3.2 shows results under different parameter settings, with $c/r = 0.1$ and $\sigma = 0.25$ for a series of $\underline{\kappa}$ and $\overline{\kappa}$

such that $\frac{\underline{\kappa}+\overline{\kappa}}{2} = 1.0$. Note that for $\underline{\kappa} = \overline{\kappa} = 1.0$, the signal does not contain any information ($\frac{\sigma_\xi}{\sigma_{\xi|\kappa}} = 1$) and we have that $\gamma = 2.527$ and $1 - \frac{c}{r} = 0.9 > \frac{1}{\gamma-1} = 0.6547$ such that from Corollary 1 we obtain that $\underline{\delta} = 0.2$.

Table 3.2: Supply chain performance with $E[\xi] = \kappa$,
$\sigma = 0.25$ and $c/r = 0.1$.

Δ_κ	$\underline{\delta}$	$\underline{\delta}'$	$\frac{\kappa_0-\underline{\kappa}}{\overline{\kappa}-\underline{\kappa}}$	$\frac{\sigma_\xi}{\sigma}$	$\widetilde{\Pi}_I - \Pi_I$	$\widetilde{\Pi}_R - \Pi_R$	$\widetilde{\Pi}_M - \Pi_M$
0.40	0.2334	0.2466	1	1.1015	0.678E-2	-0.19E-2	0.86E-2
0.35	0.2252	0.2409	1	1.0786	0.54E-2	-0.28E-3	0.57E-2
0.30	0.2165	0.2352	1	1.0583	0.41E-2	0.78E-3	0.34E-2
0.25	0.2075	0.2294	1	1.0408	0.30E-2	0.12E-2	0.17E-2
0.20	0.2003	0.2236	1	1.0263	0.19E-2	0.96E-3	0.96E-3
0.15	0.2000	0.2177	1	1.0149	0.11E-2	0.54E-3	0.54E-3
0.10	0.2000	0.2118	1	1.0066	0.48E-3	0.24E-3	0.24E-3
0.05	0.2000	0.2059	1	1.0017	0.12E-3	0.60E-4	0.60E-4
0.00	0.2000	0.2000	1	1	0	0	0

From Table 3.2, we have the following observations:

The impact of mean demand fluctuation on supply chain coordination. When the information about market fluctuation is observable to both players, supply chain coordination is always restricted, i.e., $\underline{\delta} < \underline{\delta}'$. Here, the critical market signal is always $\kappa_0 = \overline{\kappa}$. As κ is the average market demand, it is expected that the temptation to deviate will be the highest for $\kappa = \overline{\kappa}$.

The impact of mean demand fluctuation and signal information on supply chain coordination and the players' profits.
The two observations obtained for κ being the standard deviation also apply here.

In conclusion, extra market information may not always be used to implement more efficient ordering decisions, due to strategic considerations. The manufacturer seems to benefit more from such information.

3.5 Conclusions and Further Research

In this paper, we studied cooperation between a manufacturer and a retailer. The latter faces a newsvendor problem in a repeated game with the former. We developed a mathematical model that allows us to study coordination of this two-player supply chain through repeated interaction.

The single stage version of the manufacturer-retailer game with a wholesale price contract cannot coordinate the supply chain. In a repeated game context, however, a wholesale price contract can fully coordinate the supply chain with a Grim trigger strategy, provided that the players discount the future stream of profits with a factor of at least $\underline{\delta}$. When the discount value is exactly equal to $\underline{\delta}$, the manufacturer's expected profit is not higher than the profits the manufacturer would obtain in a single-stage game. The retailer's expected profit, however, is greater than his stage game profit and equal to the supply chain maximum profit minus the manufacturer's profit. For values larger than $\underline{\delta}$, a range of profit divisions is possible in equilibria. When the demand fluctuates; i.e., the demand distribution changes from period to period according to a probabilistic law but the distribution of which is observable in the beginning of each period, then the ability to coordinate is typically restricted: $\underline{\delta}$ is higher than when the signal about market fluctuation is unavailable. Furthermore, even though the supply chain profits increase, it may be that such a signal decreases the retailer's expected profits. We show that it may be not trivial to identify such a market signal.

We believe that these conclusions are of interests to a supply chain manager. Suppose that his interaction in the supply chain is indeed repeated, with the flexibility to change order quantities and wholesale prices at every interaction, demand does not fluctuate and the discount factor is not extremely low, then the manager does not have to elaborate sophisticated contracts, but he can use the trigger inventory policy. Under this policy, the manager always chooses a jointly optimizing action, but threatens to order less, forever as soon as the manufacturer increases her price. If the environment is characterized by large fluctuations, then more elaborate contract forms have to be used in order to coordinate the supply chain.

Note that for production environments with long lead times (which can be modelled as a newsvendor problem), the discount factors will be low. For example, in the fashion industry, interaction might be on a biyearly basis. In a production environment with perishable inventory (e.g., food, newspapers) which can also be modelled as a newsvendor problem, the discount factor will be rather substantially higher. The model developed in this paper would thus predict that it is easier in the second production environment to coordinate the supply chain than in the first, and that coordination in the first environment will be sensitive to demand fluctuations. This conclusion is, of course, predicated by the assumption that the interaction is limited to one retailer and one manufacturer. Further research should also make conclusions in more general environments. Empirical research could be done in order to see whether the issues that emerged from the theoretical model are also the salient issues in an industrial setting.

This research can be extended in various ways: the developed manufacturer-retailer model can be further refined, the infinitely repeated game theory can be applied to a broader class of production-inventory games and empirical research can be done to test the impact of repeated interaction on coordination in a supply chain context.

The retailer and manufacturer could have a different discount factor, δ_M and δ_R, which reflects the characteristics of the respective industries to which they belong. Furthermore, the carrot and stick strategy with a finite punishment length might be analyzed (see Gibbons, 1992), instead of the trigger strategy. This more refined strategy, which is more complex to analyze, would allow for full coordination for lower discount factors.

Another extension of the model would be to incorporate a reservation profit for the retailer, in order to model a more competitive downstream channel and redress the power imbalance between manufacturer and retailer. Another interesting extension would be to study a single-manufacturer-n-retailer setting as a game with n+1 players and see how this changes the co-ordination possibilities of the supply chain. Finally, physical links between the periods may be studied. For example, what if the market demand depends on the past service that is offered by the supply chain? What if inventories can be carried over from one period to another? A decentralized two-echelon inventory system may be studied where the order quantities are the strategic actions that are taken repeatedly by the actor at each echelon. In this setting, the Markov equilibrium concept can be used (see Tirole, 1986). This extension would then contrast with the competitive two-echelon inventory games of Cachon and Zipkin (1998), in which the inventory policy is determined in one shot, after which both players interact infinitely often with each other behaving according to the determined equilibrium policy. It would thus be interesting to consider the order quantities as the actions to be taken instead of the inventory policy.

We hope that this paper will generate more interests in studying repeated interactions in supply chains.

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3.7 Appendix

Proof of Proposition 2: At the minimum discount factor, there should exist exactly one w such that (3.6) and (3.7), evaluated for $y = y^I$, are satisfied. Otherwise, it is easy to see that the discount factor could be further reduced. Thus, we need to find the pair (w, δ) that satisfies:

$$\begin{cases} \Pi_R\left(\widehat{w}, y\left(\widehat{w}\right)\right) + \frac{\delta}{1-\delta}\Pi_R^* = \frac{1}{1-\delta}\Pi_R\left(w, y^I\right) \\ \Pi_M^* = \Pi_M\left(w, y^I\right). \end{cases}$$

It follows that $\widehat{w} = c + \frac{\Pi_M^*}{y^I}$ and as $\Pi_M\left(w, y^I\right) + \Pi_R\left(w, y^I\right) = \Pi_I$, we obtain: $\Pi_R\left(\widehat{w}, y\left(\widehat{w}\right)\right) + \frac{\delta}{1-\delta}\Pi_R^* \leq \frac{1}{1-\delta}\left(\Pi_I - \Pi_M^*\right)$, from which $\underline{\delta}$ can be solved:

$$\underline{\delta} = \frac{\Pi^I - \Pi_M^* - \Pi_R\left(\widehat{w}, y\left(\widehat{w}\right)\right)}{\Pi_R^* - \Pi_R\left(\widehat{w}, y\left(\widehat{w}\right)\right)}.$$

or,

$$\underline{\delta} = \frac{\frac{\Psi_R}{\Lambda_R}}{1 + \frac{\Psi_R}{\Lambda_R}}$$

where, $\Psi_R = \Pi_R^d - \Pi_R$, $\Lambda_R = \Pi_R - \Pi_R^*$, $\Pi_R^d = \Pi_R(\widehat{w}, y(\widehat{w}))$ and $\Pi_R = \Pi_I - \Pi_M^*$. ■

Proof of Proposition 3: The lower bound of w for which the supply chain can fully coordinate should be obtained when condition (3.8) is binding for $y = y^I$ as $\Pi_M(w, y^I)$ increases with w, i.e., $\underline{w}$ is determined by

$$\underline{w} : \Pi_M^* = \Pi_M(w, y^I)$$

As $\Pi_R(w, y^I)$ increases with w, the upper bound of w for which the supply chain can fully coordinate should be obtained when condition (3.6) is binding for $y = y^I$ or the retailer obtains his stage game profit, whichever is smaller, i.e., $\overline{w} = \min\{\overline{w}_1, \overline{w}_2\}$, where

$$\begin{aligned} \overline{w}_1 &: \Pi_R(w, y(w)) + \frac{\delta}{1-\delta}\Pi_R^* = \frac{1}{1-\delta}\Pi_R(w, y^I) \\ \overline{w}_2 &: \Pi_R^* = \Pi_R(w, y^I) \end{aligned}$$

In the following, we show that $\overline{w}_1 \le \overline{w}_2$, or to say, the inequality

$$\Pi_R(w, y(w)) + \frac{\delta}{1-\delta}\Pi_R^* \le \frac{1}{1-\delta}\Pi_R(w, y^I) \tag{3.15}$$

indicates

$$\Pi_R^* \le \Pi_R(w, y^I)$$

Suppose not. Then (3.15) becomes

$$\Pi_R(w, y(w)) < \Pi_R(w, y^I)$$

which is not true because the left hand side is the best response profit of the retailer. ■

Proof of Corrolary 1: For the uniform distribution, we can easily calculate: $y^* = \underline{\xi}$ and $y^I = \underline{\xi} + (\overline{\xi} - \underline{\xi})(1 - \frac{c}{r})$. As $y^* = \max(\frac{1}{2}y^I, \underline{\xi}) \Leftrightarrow \frac{r-c}{r} < \frac{1}{\gamma-1}$, we have that if $\frac{1}{2}y^I < \underline{\xi}$, then: $y^* = \underline{\xi}$ and $w^* = r$, from which it follows that $\Pi_R^* = 0$ and $\Pi_M^* = (r-c)\underline{\xi}$. We can easily calculate:

$$\Pi_I^* = \frac{1}{2}(r-c)\left(2\underline{\xi} + (\overline{\xi} - \underline{\xi})\left(1 - \frac{c}{r}\right)\right)$$

Thus, $\Pi_R = \Pi_I^* - \Pi_M^* = \frac{1}{2}(r-c)(\underline{\xi} + y^I) - (r-c)\underline{\xi} = \frac{1}{2}r(\overline{\xi} - \underline{\xi})(1 - \frac{c}{r})^2$. From $\Pi_M^* =$

$y^I(\widetilde{w}-c)$, we obtain that $\widetilde{w}=c+(r-c)\frac{\underline{\xi}}{y^I}$. Now we need to find Π_R^d. With the reaction

$$y(w)=\underline{\xi}+\left(\overline{\xi}-\underline{\xi}\right)\frac{r-w}{r}$$

and $y(\widetilde{w})=\underline{\xi}+\left(\overline{\xi}-\underline{\xi}\right)\left(1-\frac{c}{r}\right)\left(1-\frac{\underline{\xi}}{y^I}\right)$, we can calculate $\Pi_R^d=\Pi_R(\widetilde{w},y(\widetilde{w}))$ and find:

$$\Pi_R^d-\Pi_R=r\frac{\frac{1}{2}\left(\overline{\xi}-\underline{\xi}\right)\left(1-\frac{c}{r}\right)^2\underline{\xi}^2}{\left(\underline{\xi}+\left(\overline{\xi}-\underline{\xi}\right)\left(1-\frac{c}{r}\right)\right)^2}$$

Finally, we obtain: $\frac{\Pi_R-\Pi_R^*}{\Pi_R^d-\Pi_R}=\left(1+(\gamma-1)\left(1-\frac{c}{r}\right)\right)^2$, from which $\underline{\delta}$ follows. Note that when $\frac{r-c}{r}>\frac{1}{\gamma-1}$, then, $\underline{\delta}=\frac{1}{1+2^2}=\frac{1}{5}$. When $\frac{r-c}{r}>\frac{1}{\gamma-1}$, similar derivations show that $\underline{\delta}$ is independent of all parameters. ■

Proof of Lamma 1: Let $\overline{w}_\delta\left(\kappa,\widetilde{\Pi}_R\right)$ and $\underline{w}_\delta\left(\kappa,\widetilde{\Pi}_R\right)$ solve respectively

$$\begin{aligned}\Pi_R(w,y(w,\kappa),\kappa)-\Pi_R\left(w,y^I(\kappa),\kappa\right)&=\tfrac{\delta}{1-\delta}\left(\widetilde{\Pi}_R-\widetilde{\Pi}_R^*\right)\text{ and}\\ \widetilde{\Pi}_M^*(\kappa)-\left(\Pi_I(\kappa)-\Pi_R\left(w,y^I(\kappa),\kappa\right)\right)&=\tfrac{\delta}{1-\delta}\left(\widetilde{\Pi}_I-\widetilde{\Pi}_R-\widetilde{\Pi}_M^*\right).\end{aligned}$$

for w. Select any $\widetilde{\Pi}_R\in\left[\widetilde{\Pi}_R^*,\widetilde{\Pi}_I-\widetilde{\Pi}_M^*\right]$ as given (We will show $\widetilde{\Pi}_R\leq\widetilde{\Pi}_I-\widetilde{\Pi}_M^*$ in the following text, while $\widetilde{\Pi}_R\geq\widetilde{\Pi}_R^*$ holds because the retailer will deviates otherwise). Then, we consider the set

$$\Omega\left(\widetilde{\Pi}_R\right)\doteq\left\{w(\kappa):\forall\kappa\in[\underline{\kappa},\overline{\kappa}]:\widetilde{\Pi}_R=\mathbb{E}_\kappa\left[\Pi_R\left(w(\kappa),y^I(\kappa),\kappa\right)\right]\right\}.$$

Then,

$$w(\kappa)\in\Omega\left(\widetilde{\Pi}_R\right)\Rightarrow\mathbb{E}_\kappa[rD\left(y^I(\kappa),\kappa\right)-y^I(\kappa)w(\kappa)]=\widetilde{\Pi}_R\tag{3.16}$$

The set of $w(\kappa)$ is determined by:

$$\forall\kappa\in[\underline{\kappa},\overline{\kappa}]:\underline{w}_\delta\left(\kappa,\widetilde{\Pi}_R\right)\leq w(\kappa)\leq\overline{w}_\delta\left(\kappa,\widetilde{\Pi}_R\right)\tag{3.17}$$

Furthermore, note that: $\widetilde{\Pi}_M=\widetilde{\Pi}_I-\widetilde{\Pi}_R$. Therefore, any $w(\kappa)\in\Omega\left(\widetilde{\Pi}_R\right)$ that satisfies (3.9) and (3.10) satisfies $\forall\kappa\in[\underline{\kappa},\overline{\kappa}]$:

$$0\leq\frac{\delta}{1-\delta}\left(\widetilde{\Pi}_R-\widetilde{\Pi}_R^*\right)-\Pi_R(w(\kappa),y(w(\kappa)),\kappa)+\Pi_R\left(w(\kappa),y^I(\kappa),\kappa\right)\tag{3.18}$$

and

$$0 \leq \frac{\delta}{1-\delta}\left(\widetilde{\Pi}_I - \widetilde{\Pi}_R - \widetilde{\Pi}_M^*\right) + \Pi_M\left(w\left(\kappa\right), y^I\left(\kappa\right), \kappa\right) - \widetilde{\Pi}_M^*\left(\kappa\right) \tag{3.19}$$

If $\underline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right)$ crosses with $\overline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right)$ at some κ, i.e., $\underline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right) \geq \overline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right)$ does not hold for all $\kappa \in [\underline{\kappa}, \overline{\kappa}]$, then it is impossible to find a $w\left(\kappa\right)$ satisfying the conditions for a given $\widetilde{\Pi}_R$. If $\underline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right) \leq \overline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right)$ for all $\kappa \in [\underline{\kappa}, \overline{\kappa}]$, then, for a given $\widetilde{\Pi}_R$, we can show the following statement holds:

$$\exists\ w_\delta\left(\kappa\right) : \underline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right) \leq w_\delta\left(\kappa\right) \leq \overline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right) \text{ and } (3.16) \Leftrightarrow$$

$$\begin{cases} \underline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right) \leq \overline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right) \\ \mathbb{E}_\kappa[rD\left(y^I, \kappa\right) - y^I\left(\kappa\right)\overline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right)] \leq \widetilde{\Pi}_R \leq \mathbb{E}_\kappa[rD\left(y^I, \kappa\right) - y^I\left(\kappa\right)\underline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right)] \end{cases}$$

The $\Rightarrow$ part is immediate.
In order to prove the $\Longleftarrow$ part, let

$$\alpha = \frac{E_\kappa[rD\left(y^I, \kappa\right) - y^I\left(\kappa\right)\underline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right)] - \widetilde{\Pi}_R}{\mathbb{E}_\kappa[rD\left(y^I\left(\kappa\right), \kappa\right) - y^I\left(\kappa\right)\underline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right)] - \mathbb{E}_\kappa[rD\left(y^I\left(\kappa\right), \kappa\right) - y^I\left(\kappa\right)\overline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right)]} \in [0,1]$$

then,

$$\begin{aligned} \widetilde{\Pi}_R &= \alpha\mathbb{E}_\kappa[rD\left(y^I\left(\kappa\right), \kappa\right) - y^I\left(\kappa\right)\overline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right)] \\ &\quad +(1-\alpha)\mathbb{E}_\kappa[rD\left(y^I\left(\kappa\right), \kappa\right) - y^I\left(\kappa\right)\underline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right)] \end{aligned}$$

We construct:

$$w'_\delta\left(\kappa, \widetilde{\Pi}_R\right) = \alpha\overline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right) + (1-\alpha)\underline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right) \tag{3.20}$$

By taking an expectation on both side of (3.20), we have:

$$\widetilde{\Pi}_R = \mathbb{E}_\kappa[rD\left(y^I\left(\kappa\right), \kappa\right) - y^I\left(\kappa\right)w'_\delta\left(\kappa, \widetilde{\Pi}_R\right)]$$

From (3.20), we also know:

$$\underline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right) \leq w'_\delta\left(\kappa, \widetilde{\Pi}_R\right) \leq \overline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right)$$

or,

$$\overline{w}_\delta\left(\kappa,\widetilde{\Pi}_R\right)\leq w'_\delta\left(\kappa,\widetilde{\Pi}_R\right)\leq \underline{w}_\delta\left(\kappa,\widetilde{\Pi}_R\right)$$

but the latter is impossible because $\underline{w}_\delta\left(\kappa,\widetilde{\Pi}_R\right)\leq\overline{w}_\delta\left(\kappa,\widetilde{\Pi}_R\right)$. ∎

Lemma A 1. *For a given triple, $\left(\kappa,\widetilde{\Pi}_R,\delta\right)$, we obtain that:*

$$\underline{w}_\delta\left(\kappa,\widetilde{\Pi}_R\right)=c+\frac{1}{y^I(\kappa)}\left[\Pi_M^*(\kappa)-\frac{\delta}{1-\delta}\left(\widetilde{\Pi}_I-\widetilde{\Pi}_M^*-\widetilde{\Pi}_R\right)\right]\tag{3.21}$$

and $\overline{w}_\delta\left(\kappa,\widetilde{\Pi}_R\right)$ is the solution of w in:

$$r\int_{y^I(\kappa)}^{\overline{\Phi}_\kappa^{-1}\left(\frac{w}{r}\right)}\xi\phi_\kappa(\xi)\,d\xi+y^I(\kappa)(w-c)=\frac{\delta}{1-\delta}\left(\widetilde{\Pi}_R-\widetilde{\Pi}_R^*\right).\tag{3.22}$$

Proof of Lemma A1: (3.21) follows immediately from (3.19), where, $\widetilde{\Pi}_M^*=\mathbb{E}_\kappa\left[\Pi_M^*(\kappa)\right]$. From (3.18), we cannot obtain a closed form for $\overline{w}_\delta\left(\kappa,\widetilde{\Pi}_R\right)$ with a general distribution. For a given distribution, it is given by (3.22). ∎

Lemma A 2. *Define:*

$$\Delta w_\delta\left(\kappa,\widetilde{\Pi}_R\right)=\overline{w}_\delta\left(\kappa,\widetilde{\Pi}_R\right)-\underline{w}_\delta\left(\kappa,\widetilde{\Pi}_R\right),$$

then:
(1) $\underline{w}_\delta\left(\kappa,\widetilde{\Pi}_R\right)$ and $\overline{w}_\delta\left(\kappa,\widetilde{\Pi}_R\right)$ increase with $\widetilde{\Pi}_R$, and the increasing rate of $\overline{w}_\delta\left(\kappa,\widetilde{\Pi}_R\right)$ is greater than that of $\underline{w}_\delta\left(\kappa,\widetilde{\Pi}_R\right)$;
(2) $\Delta w_\delta\left(\kappa,\widetilde{\Pi}_R\right)$ increases with $\widetilde{\Pi}_R$; and
(3) $\frac{\partial \underline{w}}{\partial\delta}\leq 0$, $\frac{\partial\overline{w}}{\partial\delta}\geq 0$ for $\widetilde{\Pi}_R\in[\widetilde{\Pi}_R^*,\widetilde{\Pi}_I-\widetilde{\Pi}_M^*]$, and $\Delta w_\delta\left(\kappa,\widetilde{\Pi}_R\right)$ strictly increases with δ.

Proof of Lemma A2. For notational simplicity, we introduce $\widehat{\delta}=\frac{\delta}{1-\delta}$.
(1) From (3.21), we have:

$$\frac{\partial}{\partial\widetilde{\Pi}_R}\underline{w}_\delta\left(\kappa,\widetilde{\Pi}_R\right)=\frac{\widehat{\delta}}{\overline{\Phi}_\kappa^{-1}\left(\frac{c}{r}\right)}\geq 0$$

Taking derivative with respect to $\widetilde{\Pi}_R$ on both sides of (3.22) gives:

$$\begin{aligned}
\overline{\Phi}_\kappa^{-1}\left(\frac{\overline{w}}{r}\right)\phi_\kappa\left[\overline{\Phi}_\kappa^{-1}\left(\frac{\overline{w}}{r}\right)\right]\frac{\partial}{\partial\xi}\overline{\Phi}_\kappa^{-1}\left(\frac{\overline{w}}{r}\right)\frac{\partial\overline{w}}{\partial\widetilde{\Pi}_R}+y^I(\kappa)\frac{\partial\overline{w}}{\partial\widetilde{\Pi}_R} &= \widehat{\delta} \\
-\overline{\Phi}_\kappa^{-1}\left(\frac{\overline{w}}{r}\right)\frac{\partial\overline{w}}{\partial\widetilde{\Pi}_R}+y^I(\kappa)\frac{\partial\overline{w}}{\partial\widetilde{\Pi}_R} &= \widehat{\delta}
\end{aligned}$$

or,

$$\frac{\partial}{\partial\widetilde{\Pi}_R}\overline{w}_\delta\left(\kappa,\widetilde{\Pi}_R\right)=\frac{\widehat{\delta}}{\overline{\Phi}_\kappa^{-1}\left(\frac{c}{r}\right)-\overline{\Phi}_\kappa^{-1}\left(\frac{\overline{w}}{r}\right)}\geq 0$$

and

$$\frac{\partial}{\partial\widetilde{\Pi}_R}\overline{w}_\delta\left(\kappa,\widetilde{\Pi}_R\right)>\frac{\partial}{\partial\widetilde{\Pi}_R}\underline{w}_\delta\left(\kappa,\widetilde{\Pi}_R\right)$$

(2) We have:

$$\begin{aligned}
\frac{\partial}{\partial\widetilde{\Pi}_R}\Delta w_\delta\left(\kappa,\widetilde{\Pi}_R\right) &= \frac{\partial}{\partial\widetilde{\Pi}_R}\overline{w}_\delta\left(\kappa,\widetilde{\Pi}_R\right)-\frac{\partial}{\partial\widetilde{\Pi}_R}\underline{w}_\delta\left(\kappa,\widetilde{\Pi}_R\right) \\
&= \widehat{\delta}\frac{\overline{\Phi}_\kappa^{-1}\left(\frac{\overline{w}}{r}\right)}{\overline{\Phi}_\kappa^{-1}\left(\frac{c}{r}\right)\left[\overline{\Phi}_\kappa^{-1}\left(\frac{c}{r}\right)-\overline{\Phi}_\kappa^{-1}\left(\frac{\overline{w}}{r}\right)\right]}
\end{aligned}$$

which is positive (zero at $\delta=0$) because $\overline{w}>c$ and $\overline{\Phi}_\kappa^{-1}(\cdot)$ is a decreasing function.
(3) From (3.22), we have:

$$\frac{\partial}{\partial\widehat{\delta}}\underline{w}_\delta\left(\kappa,\widetilde{\Pi}_R\right)=\frac{1}{y^I(\kappa)}\left(\widetilde{\Pi}_M^*+\widetilde{\Pi}_R-\widetilde{\Pi}_I\right)\leq 0$$

Taking derivative with respect to $\widehat{\delta}$ on both sides of (3.22) gives

$$\begin{aligned}
r\int_{y^I(\kappa)}^{\overline{\Phi}_\kappa^{-1}\left(\frac{w}{r}\right)}\xi\phi_\kappa(\xi)\,d\xi+y^I(\kappa)(w-c) &= \frac{\delta}{1-\delta}\left(\widetilde{\Pi}_R-\widetilde{\Pi}_R^*\right) \\
\overline{\Phi}_\kappa^{-1}\left(\frac{\overline{w}}{r}\right)\phi_\kappa\left[\overline{\Phi}_\kappa^{-1}\left(\frac{\overline{w}}{r}\right)\right]\frac{\partial}{\partial\xi}\overline{\Phi}_\kappa^{-1}\left(\frac{\overline{w}}{r}\right)\frac{\partial\overline{w}}{\partial\widehat{\delta}}+y^I(\kappa)\frac{\partial\overline{w}}{\partial\widehat{\delta}} &= \widetilde{\Pi}_R-\widetilde{\Pi}_R^* \\
-\overline{\Phi}_\kappa^{-1}\left(\frac{\overline{w}}{r}\right)\frac{\partial\overline{w}}{\partial\widehat{\delta}}+y^I(\kappa)\frac{\partial\overline{w}}{\partial\widehat{\delta}} &= \widetilde{\Pi}_R-\widetilde{\Pi}_R^*
\end{aligned}$$

$$\frac{\partial}{\partial\widehat{\delta}}\overline{w}_\delta\left(\kappa,\widetilde{\Pi}_R\right)=\frac{1}{y^I(\kappa)-\overline{\Phi}_\kappa^{-1}\left(\frac{\overline{w}}{r}\right)}\left(\widetilde{\Pi}_R-\widetilde{\Pi}_R^*\right)\geq 0$$

We then have

$$\begin{aligned}
\frac{\partial}{\partial\widehat{\delta}}\Delta w_{\delta}\left(\kappa,\widetilde{\Pi}_R\right) &= \frac{\widetilde{\Pi}_R-\widetilde{\Pi}_R^*}{y^I(\kappa)-\overline{\Phi}_{\kappa}^{-1}\left(\frac{\overline{w}}{r}\right)}-\frac{\widetilde{\Pi}_M^*+\widetilde{\Pi}_R-\widetilde{\Pi}_I}{y^I(\kappa)} \\
&\geq \frac{\widetilde{\Pi}_R-\widetilde{\Pi}_R^*}{y^I(\kappa)}-\frac{\widetilde{\Pi}_M^*+\widetilde{\Pi}_R-\widetilde{\Pi}_I}{y^I(\kappa)} \\
&= \frac{\widetilde{\Pi}_I-\widetilde{\Pi}_M^*-\widetilde{\Pi}_R^*}{y^I(\kappa)}>0
\end{aligned}$$

i.e., $\Delta w_{\delta}\left(\kappa,\widetilde{\Pi}_R\right)$ strictly increases with $\widehat{\delta}$, or δ. ■

Lemma A 3. *For a given δ, define $\widetilde{\Pi}_{RLower}(\delta)$ and $\widetilde{\Pi}_{RUpper}(\delta)$ as the solutions to (3.14) for $\widetilde{\Pi}_R$ (by replacing inequalities with equalities).*
(1) (3.14) is satisfied for $\widetilde{\Pi}_R\in\left[\widetilde{\Pi}_R^*,\widetilde{\Pi}_I-\widetilde{\Pi}_M^*\right]$ if $\widetilde{\Pi}_{RLower}(\delta)\leq\widetilde{\Pi}_R\leq\widetilde{\Pi}_{RUpper}(\delta)$
(2) $\widetilde{\Pi}_{RUpper}(\delta)=\widetilde{\Pi}_I-\widetilde{\Pi}_M^*$, i.e., $\widetilde{\Pi}_{RUpper}(\delta)$ is independent of δ.
(3) $\widetilde{\Pi}_{RLower}(\delta)$ decreases with δ if $\widetilde{\Pi}_R^*\leq\widetilde{\Pi}_{RLower}(\delta)\leq\widetilde{\Pi}_I-\widetilde{\Pi}_M^*$
(4) Let $\widetilde{\Pi}_{RLower}\left(\delta^0\right)=\widetilde{\Pi}_I-\widetilde{\Pi}_M^*$, $\underline{w}_{\delta^0}\left(\kappa,\widetilde{\Pi}_I-\widetilde{\Pi}_M^*\right)\leq\overline{w}_{\delta^0}\left(\kappa,\widetilde{\Pi}_I-\widetilde{\Pi}_M^*\right)$ cannot be satisfied for all $\kappa\in[\underline{\kappa},\overline{\kappa}]$, i.e., $\underline{\delta}>\delta^0$.

Proof of Lemma A3.
(1) Follows immediately from the definitions of $\widetilde{\Pi}_{RLower}(\delta)$ and $\widetilde{\Pi}_{RUpper}(\delta)$
(2) From $\widetilde{\Pi}_{RUpper}=\mathbb{E}_{\kappa}\left[rD\left(y^I(\kappa),\kappa\right)-y^I(\kappa)\,\underline{w}_{\delta}\left(\kappa,\widetilde{\Pi}_{RUpper}\right)\right]$, we have:

$$\begin{aligned}
\widetilde{\Pi}_{RUpper} &= \mathbb{E}_{\kappa}\left[rD\left(y^I(\kappa),\kappa\right)-cy^I(\kappa)\right]-\mathbb{E}_{\kappa}\left[\frac{f(\kappa)}{y^I(\kappa)}\left[\Pi_M^*(\kappa)+\widehat{\delta}\left(\widetilde{\Pi}_M^*+\widetilde{\Pi}_{RUpper}-\widetilde{\Pi}_I\right)\right]\right] \\
&= \widetilde{\Pi}_I-\mathbb{E}_{\kappa}\left[\Pi_M^*(\kappa)+\widehat{\delta}\left(\widetilde{\Pi}_M^*+\widetilde{\Pi}_{RUpper}-\widetilde{\Pi}_I\right)\right] \\
&= \widetilde{\Pi}_I-\widetilde{\Pi}_M^*-\widehat{\delta}\left(\widetilde{\Pi}_M^*+\widetilde{\Pi}_{RUpper}-\widetilde{\Pi}_I\right)
\end{aligned}$$

or, $\widetilde{\Pi}_{RUpper}=\widetilde{\Pi}_I-\widetilde{\Pi}_M^*$.
(3) From the definition of $\widetilde{\Pi}_{RLower}$, we obtain:

$$\left(1+\mathbb{E}_{\kappa}\left[y^I(\kappa)\frac{\partial\overline{w}\left(\kappa,\widetilde{\Pi}_{Rlower},\delta\right)}{\partial\widetilde{\Pi}_R}\right]\right)\frac{\partial\widetilde{\Pi}_{Rlower}}{\partial\delta}=-\mathbb{E}_{\kappa}\left[y^I(\kappa)\frac{\partial\overline{w}}{\partial\delta}\right]$$

As $\frac{\partial\overline{w}}{\partial\widetilde{\Pi}_R}\geq 0$ and $\frac{\partial\overline{w}}{\partial\delta}\geq 0$ (see Lemma 2), we have that
$\frac{\partial\widetilde{\Pi}_{Rlower}}{\partial\delta}\leq 0$.

(4) If $\underline{w}_{\delta^0}\left(\kappa, \widetilde{\Pi}_I - \widetilde{\Pi}_M^*\right) \leq \overline{w}_{\delta^0}\left(\kappa, \widetilde{\Pi}_I - \widetilde{\Pi}_M^*\right)$, then, we should have that $\mathbb{E}_\kappa\left[rD\left(y^I(\kappa), \kappa\right) - y^I(\kappa)\,\overline{w}_\delta\left(\kappa, \widetilde{\Pi}_I - \widetilde{\Pi}_M^*\right)\right] \leq \mathbb{E}_\kappa\left[rD\left(y^I(\kappa), \kappa\right) - y^I(\kappa)\,\underline{w}_\delta\left(\kappa, \widetilde{\Pi}_I - \widetilde{\Pi}_M^*\right)\right]$, which is impossible at δ^0, unless $\overline{w}_\delta\left(\kappa, \widetilde{\Pi}_I - \widetilde{\Pi}_M^*\right) = \underline{w}_\delta\left(\kappa, \widetilde{\Pi}_I - \widetilde{\Pi}_M^*\right)$ for all $\kappa \in [\underline{\kappa}, \overline{\kappa}]$. By definition, the latter can never be the case. ■

Lemma A 4. *Define $\widetilde{\Pi}_{RMin}(\delta)$ as the solution to:*

$$\widetilde{\Pi}_{RMin}(\delta) = \min_{\widetilde{\Pi}_R \in \left[\widetilde{\Pi}_R^*, \widetilde{\Pi}_I - \widetilde{\Pi}_M^*\right]} \widetilde{\Pi}_R \ s.t.\ \Delta w_\delta\left(\kappa, \widetilde{\Pi}_R\right) \geq 0 \ \forall \kappa \in [\underline{\kappa}, \overline{\kappa}] \tag{3.23}$$

then,
(1) (3.13) is satisfied if $\widetilde{\Pi}_R \geq \widetilde{\Pi}_{RMin}(\delta)$ for $\widetilde{\Pi}_R \in [\widetilde{\Pi}_R^*, \widetilde{\Pi}_I - \widetilde{\Pi}_M^*]$
(2) $\widetilde{\Pi}_{RMin}(\delta)$ decreases with δ in the region $[\widetilde{\Pi}_R^*, \widetilde{\Pi}_I - \widetilde{\Pi}_M^*]$.

Proof of Lemma A4.
(1) From Lemma 2 (2): $\Delta w_\delta\left(\kappa, \widetilde{\Pi}_R\right)$ is increasing in $\widetilde{\Pi}_R$ for any κ, we have that if $\Delta w_\delta\left(\kappa, \widetilde{\Pi}_R\right) \geq 0$ is satisfied for all $\kappa \in [\underline{\kappa}, \overline{\kappa}]$, then, $\Delta w_\delta\left(\kappa, \widetilde{\Pi}'_R\right) \geq 0$ for all for $\kappa \in [\underline{\kappa}, \overline{\kappa}]$ if $\widetilde{\Pi}'_R \geq \widetilde{\Pi}_R$.
(2) (3.23) is equivalent to: $\widetilde{\Pi}_{RMin}(\delta) = \max_\kappa \widetilde{\Pi}'_R(\kappa, \delta)\ s.t.\ \Delta w_\delta\left(\kappa, \widetilde{\Pi}'_R\right) = 0$. Because $\Delta w_\delta\left(\kappa, \widetilde{\Pi}_R\right)$ increases with δ and $\widetilde{\Pi}_R$ for $\widetilde{\Pi}_R \in [\widetilde{\Pi}_R^*, \widetilde{\Pi}_I - \widetilde{\Pi}_M^*]$, it immediately follows that for a given κ, $\widetilde{\Pi}'_R(\kappa, \delta)$ decreases with δ in the region $[\widetilde{\Pi}_R^*, \widetilde{\Pi}_I - \widetilde{\Pi}_M^*]$. It then follows that $\widetilde{\Pi}_{RMin}(\delta)$ decreases with δ in the region $[\widetilde{\Pi}_R^*, \widetilde{\Pi}_I - \widetilde{\Pi}_M^*]$, because $\widetilde{\Pi}_{RMin}(\delta) = \max_\kappa[\widetilde{\Pi}'_R(\kappa, \delta)]$. ■

Proof of Proposition 4. From Lemma A 3 and Lemma A 4, we obtain that there exist a $\widetilde{\Pi}_R \in [\widetilde{\Pi}_R^*, \widetilde{\Pi}_I - \widetilde{\Pi}_M^*]$ that satisfies (3.13) and (3.14) iff there exist a

$$\widetilde{\Pi}_R \in [\max\left(\widetilde{\Pi}_{RMin}(\delta), \widetilde{\Pi}_{RLower}(\delta)\right), \widetilde{\Pi}_I - \widetilde{\Pi}_M^*]$$

From Lemma A 3 and Lemma A 4, we already obtained that $\widetilde{\Pi}_{RMin}\left(\delta^0\right) \geq \widetilde{\Pi}_{RLower}\left(\delta^0\right)$. Therefore, $\underline{\delta}$ is determined by

$$\widetilde{\Pi}_I - \widetilde{\Pi}_M^* = \widetilde{\Pi}_{RMin}(\underline{\delta})$$

Thus, the unique $\widetilde{\Pi}_R$ that is possible is: $\widetilde{\Pi}_I - \widetilde{\Pi}_M^*$. For a given δ, $\widetilde{\Pi}_{RMin}(\delta)$ is the minimum $\widetilde{\Pi}_R$ satisfying $\Delta w_\delta\left(\kappa, \widetilde{\Pi}_R\right) \geq 0$. Alternatively, for a given $\widetilde{\Pi}_R$, we can find the minimum δ satisfying $\Delta w_\delta\left(\kappa, \widetilde{\Pi}_R\right) \geq 0$, as Δw is increasing in δ. Therefore, $\underline{\delta}$ is determined by:

$$\underline{\delta} = \max_{\Delta w_\delta\left(\kappa, \widetilde{\Pi}_I - \widetilde{\Pi}_M^*\right) \geq 0 \ \forall \kappa \in [\underline{\kappa}, \overline{\kappa}]} \delta$$

From (3.21), we have

$$\underline{w}_{\delta}\left(\kappa, \widetilde{\Pi}_{I}-\widetilde{\Pi}_{M}^{*}\right)=\frac{\Pi_{M}^{*}(\kappa)}{y^{I}(\kappa)}+c$$

Substitute it into (3.22), and let $\widetilde{\Pi}_{R}=\widetilde{\Pi}_{I}-\widetilde{\Pi}_{M}^{*}$, we have:

$$\Psi_{M}(\kappa)=\frac{\delta}{1-\delta}\left(\widetilde{\Pi}_{I}-\widetilde{\Pi}_{M}^{*}-\widetilde{\Pi}_{R}^{*}\right)$$

with

$$\begin{aligned}
\Psi_{M}(\kappa) &= r \int_{y^{I}(\kappa)}^{\overline{\Phi}_{\kappa}^{-1}\left[\frac{1}{r}\left(\frac{\Pi_{M}^{*}(\kappa)}{y^{I}(\kappa)}+c\right)\right]} \xi \phi_{\kappa}(\xi)\, d\xi+\Pi_{M}^{*}(\kappa) \\
&= \Pi_{R}\left(w_{\kappa}, y(w_{\kappa}), \kappa\right)+\Pi_{M}^{*}(\kappa)-\Pi_{R}\left(w_{\kappa}, y^{I}(\kappa), \kappa\right)-y^{I}(\kappa)\left(w_{\kappa}-c\right) \\
&= \Pi_{R}\left(w_{\kappa}, y(w_{\kappa}), \kappa\right)-\Pi_{R}\left(w_{\kappa}, y^{I}(\kappa), \kappa\right)
\end{aligned}$$

Therefore, we can define:

$$\delta(\kappa)=\frac{\frac{\Psi_{R}(\kappa)}{\Lambda_{R}}}{1+\frac{\Psi_{R}(\kappa)}{\Lambda_{R}}}$$

where, $\Psi_{R}(\kappa)=\Pi_{R}(\widehat{w}, y(\widehat{w}), \kappa)-\Pi_{R}\left(w_{\kappa}, y^{I}(\kappa), \kappa\right)=r \int_{y^{I}(\kappa)}^{\overline{\Phi}_{\kappa}^{-1}\left[\frac{1}{r}\left(\frac{\Pi_{M}^{*}(\kappa)}{y^{I}(\kappa)}+c\right)\right]} \xi \phi_{\kappa}(\xi)\, d\xi+\Pi_{M}^{*}(\kappa)$ and $\Lambda_{R}=\widetilde{\Pi}_{I}-\widetilde{\Pi}_{M}^{*}-\widetilde{\Pi}_{R}^{*}$.

We then have: $\underline{\delta}=\max_{\kappa} \delta(\kappa)=\max_{\kappa}\left[r \int_{y^{I}(\kappa)}^{\overline{\Phi}_{\kappa}^{-1}\left[\frac{1}{r}\left(\frac{\Pi_{M}^{*}(\kappa)}{y^{I}(\kappa)}+c\right)\right]} \xi \phi_{\kappa}(\xi)\, d\xi+\Pi_{M}^{*}(\kappa)\right]$.

Clearly, for $\delta=\underline{\delta}$, $\widetilde{\Pi}_{R}=\widetilde{\Pi}_{I}-\widetilde{\Pi}_{M}^{*}$, $\widetilde{\Pi}_{M}=\widetilde{\Pi}_{M}^{*}$, and the wholesale price contract is unique, which is given by:

$$w(\kappa)=\underline{w}_{\delta}\left(\kappa, \widetilde{\Pi}_{I}-\widetilde{\Pi}_{M}^{*}\right)=c+\frac{\Pi_{M}^{*}(\kappa)}{y^{I}(\kappa)}$$

■

Proof of Proposition 5. In the following, we first show that $\widetilde{\Pi}_{RMin}(\delta)$ and $\widetilde{\Pi}_{R}^{*}$ must intersect, then we show that $\widetilde{\Pi}_{RMin}(\delta)$ and $\widetilde{\Pi}_{RLower}(\delta)$ must intersect at some $\overline{\delta}$.
When $\underline{w}_{\delta}\left(\kappa, \widetilde{\Pi}_{R}\right)=\overline{w}_{\delta}\left(\kappa, \widetilde{\Pi}_{R}\right)$, we have

$$r \int_{y^{I}(\kappa)}^{\overline{\Phi}_{\kappa}^{-1}\left(\frac{c}{r}+\frac{1}{r y^{I}(\kappa)}\left[\Pi_{M}^{*}(\kappa)-\widehat{\delta}\left(\widetilde{\Pi}_{I}-\widetilde{\Pi}_{M}^{*}-\widetilde{\Pi}_{R}\right)\right]\right)} \xi \phi_{\kappa}(\xi)\, d\xi=\widehat{\delta}\left(\widetilde{\Pi}_{I}-\widetilde{\Pi}_{M}^{*}-\widetilde{\Pi}_{R}^{*}\right)-\Pi_{M}^{*}(\kappa)$$

By inspection, one possible solution is that $\widetilde{\Pi}_{R}=\widetilde{\Pi}_{R}^{*}$, and $\widehat{\delta}=\frac{\Pi_{M}^{*}(\kappa)}{\widetilde{\Pi}_{I}-\widetilde{\Pi}_{M}^{*}-\widetilde{\Pi}_{R}^{*}}$ or $\delta=\frac{\Pi_{M}^{*}(\kappa)}{\widetilde{\Pi}_{I}-\widetilde{\Pi}_{M}^{*}-\widetilde{\Pi}_{R}^{*}+\Pi_{M}^{*}(\kappa)}$

denoted by $\delta^*(\kappa)$. This solution exists as long as $\delta^*(\kappa) \leq 1$, which must hold because otherwise $\widetilde{\Pi}_I < \widetilde{\Pi}_M^* + \widetilde{\Pi}_R^*$, i.e., $\widetilde{\Pi}_{RMin}$ and $\widetilde{\Pi}_R^*$ must intersect with each other at $\delta^* = \max_\kappa \delta^*(\kappa)$.
Further, at this solution ($\widetilde{\Pi}_R = \widetilde{\Pi}_R^*$, $\delta = \delta^*(\kappa)$), we have

$$\overline{w}_{\delta^*}\left(\kappa, \widetilde{\Pi}_R^*\right) = \underline{w}_{\delta^*}\left(\kappa, \widetilde{\Pi}_R^*\right) = c$$

As $\underline{w}$ decreases with δ and increases with $\widetilde{\Pi}_R$, it follows that for any κ, $\underline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right) < c$, for all $\widetilde{\Pi}_R < \widetilde{\Pi}_R^*$, and $\delta > \delta^*(\kappa)$. Clearly, it is impossible that $\overline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right) = \underline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right) < c$. It follows that, $\widetilde{\Pi}_R^*$ is the lowest value of $\widetilde{\Pi}_R$ as a solution to $\underline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right) = \overline{w}_\delta\left(\kappa, \widetilde{\Pi}_R\right)$ for any κ, i.e., $\widetilde{\Pi}_{RMin}(\delta) \geq \widetilde{\Pi}_R^*$, for all δ.
In the following, we show that there doesn't exist a δ, such that $\widetilde{\Pi}_{RLower}(\delta) = \widetilde{\Pi}_R^*$, i.e., $\widetilde{\Pi}_{RLower}(\delta) > \widetilde{\Pi}_R^*$, for all δ, it then follows that $\widetilde{\Pi}_{RLower}$ and $\widetilde{\Pi}_{RMin}$ intersect with each other at some $\overline{\delta}$ ($\underline{\delta} < \overline{\delta} < \delta^*$), because both $\widetilde{\Pi}_{RMin}(\delta)$ and $\widetilde{\Pi}_{RLower}(\delta)$ decrease with δ, and at $\underline{\delta}$, $\widetilde{\Pi}_{RLower}(\underline{\delta}) \leq \widetilde{\Pi}_{RLower}\left(\delta^0\right) = \widetilde{\Pi}_I - \widetilde{\Pi}_M^* = \widetilde{\Pi}_{RMin}(\underline{\delta})$ (see Lemmas A 3 and A 4).
We know that $\widetilde{\Pi}_{RLower}$ is determined by

$$\widetilde{\Pi}_{RLower} = \mathbb{E}_\kappa\left[rD\left(y^I, \kappa\right) - y^I(\kappa)\,\overline{w}_\delta\left(\kappa, \widetilde{\Pi}_{RLower}\right)\right]$$

or,

$$\widetilde{\Pi}_{RLower} = \widetilde{\Pi}_I - \mathbb{E}_\kappa\left[y^I(\kappa)\left(\overline{w}_\delta\left(\kappa, \widetilde{\Pi}_{RLower}\right) - c\right)\right]$$

Let's assume at some δ, $\widetilde{\Pi}_{RLower}(\delta) = \widetilde{\Pi}_R^*$, i.e.,

$$\widetilde{\Pi}_R^* = \widetilde{\Pi}_I - \mathbb{E}_\kappa\left[y^I(\kappa)\left(\overline{w}_\delta\left(\kappa, \widetilde{\Pi}_R^*\right) - c\right)\right] \tag{3.24}$$

While $\overline{w}_\delta\left(\kappa, \widetilde{\Pi}_R^*\right)$ is determined by:

$$r\int_{y^I(\kappa)}^{\overline{\Phi}_\kappa^{-1}\left(\frac{w}{r}\right)} \xi\phi_\kappa(\xi)\,d\xi + y^I(\kappa)(w - c) = 0$$

so $\overline{w}_\delta\left(\kappa, \widetilde{\Pi}_R^*\right)$ is independent of δ. Hence, (3.24) holds either for all possible δ or for no δ. The former possibility doesn't exist because we know that $\widetilde{\Pi}_{RLower}(\delta)$ is decreasing in δ. Therefore, there doesn't exist a δ, such that $\widetilde{\Pi}_{RLower}(\delta) = \widetilde{\Pi}_R^*$, namely, $\widetilde{\Pi}_{RLower}(\delta) > \widetilde{\Pi}_R^*$, for all δ, because $\widetilde{\Pi}_{RLower}\left(\delta^0\right) = \widetilde{\Pi}_I - \widetilde{\Pi}_M^* > \widetilde{\Pi}_R^*$.

Further, we show that at $\delta = \delta^*$, $\widetilde{\Pi}_{RLower}(\delta)$ exists, which further confirms that $\widetilde{\Pi}_{RLower}$ and $\widetilde{\Pi}_{RMin}$ intersect with each other at some $\overline{\delta} < \delta^*$. Let $y_1 = \widetilde{\Pi}_I - \widetilde{\Pi}_{RLower}$, which strictly decreases from $\widetilde{\Pi}_I - \widetilde{\Pi}^*_M$ to $\widetilde{\Pi}^*_M$ over the region $\widetilde{\Pi}_{RLower} \in [\widetilde{\Pi}^*_R, \widetilde{\Pi}_I - \widetilde{\Pi}^*_M]$. Let $y_2 = \mathbb{E}_\kappa\left[y^I(\kappa)\left(\overline{w}_{\delta^*}\left(\kappa, \widetilde{\Pi}_{RLower}\right) - c\right)\right]$, which is a strictly increasing function of $\widetilde{\Pi}_{RLower}$ ($\overline{w}$ increases with $\widetilde{\Pi}_{RLower}$). When $\widetilde{\Pi}_{RLower} = \widetilde{\Pi}^*_R$, y_2 is close to 0 since $\overline{w}_{\delta^*}\left(\kappa, \widetilde{\Pi}^*_R\right)$ is equal to c for $\kappa = \arg\max_\kappa \delta^*(\kappa)$, and slightly greater than c otherwise; when $\widetilde{\Pi}_{RLower} = \widetilde{\Pi}_I - \widetilde{\Pi}^*_M$, y_2 must be greater than $\widetilde{\Pi}^*_M$, because $\overline{w}_{\delta^*}\left(\kappa, \widetilde{\Pi}_I - \widetilde{\Pi}^*_M\right) > \underline{w}_{\delta^*}\left(\kappa, \widetilde{\Pi}_I - \widetilde{\Pi}^*_M\right)$ and $\mathbb{E}_\kappa\left[y^I(\kappa)\left(\underline{w}_{\delta^*}\left(\kappa, \widetilde{\Pi}_I - \widetilde{\Pi}^*_M\right) - c\right)\right]$ must be greater than $\widetilde{\Pi}^*_M$ (by the definition of $\underline{w}$). Therefore, y_1 and y_2 must intersect with each other in the region $\widetilde{\Pi}_{RLower} \in [\widetilde{\Pi}^*_R, \widetilde{\Pi}_I - \widetilde{\Pi}^*_M]$ i.e., $\widetilde{\Pi}_{RLower}(\delta^*)$ exists.

We then have that: 1) When $\underline{\delta} < \delta < \overline{\delta}$, the lower bound of the retailer's profit is $\widetilde{\Pi}_{RMin}(\delta)$; and 2) When $\overline{\delta} \leq \delta \leq 1$, the lower bound of the retailer's profit is $\widetilde{\Pi}_{RLower}(\delta)$.

$\overline{\delta}$ is calculated as follows. Think of κ and δ as given, and solve:

$$\begin{cases} w = c + \frac{1}{y^I(\kappa)}\left[\Pi^*_M(\kappa) + \frac{\delta}{1-\delta}\left(\widetilde{\Pi}^*_M - \widetilde{\Pi}_I + \widetilde{\Pi}_R\right)\right] \\ r\int_{y^I(\kappa)}^{\overline{\Phi}_\kappa^{-1}\left(\frac{w}{r}\right)} \xi\phi_\kappa(\xi)\, d\xi + y^I(\kappa)(w - c) = \frac{\delta}{1-\delta}\left(\widetilde{\Pi}_R - \widetilde{\Pi}^*_R\right) \end{cases}$$

for $\widetilde{\Pi}_R(\kappa, \delta)$. Let $\widetilde{\Pi}_{RMin}(\delta) = \max_\kappa \widetilde{\Pi}_R(\kappa, \delta)$, and

$\overline{w}_\delta\left(\kappa, \widetilde{\Pi}_{RMin}\right) = c + \frac{1}{y^I(\kappa)}\left[\Pi^*_M(\kappa) + \frac{\delta}{1-\delta}\left(\widetilde{\Pi}^*_M - \widetilde{\Pi}_I + \widetilde{\Pi}_{RMin}(\delta)\right)\right]$. Substitute $\widetilde{\Pi}_{RMin}(\delta)$ and $\overline{w}_\delta\left(\kappa, \widetilde{\Pi}_{RMin}\right)$ into:

$$\widetilde{\Pi}_{RMin}(\delta) = \widetilde{\Pi}_I - \mathbb{E}_\kappa\left[y^I(\kappa)\left(\overline{w}_\delta\left(\kappa, \widetilde{\Pi}_{RMin}\right) - c\right)\right]$$

and solve it for $\overline{\delta}$. ■