

UNIVERSITY OF CALIFORNIA SAN DIEGO

**A Model-Based Theory Creation and Validation of Technology Supply
Chains**

A dissertation submitted in partial satisfaction of the
requirements for the degree
Doctor of Philosophy

in

Management

by

Junghee Lee

Committee in charge:

Professor Vish Krishnan, Chair
Professor Hyoduk Shin, Co-Chair
Professor Terrence August
Professor Sanjiv Erat
Professor Joel Watson

2018

ProQuest Number:10809215

All rights reserved

INFORMATION TO ALL USERS

The quality of this reproduction is dependent upon the quality of the copy submitted.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if material had to be removed, a note will indicate the deletion.



ProQuest 10809215

Published by ProQuest LLC (2018). Copyright of the Dissertation is held by the Author.

All rights reserved.

This work is protected against unauthorized copying under Title 17, United States Code
Microform Edition © ProQuest LLC.

ProQuest LLC.
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106 – 1346

Copyright
Junghee Lee, 2018
All rights reserved.

The dissertation of Junghee Lee is approved, and it is acceptable in quality and form for publication on micro-film and electronically:

Co-Chair

Chair

University of California San Diego

2018

DEDICATION

To my wife Sunae for her love and unwavering support through my
doctoral journey.

EPIGRAPH

Wisdom must be intuitive reason combined with scientific knowledge. –Aristotle,
Nicomacheian Ethics, VI.7.

TABLE OF CONTENTS

Signature Page	iii
Dedication	iv
Epigraph	v
Table of Contents	vi
List of Figures	ix
List of Tables	x
Acknowledgements	xi
Vita	xii
Abstract of the Dissertation	xiii
Chapter 1 Product Innovation in Technology Supply Chains	1
1.1 Introduction	2
1.1.1 Upstream Battery Technology Development	4
1.2 Literature Review	6
1.3 Model	9
1.3.1 Decision Sequence	14
1.3.2 Benchmark: Vertical Integration vs. Supply Chain	15
1.4 Analysis	18
1.4.1 Equilibrium Prices, Quantities, and Qualities	18
1.4.2 Optimal Investment Anchor for Welfare Objectives	24
1.4.3 Equilibrium Investment Anchor	28
1.5 Investment Anchor for Cost Reducing R&D	31
1.6 Model Extensions and Robustness Checks	37
1.6.1 Revenue Sharing	37
1.6.2 Simultaneous Contracting	39
1.6.3 Investment Anchoring Under Concave Costs	42
1.7 Discussion and Conclusion	43
Chapter 2 Business Models for Technology-Intensive Supply Chains	46
2.1 Introduction	47
2.2 Literature Review	52
2.3 The Model	56
2.3.1 Model Description	56
2.3.2 Business Model for Technology Provider	61

2.4	Analysis	63
2.4.1	Business Models under Monopolistic Supplier and Manufacturer	63
2.4.2	Business Models Under Symmetric Suppliers and Manufacturers	67
2.4.3	Fixed Fee and Royalty Rate Licensing	78
2.5	Business Model Adaptation and Forward Integration	81
2.5.1	Subsystem Base Business Model for the Integrated Technology Provider	82
2.5.2	Full System Base Business Model for the Integra- ted Technology Provider	84
2.6	Extensions: Manufacturer Backward Integration and Com- petition in Technology Provision	87
2.6.1	Backward Integration	88
2.6.2	Integration Cost	89
2.6.3	Multiple Technology Providers	91
2.7	Managerial Insights and Implications	92
Chapter 3	Does Competition Help Drug Shortage Recovery?	96
3.1	Introduction	96
3.2	Literature Review	99
3.3	Hypothesis Development	102
3.4	Empirical Evidence on the Link Between Competition and Recovery Time	104
3.4.1	Data	104
3.4.2	Empirical Result	107
3.5	Theoretical Model: n -firm Recovery Competition	110
3.6	Discussion	113
3.6.1	Robustness Check	114
3.6.2	Alternative Explanations	116
3.7	Conclusion	117
Appendix A	Proofs for Chapter 1	121
Appendix B	Proofs for Chapter 2	139
B.1	Business Model Adaptation with Two Different Suppliers for the Non-Integrated Technology Provider	184
B.2	Analysis of Multiple Technology Providers and Proof of Proposition 2.7	201
B.2.1	Substitutable Technology Providers	201
B.2.2	Complementary Technology Providers	205
Appendix C	Proofs for Chapter 3	208

Bibliography 210

LIST OF FIGURES

Figure 1.1: Operating Profit and Consumer Surplus Comparison under the Vertically Integrated Firm and a Supply Chain ¹	16
Figure 1.2: Price and quantity choice under Tier 0 contract leader	18
Figure 1.3: Misalignment Penalty and Quality Expansion ²	22
Figure 1.4: Threshold values of γ for optimal innovation investment anchor for various objectives. ³	27
Figure 1.5: Optimal Innovation Investment Anchor: Firm's Profits ⁴	30
Figure 1.6: Market Coverage, Social Welfare, and Benefits of being the Investment Anchor under Cost Reduction R&D ⁵	34
Figure 1.7: Product Qualities and Supply Chain Profits under Different Contracting Schemes ⁶	41
Figure 2.1: Subsystem Base Business Model (SSB) and Full System Base Business Model (FSB)	62
Figure 2.2: Decision Sequence	62
Figure 2.3: The optimal royalty rate (R^*) and the optimal technology quality (T^*) under FSB Full coverage ⁷	71
Figure 2.4: Technology Provider's Market Coverage Comparison between FSB and SSB ⁸	72
Figure 2.5: Technology Provider's Optimal Business Model in v_h/v_l and α Under Varying Downstream Competition ⁹	74
Figure 2.6: Profit Differences of TP and M_2 under FSB and SSB	77
Figure 2.7: Technology Provider's Profits in β under SSB and FSB for Low Market Inequality ¹⁰	85
Figure 2.8: Value of Subsystem Manufacturing Integration for FSB Technology Provider ¹¹	86
Figure 3.1: New Shortages by Year	98
Figure B.1: Technology Provider's Optimal Business Model in v_h/v_l and α ¹²	153
Figure B.2: Technology Provider's Business Model Preference with respect to β and v_h ¹³	187

LIST OF TABLES

Table 1.1:	The Optimal Investment Anchor in Equilibrium ¹⁴	36
Table 2.1:	Optimal Business Model For Each Entity In Market Inequality ¹⁵	75
Table 2.2:	TP's Business Model with Forward Integration and Manufacturers' Backward Integration with Integration Cost ¹⁶	90
Table 3.1:	Dependent and Independent Variable Descriptions	106
Table 3.2:	Descriptive Statistics	107
Table 3.3:	Empirical Results	108
Table 3.4:	Regression and CEM Results	115

ACKNOWLEDGEMENTS

I would like to first acknowledge my parents Seokkee Lee and Hyuhyun Kwon for their love and encouragement. I also acknowledge the unflinching support of Prof. Vish Krishnan and Prof. Hyoduk Shin, my PhD advisors in helping me navigate the PhD program.

I would also like to express gratitude to Prof. Terrence August, Prof. Sanjiv Erat, Prof. Joel Watson, and Prof. Vincent Nijs for their constructive feedback on my research projects. I am also thankful to my kids for empathizing with my absence at home on several weekend days, to my in-laws, extended family and friends for providing encouragement. I would also like to acknowledge Erin Fox, Director of Drug Information at University of Utah, who generously shared the data that enabled me to conduct research presented in Chapter 3.

Chapter 1, in full, has been submitted as a manuscript to the journal Manufacturing & Service Operations Management and was co-authored with Junghee Lee, Vish Krishnan and Hyoduk Shin. The dissertation author was the primary investigator and author of this paper.

Chapter 2, in full, has been submitted as a manuscript to the journal Management Science and was co-authored with Junghee Lee, Vish Krishnan and Hyoduk Shin. The dissertation author was the primary investigator and author of this paper.

Chapter 3, in part, is currently being prepared for submission for publication and was co-authored with Junghee Lee, Vish Krishnan and Hyoduk Shin. The dissertation author was the primary investigator and author of this paper.

VITA

2006	B.S. in Information and Industrial Engineering, Yonsei University, Korea
2008	M.S. in Industrial and Operations Engineering, University of Michigan at Ann Arbor
2018	Ph.D. in Management, University of California San Diego

FIELDS OF STUDIES

Major Field: Management

- Studies in Innovation, Technology, and Operations Management
- Professors Vish Krishnan and Hyoduk Shin

ABSTRACT OF THE DISSERTATION

A Model-Based Theory Creation and Validation of Technology Supply Chains

by

Junghee Lee

Doctor of Philosophy in Management

University of California San Diego, 2018

Professor Vish Krishnan, Chair
Professor Hyoduk Shin, Co-Chair

Technology plays an increasingly critical role in various supply chains by endowing products with sought-after capabilities. For these supply chains to perform, both the creation and the reliable supply of technology are necessary. The current dissertation consists of three essays related to this theme.

In the first essay the focus is on a supply chain where there is an innovation opportunity in the upstream supplier. We investigate when the supplier should ask the downstream manufacturer to invest in the supplier's innovation in return for

the procurement contract initiation right. Interestingly, the supplier's strategy is contingent on the nature of the innovation such as quality improvement and cost reduction.

In the second essay, we study business models for the technology provider that can not only license its proprietary technology but also produce the technology embedded subsystem. A widely used royalty-driven approach has gotten complicated in multi-tier supply chains because there are multiple royalty bases. We characterize the appropriateness of different business models for markets with varying levels of customer diversity and competitive intensity in the supply chain.

In the third essay, the focus is on when a technology supply chain is more reliable. We investigate this question in pharmaceutical drug supply chain, where drug shortages frequently occur due to manufacturing issues. Using the drug shortage history data between 2010 and 2015, we found that increasing competition may not monotonically mitigate or prolong the drug shortage recovery time contrary to common theory predictions. We develop a model and provide a new theory that can plausibly explain the empirical observations.

In summary, this dissertation makes the following contributions. First, it shows how firms in a technology supply chain can productize their innovation and serve lower ends of the market while maximizing profit. Second, it establishes how technologies can be monetized in a supply chain with powerful intermediaries and complementary capabilities. Third, this work shows that sufficient competition in a supply chain is necessary to provide an innovative product to the market in a reliable manner.

Chapter 1

Product Innovation in Technology

Supply Chains

Managers introducing new products with advanced component technologies frequently face the dual task of managing both revenues and profits. This task is made challenging, in part, due to the tendency of new technologies to traverse a sequentially downward path of gradually lowering costs and prices, which limits their initial availability and affordability, crimping market coverage and revenues. In this paper, we focus on this product management challenge, show how it is amplified in a supply chain, and propose a new degree of freedom in a supply chain, namely innovation investment anchoring, that offers product managers and their firms the ability to expand market coverage and improve both revenues and profits. After motivating with a detailed industry field-study, we formally characterize the problem and show that deliberate choice of the innovation investment anchor leads to greater investments in innovation, revenues and profits. We compare and contrast product quality improvement and cost reduction investments in a product management setting. These findings have subtle, but important, implications for

firms launching innovative products and aspiring to expand product sales and profits. Specifically, innovating firms in a supply chain should broaden the quest for an investment anchor, offer them incentives to invest, and finely tune the level of innovation investment with product qualities, prices, and quantities for increasing revenues and profits.

1.1 Introduction

Technological advances offer firms and their product managers the opportunity to launch new products with additional capability such as intelligent automation, networking, and advanced data analytics. New component technologies, however, are expensive to develop, test, and produce, which makes them unaffordable initially to large segments of the market and limiting the developing firm's total available market, revenues and profits. Innovating firms and their managers, on the other hand, are evaluated by their stakeholders/investors on their market size, revenues, and profits. Breakthrough innovations, such as electric vehicles and high throughput gene sequencers, traditionally traverse a learning curve-driven sequential path of gradually lowering costs and expanding market coverage limiting initial market size and sales (Bhattacharya et al. 2003). This is partly due to the higher costs of component technologies and also due to the firm's desire to segment the market and extract the surplus of the higher-end of the market, a phenomenon accentuated in a supply chain as we will formalize later in the paper. However, this pattern of lower initial sales and gradual market expansion is challenged by the pressure for revenue growth from investors and the threat of entry of new substitutes, which motivates managers to increase unit sales by expanding their market coverage.

A product manager's quest for higher unit sales and profits is hampered by component technology quality/cost, market segmentation dilemmas, and coordination issues in a supply chain, which form the focus of this paper. Although it is evident that vertical integration of supply chain mitigates the aforementioned issues, downstream manufacturers specialized in integration of components and sales may lack development capabilities of new software (e.g., data analytics) or component (e.g., more efficient battery), which make them rely on expert suppliers. Higher development cost of breakthrough component technologies is particularly the case for many innovative products such as electric vehicles whose performance improvement entails significant and non-linear development cost in quality (Mussa and Rosen 1978; Moorthy and Png 1992) and production cost in manufacturing scale (Majumder and Srinivasan 2008; Maynard 2014; Hull 2017). As seen in the next subsection, technology suppliers who specialize in developing these components often wonder whether the investment might generate a healthy return. Downstream manufacturers that integrate these components into finished products and sell them to end consumers might price these innovative products high enough to extract the surplus of high-end consumers for their own profit maximizations, resulting in less incentive for the suppliers to invest in innovation. Such lack of component innovation investment can lower the profits of downstream firms as well. It is imperative for supply chain firms to develop a mechanism to avoid such a distortion in innovation investment resulting in reduced unit sales, revenues, and profits.

In this paper, we propose an innovation investment anchoring approach that helps supply chain partners offset distorted innovation investments due to misalignment between the partners. A downstream manufacturer that relies on an upstream supplier's R&D for quality improvement or cost reduction of the supplier's component would find it optimal to go beyond the traditional approach of always

having the upstream supplier invest in the R&D projects. Specifically, the two supply chain partners may agree in some cases for the downstream manufacturer to anchor or initiate the upstream R&D investment, in return for receiving additional decision rights that makes it worthwhile for the downstream firm to do so. Upstream suppliers also find this approach to be in their best interests as it provides appropriate incentives for downstream firms to aggressively price their innovative products to expand unit sales, revenues, and profits. We characterize when this investment anchoring approach is beneficial for both firms in equilibrium. For the case of quality-improvement R&D investments, when the component R&D cost is low, both the supplier and the manufacturer are better off if the supplier is the investment anchor. In contrast, for high R&D costs, the downstream manufacturer anchoring the development investment becomes Pareto-optimal. Moreover, we find that the types of innovation, namely, quality improvement or cost reduction, also impact the returns from investment anchoring. We first begin with a detailed case example from an industry field study to frame and ground the problem studied.

1.1.1 Upstream Battery Technology Development

Our study company, Tesla, that designs, assembles and markets electric vehicles (EVs), offers a good illustration of the underlying issues considered in the paper. EVs offer a cleaner emission-free alternative to conventional internal combustion engine-based automobiles. Transportation accounts for 25-30 percent of U.S. greenhouse-gas emissions, so mass adoption of EVs could not only be a major source of revenues and profits for automobile manufacturers but also be of a major benefit to society. However, adoption and growth of the EV market is constrained by the high price of electric vehicles and cost of batteries for automobile manufacturers (Bullis 2015).

Studies by scholars of the battery segment of EV supply chain show that development of battery is fraught with intricate technical challenges relating to battery chemistry. Over the last decade, the battery segment has been dominated by a handful of suppliers, most notably Panasonic of Japan which supplied to major US auto manufacturers. Our interviews indicate that Panasonic may have been reluctant to invest in battery market both due to the technical challenges associated with battery chemistry and also due to its concern that it may not be able to capture the value realized from the innovation because of the role of large downstream supply chain partners (automobile manufacturers such as GM and Ford). Some downstream companies like Nissan formed joint ventures with suppliers such as NEC to foster investments in development and production of batteries. However, the joint venture approach came with its own challenges resulting in the disbanding of the joint ventures (Wells 2017).

Tesla chose to actively “partner” with its battery supplier, Panasonic, initially in the development and more recently in the production of automobile batteries. During the period of 2008-2014, the partnership was mostly in the development phase of the battery, resulting in the development of robust lithium-ion batteries (Tesla 2010). Our interviews with Tesla managers indicate that the partnership was designed to address Panasonic’s concerns about the attractiveness of the battery innovation investments. While Tesla did not take the joint-venture approach adopted by Nissan, it seems to have gone beyond the traditional arms-length relationship between automobile manufacturers and their suppliers, by actively collaborating and sharing the cost of development and testing of batteries, which seems to also have assuaged Panasonic’s concerns and stimulated active component technology development. Specific details of the contractual relationship between Tesla and Panasonic are confidential, but our interviews of past and present Tesla

managers shed light on the nature of the discussions which inspire the modeling approach used in the paper. Since 2008, the storage capacity of Tesla's battery packs supplied by Panasonic has nearly doubled and the cost more than halved, far outpacing the competition and resulting in the market share and market value expansion of both these companies (Fehrenbacher 2016; Lambert 2017).

The analysis presented in the paper offers technology supply chain partners additional degrees of freedom on the anchoring of innovation investments that results in higher-quality products and increased sales and profits through broader market coverage for such innovations. We now begin with a discussion of the literature related to our work.

1.2 Literature Review

There exists a substantial body of literature in the Economics and Management domains on the investments needed for innovation/R&D and the impact they engender in terms of social welfare and firm profits. However, most papers in this stream of literature do not detail who should make these investments in a network of firms to achieve the best social/economic outcomes. Product innovation has been a topic of active research interest in the Management Science/Operations Management literature - one review of this stream is provided by Krishnan and Ulrich (2001), but most of the literature has tended to be single-firm-centric focusing on project scheduling and management. There is a small stream of work on the interactions between product and supply chain design decisions (Ulrich and Ellison 2005; Grahovac and Parker 2003). However, this literature focuses only on how a single firm should make decisions involving its suppliers, rather than the interaction between the decisions of firms. Closer to our paper is the work of Bhaskaran and

Krishnan (2009) who study the joint-development of products in a bi-lateral supply chain context; however, they focus on contractual arrangements between firms that extend beyond revenue sharing to include the sharing of development cost and work. In contrast, this paper focuses on understanding the linkage between the source of innovation investments and the ensuing market coverage in a bilateral supply chain.

Innovative products exhibiting strong integration of hardware and software components require the careful modeling of both variable and fixed costs. For example, our study company, Tesla, incurs both the development cost of attaining technical capacity to deliver vehicles with a specific battery range as well as the production cost associated with manufacturing and customer support. The effects of development cost in isolation have been studied in the vertical product differentiation literature in Economics - specifically, Shaked and Sutton (1982) and Bonanno (1986) examine environments in which investment in quality is primarily associated with development costs. Alternatively, increased product quality may result in production costs that are convex in product quality as modeled by the seminal paper, Mussa and Rosen (1978). Krishnan and Zhu (2006) incorporate both development and quality related production costs within a single firm setting. Lee et al. (2018a) investigate a three-tier supply chain where technology and final product are developed separately focusing on the impact of royalty base on the business model of the technology provider. However, both aforementioned papers assume that production cost is linear implying that scaling-up production capacity for innovative products is not an issue. In contrast, this capacity issue is indeed commonly observed not only in the electric vehicle industry (Maynard 2014; Kessler 2015; Hull 2017) but also other industries (Murai 2014; Lee 2015). Although increasing marginal production cost has been adopted to model various production

challenges such as scarcity of cheap procuring sources (Tunca and Wu 2009) and limited farming areas (Holmes and Lee 2012), these studies abstract away product quality. We differentiate this paper by considering a setting where both production and development costs are significant to incorporate the common capacity scale-up challenge for innovative products, which requires more than combining the two strands of literature.

Suppliers that invest in component technological innovation often wrestle with the issue of other supply chain participants not making mutually aligned decisions; as a result, they may under-invest in component technologies. In such cases, downstream firms, instead of upstream suppliers, may decide to make the investment to foster innovation. Many papers in marketing and supply chain management have studied the interaction between firms within a supply chain and have proposed mechanisms to deal with price-quantity coordination problems (Jeuland and Shugan 1983; Lee and Staelin 1997; Cvsa and Gilbert 2002). Similar models have been used to analyze the effect of innovation by one of the firms on its channel partners. Gupta and Loulou (1998) study how interactions between firms in a channel affect innovation. Gilbert and Cvsa (2003) analyze the effect of strategic commitment to price by a supplier to stimulate downstream innovation in a supply chain. However, this stream of literature deals primarily with prices and quantities and ignores the decision-making about product quality, which constitutes the core of product innovation. We address the misalignment/coordination problems, including investments in quality improvement and cost reduction, in a way that keeps contracts simple - similar to the approach taken by Jerath et al. (2007) for aligning marketing and operations efforts within a firm. The optimality of a contract leader position in a supply network has been examined by Majumder and Srinivasan (2008), who generalize the notion of double-marginalization from Spengler (1950) to

show that contract leadership affects total supply chain profits. Our paper differs from Majumder and Srinivasan (2008) in that we go beyond quantity-price decisions in a supply chain by exploring investment decisions in quality improvement and cost reduction. We also find that incentive compatibility of optimal leadership may or may not hold depending on the nature of underlying innovation (whether it involves quality improvement or cost reduction). Our findings show that cost reduction increases the total supply chain profit, but does not necessarily increase a firm's profit if the firm's cost is reduced, which is in contrast to the conjecture provided in Majumder and Srinivasan (2008) for price/quantity decisions.

There is also an emerging stream of literature studying the impact of the supply chain and organization structure on equilibrium outcomes in static environments. Bimpikis et al. (2014) use a supply network perspective to show adverse effects of multi-sourcing in mitigating the aggregate disruption risk. Girotra et al. (2010) identify optimal organizational structure for the generation of new product ideas and Roels et al. (2010) study optimal contract types for delivering collaborative services. Our work, however, is focused on the notion of an investment anchor position for innovative products, and explores the impact of the investment anchor on the different supply chain parties as well as social welfare for quality-improving and cost-reducing innovations.

1.3 Model

We consider a two-tier supply chain that involves the development, production and distribution of an innovative product. Critical components are supplied from an upstream supplier (Tier 1) to a downstream manufacturer (Tier 0) for final integration, marketing and distribution. For example, in the EV case discussed

above, the battery company represents the supplier, and the EV manufacturer is considered as the manufacturer, which sells products to consumers whose total market size is N . Our stylized model and analysis methodology can be easily extended to more tiers and supply networks, and key qualitative insights are preserved in monopolistic settings with deterministic demand.

The quality of the product to consumers is a function of its marketing, assembly and the quality of the components. For instance, in the case of an innovative product such as an EV, the quality of a product is a function of its component performance (such as battery range) and the finished product quality and marketing (ease of use, safety, reliability, and design attractiveness). Each of these product features is associated with value added at one or multiple tier(s).

While our model can be extended to the case in which the manufacturer's quality also affects the quality of the end product through the use of an appropriate (e.g., multiplicative or additive) quality functions, we aim to represent a simple, yet consistent, model that captures the underlying issues of the motivating case of EVs and other technology-driven products, by focusing on the supplier's quality; for example, one of the key hurdles for adoption of EVs under the current technology is consumer's range anxiety related to the quality of batteries, or, equivalently, the quality of components produced at the supplier. In addition, in the electronics industry, including personal computers and cell phones, one of the key components that determines the end product quality is the performance of processing units or chips produced by component suppliers. In other words, we focus on the case in which a critical product feature limiting market penetration is associated with the quality of components supplied by an upstream firm. Our approach is similar to that of Altug and Ryzin (2013), who also consider a problem in which consumer's willingness to pay is modeled as a function of the supplier's component quality,

and the manufacturer does not contribute significant additional value in excess of what is derived from components themselves. Furthermore, our insights and results remain valid if a constraining product characteristic is associated with a different tier within the supply chain, as long as there exists a single primary bottleneck technology limiting the product's market penetration.

On the consumer demand side, we follow the traditional vertical differentiation model of quality (e.g., Mussa and Rosen 1978; Moorthy and Png 1992); specifically, given the product quality Θ , each consumer's type denoted as α is uniformly distributed on $[0, 1]$, such that when a consumer of type α purchases a product with quality Θ at price p , her net utility is $U = \alpha\Theta^\beta - p$ with $\beta \leq 1$, which captures the saturation or decreasing returns to quality. A consumer's reservation utility when she purchased none is normalized to zero. Consequently, a product of quality Θ with price p is purchased by all consumer types with non-negative net utility, $\alpha \geq \underline{\alpha} = \frac{p}{\Theta^\beta}$. Here, $\underline{\alpha}$ corresponds to the marginal consumer who derives zero utility. Thus, depending on the product quality Θ , such a product exhibits market coverage $\rho(\Theta) = 1 - \underline{\alpha}$, and the total market demand becomes $N \cdot \rho(\Theta)$. Our focus on the case in which a key bottleneck technology is at the components produced by the supplier leads us to the following assumption:

Assumption 1. The product quality Θ is primarily associated with the performance of the supplier's component and the quality of the manufacturer is fixed.

On the cost side, we consider both the production cost and the development cost of innovation. We begin with the following form of production costs:

Assumption 2. For the supplier (Tier 1) being a critical determinant of product quality, the production cost of delivering q_1 units of components with quality Θ is $C_1(q_1, \Theta) = K_1\Theta^{\delta_\theta}q_1^2$ with $\delta_\theta > 1$. For the manufacturer (Tier 0), the production

cost is $C_0(q_0) = K_0q_0^2$ for producing q_0 units.

For the upstream supplier that is associated with the key bottleneck technology, its production cost is increasing and convex in quality Θ as similarly modeled by Mussa and Rosen (1978) and Gal-Or (1983). Convexity in the quality parameter ($\delta_\theta > 1$) captures the diseconomies associated with the production of an increasingly higher quality product resulting from the use of more expensive raw materials or skilled labor. Moreover, consistent with the Operations/Supply Chain literature (e.g., Majumder and Srinivasan 2008; Tunca and Wu 2009), we also focus on the production costs that are quadratic in quantity to incorporate capacity/resource constraints. Convex production cost in quantity with new innovative products represents scarcity of talent/resources, diseconomies of scale or the difficulty in scaling-up production/achieving high yield. If a manufacturing process requires rare materials (such as dysprosium and terbium for new electric vehicle battery), the manufacturer uses the cheaper options first and moves to more expensive ones later resulting in convex production cost in quantity (Tunca and Wu 2009). In addition, when a substantial manufacturing process development is necessary to accommodate a new product innovation opportunity, a firm usually experiences diseconomies of scale or has difficulty in scaling-up capacity implying convex production cost in quantity. Our study company, Tesla, presents an illustration of the production scaling-up challenge for years (Maynard 2014; Kessler 2015; Hull 2017). Furthermore, this challenge is not unique to the EV industry and is also seen in the semi-conductor and biotechnology industries. When new types of screens were required for smartphones, display suppliers had a hard time to scale and stabilize their manufacturing lines (Murai 2014; Lee 2015). New drug launch and production ramp up at Genentech shows similar challenges.¹ To be general, we also discuss

¹<https://www.gene.com/stories/how-hard-can-it-be>

the case when the production cost is concave in quantity in Section 6.2, which is not likely to be the case for the production ramp up of highly innovative products.

The supplier may have an R&D opportunity that entails quality-improvement or cost-reduction. For the quality improvement case, the firm exerts effort in R&D to increase the existing stock of product quality Θ to a new level $\hat{\Theta}$ such that $\hat{\Theta} \geq \Theta$. If the innovation opportunity is about cost-reduction, the firm exerts R&D effort to reduce the manufacturing cost by x , specifically, from K_1 to $K_1 - x$. We assume the following forms of the R&D cost depending on their types:

Assumption 3. The R&D cost to improve the quality from the existing stock of product quality Θ to the target quality $\hat{\Theta}$ is $\gamma(\hat{\Theta}^{\delta_D} - \Theta^{\delta_D})$ with $\delta_D > 1$. The R&D cost to reduce the component production cost by x is $\eta x / (K_1 - x)$ with $\eta > 0$.

The marginal cost of expanding stock of product quality Θ to a new level $\hat{\Theta}$ is increasing both in the initial quality level Θ and incremental improvement $(\hat{\Theta} - \Theta)$, i.e., $\delta_D > 1$, which is consistent with the literature (e.g., Jones and Mendelson 2011). We note that whereas the quality can be expanded arbitrarily, the production cost cannot be reduced more than the current cost K_1 . To model this, we adopt a different functional form for the cost reduction investment, which is also commonly found in the literature (e.g., Dasgupta and Stiglitz 1980; Bernstein and K ok 2009).

One of the major contributions of this paper is to decouple the monetary investment needed from the actual investment of effort in R&D. While the supplier firm always exerts R&D effort, the investment entailed may be underwritten by the supplier or the manufacturer who funds the monetary value of efforts and expenses to improve quality or to reduce cost. While the investor's problem can be equivalently formulated with respect to the monetary value of investment, for the purpose of cleaner exposition of results, we deliberately let $\hat{\Theta}$ or x be the investor's choice variable.

1.3.1 Decision Sequence

We now detail the sequence in which decisions are made in this technology supply chain. Consider the case where there is an R&D opportunity to improve the quality or reduce the cost of the supplier's component (for example, increasing the battery density or reducing battery production cost in electric vehicle). A proper amount of capital needs to be invested to employ personnel and realize discovery and validation activities. We propose that this invested amount may be borne by either party even though the effort is expended at the supplier firm. In fact, in many real-world situations, similar to the Tesla example mentioned before, one of the parties must lead/anchor the investment to avoid an innovation impasse (as Tesla seems to have done in the case reported above). We refer to this approach of one of the two firms stepping up to the plate to fund the innovation or lead the decision making as, *anchoring*. While the term leader has been more commonly used in sequential games to refer to the entity who goes first, we use the term anchoring/anchor to denote the entity who breaks a deadlock but we also use the term leader interchangeably. To pinpoint the impact of different investor choices on various performance measures such as firm's profit, market coverage, and even social welfare, we focus on an exclusive investor rather than joint investments by both parties, which has been explored in previous literature including Bhaskaran and Krishnan (2009). To keep the focus on innovation investments, we also model that the subsequent price-quantity decisions for the supplier's component are covered by a standard wholesale price contract, later ensuring that our results hold for other types of contracts.

There are two anchor/leader roles in our model; the innovation investment anchor and the supply chain contract initiator. The investment anchor refers to the firm that steps up to invest in the innovation opportunity and the latter

denotes the firm determining the component price. Corresponding to each anchor is a follower who responds to the decision. We propose that to avoid problems of hold-up and opportunism the two anchor roles be contractually agreed before any specific business decisions such as the investment and the production levels are made. Although there are four cases from two different roles between the two firms, we formally show in Proposition 1.1 that it is Pareto-optimal and mutually acceptable to both parties for the innovation anchor to be the contract initiator for a wide range of parameter settings.

Note that the upstream supplier is a specialist in developing and producing the critical quality component. If there is an R&D opportunity, the supplier is more closely situated to pursue it. Therefore, when it comes to determining the investment anchor and the contract leader, we model it as a sequential game with the supplier moving first. Specifically, the supplier first proposes who to be the investment anchor and who to be the contract initiator. If the manufacturer agree on these roles, both firms are committed to their roles.² Otherwise, the game ends. As a result, in the first stage, the two leaders are determined. Next, in the second stage, the investment anchor makes the investment in the R&D project. Lastly, in the third stage, the price-quantity decisions are made; specifically, the contract leader sets the component price, the other party, the follower, decides order or production quantity but the downstream manufacturer always sets retail price.

1.3.2 Benchmark: Vertical Integration vs. Supply Chain

Before fully analyzing the different investment anchor's impact on innovation in a supply chain, we contrast profits, R&D investments, and market coverage of

²In practice, they can write a legally binding contract or seal their trust with an escrow-like arrangement, which ensures that either party does not renege on this previously agreed decision rights.

a vertically integrated firm against a decentralized supply chain. Let us focus on price and quantity decisions for a given quality. The integrated firm produces the critical component and manufactures the final product. In a supply chain where the supplier sells the component to the manufacturer, the component price is set greater than the unit production cost for the supplier to maximize her own profit. The manufacturer should incur more cost to produce the same quantity as the integrated firm does due to the higher wholesale price. Thus, the downstream firm orders less or covers less market than the integrated firm, by setting a higher retail price. As the profit is smaller in a decentralized supply chain, the investment in R&D is in turn smaller as well.

Result 1.1. *R&D investment, market coverage, and revenue generated in a supply chain are less than those in a vertically integrated firm with the same cost parameters.*³

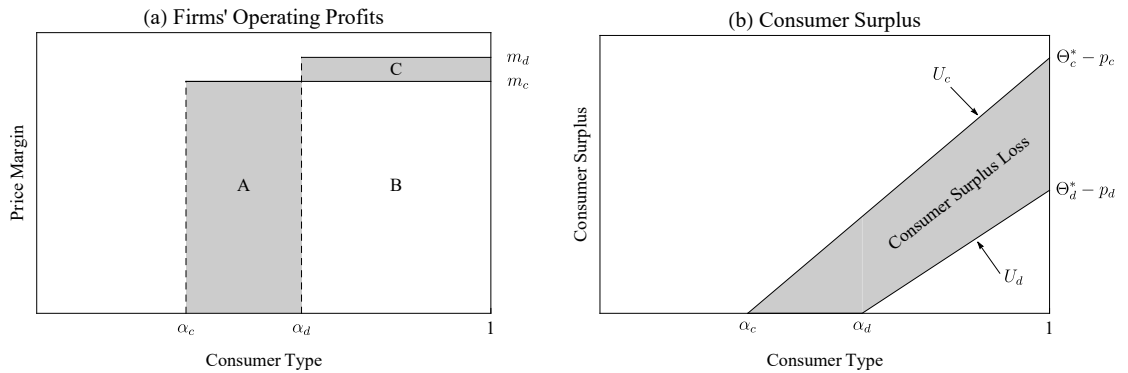


Figure 1.1: Operating Profit and Consumer Surplus Comparison under the Vertically Integrated Firm and a Supply Chain⁴

Figure 1.1(a) illustrates Result 1 well and a simple reasoning is as follows. The vertically integrated firm has the demand $N(1 - \alpha_c)$ with margin m_c , accruing

³Although this is generally true unless a special mechanism is employed in the supply chain, we present the proofs for both results 1 and 2 in the Appendix under our setup.

⁴Compared to the vertically integrated case, the profit loss in the supply chain is $N(A - C)$. All of the results are based on Lemmas A.1 and A.2.

$N(A + B) = N(1 - \alpha_c)m_c$ as its operating profit. In the supply chain, a higher price leads the higher margin $m_d > m_c$ but the smaller demand $N(1 - \alpha_d)$. The supply chain's profit $N(B + C) = N(1 - \alpha_d)m_d$ is smaller than the integrated firm's because of $A > C$. Similarly, the consumer surplus is also less in the supply chain by the shaded area illustrated in Figure 1.1(b).

We remind that the component prices are different across aforementioned industry structures. If the revenue is a higher priority than the profit, then the retail price is identical regardless of industry structures as the revenue is not associated with costs. Thus, we have the following result, whose proof is provided in the appendix.

Result 1.2. *The revenue maximizing market coverages for a vertically integrated firm and a decentralized supply chain are the same. Moreover, the revenue maximizing market coverage is larger than the profit maximizing market coverage under both industry structures.*

What the above result shows is that profit maximization by individual firms in a supply chain leads to reduced market coverage that can hurt their revenues. This effect is particularly more pronounced in a supply chain. As unbundling of vertically integrated firms into supply chains is well underway (Hagel III and Singer 2000), we need to find creative and implementable solutions that can help firms manage both revenues and profits. In this paper, we propose that allowing the R&D investor to be different from the R&D conducting firm is one such approach. We now start by analyzing the quality-improving innovation followed by the cost-reducing innovation.

1.4 Analysis

We analyze the model via backward induction, starting with the third stage in which the equilibrium price and quantity are determined given the product quality, followed by innovation investment decision in the second stage that maximizes the investment anchor's profit. Then, we compare the supplier's profits under the different anchor positions to study when the firm is going to be the anchor with respect to R&D and production cost parameters. Prices and quantities can be determined for any stock of quality Θ . Hence, general Θ is used instead of $\hat{\Theta}$ when we discuss the price-quantity equilibrium in the next subsection.

1.4.1 Equilibrium Prices, Quantities, and Qualities

Once an investment anchor has chosen her contribution to the stock of product quality Θ , firms contract to determine the price and quantity. There are two cases for the sequence of contracts depending on who initiates the contract, or, equivalently, who is the contract leader.

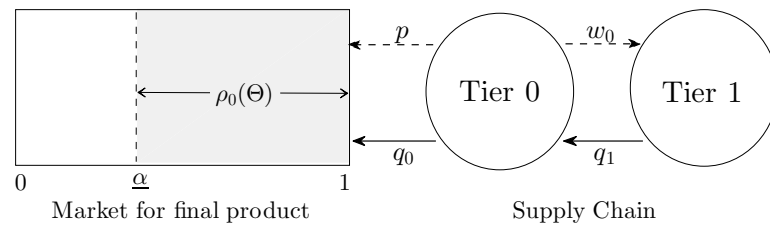


Figure 1.2: Price and quantity choice under Tier 0 contract leader

First, consider the case in which Tier 0 is the contract leader, as illustrated in Figure 1.2. Tier 0 determines the final product price p and orders q_0 , offering w_0 as a unit price to Tier 1. Given this information, the Tier 1 supplier determines how much to produce, q_1 . The tier-wise profit expressions Π_i for Tier i can be

expressed as follows.

$$\begin{aligned}\Pi_0(p, q_0, w_0) &= pq_0 - w_0q_1 - K_0q_0^2, \quad \text{s.t. } q_0 \leq \min\{q_1, N(1 - p\Theta^{-\beta})\}, \\ \Pi_1(q_1; q_0, w_0) &= w_0q_1 - K_1\Theta^{\delta_\theta}q_1^2\end{aligned}\quad (1.1)$$

Tier 1 obtains the revenue of w_0q_1 by selling q_1 units at the unit price w_0 to Tier 0 by incurring an assembly/production cost of $K_1\Theta^{\delta_\theta}q_1^2$. Tier 0 earns sales profit after incurring procurement and production costs, w_0q_1 and $K_0q_0^2$.

We analyze the equilibrium quantities and prices backward, following the marginalization operation presented in Majumder and Srinivasan (2008). For any w_0 , the Tier 1's unconstrained problem has the interior solution of $q_1(w_0) = w_0/2K_1\Theta^{\delta_\theta}$. Thus, the optimal produce quantity is $q_1^* = \min\{q_1(w_0), q_0\}$. Tier 0 takes this optimal response into consideration, and offers w_0 so that $q_1^*(w_0) = q_0$, because $q_1(w_0)$ decreases as w_0 decreases. Technically, $q_1^*(w_0)$ constitutes an inverse factor demand for Tier 0, $w_0(q_0) = 2K_1\Theta^{\delta_\theta}q_0$. Tier 0 replaces w_0 in its profit function with $w_0(q_0)$. Then, the manufacturer now determines the consumer price p and how much to order, q_0 , where the market demand is $N \cdot (1 - p\Theta^{-\beta})$. Notice that under optimality, p is set such that the order quantity and the demand are equal. Thus, the tier-wise profit expressions in (1.1) can be reduced to a single contract leader's problem as follows.

$$\max_{q_0} \quad \tilde{\Pi}_0(q_0) = p(q_0)q_0 - \tilde{C}_0(q_0; \Theta), \quad (1.2)$$

where $p(q) = (1 - q/N)\Theta^\beta$ and $\tilde{C}_0(q_0; \Theta) = (K_0 + 2K_1\Theta^{\delta_\theta})q_0^2$. After optimizing $\tilde{\Pi}_0(q_0)$ with respect to q_0 , we subsequently obtain the equilibrium prices p and w_0 depending on the expanded stock of product quality Θ .

Second, in the case of Tier 1 contract leadership, for an offered wholesale price

w_1 and the available components q_1 , Tier 0 sets the order quantity q_0 and the price p to maximize its profit, where q_0 is constrained by q_1 and the demand. Similar to Tier 0 leader case, p is set such that q_0 is equal to the demand under optimality. Tier 0 maximizes its profit $\Pi_0(q_0; w_1) = p(q_0)q_0 - w_1q_0 - K_0q_0^2$ with respect to q_0 , which results in the inverse factor demand faced by Tier 1, $w_1(q) = p(q) - (2NK_0 + \Theta^\beta)q/N$. Since producing more than the order quantity cannot be optimal, Tier 1 equates the production quantity (q_1) and the order quantity (q_0). After incorporating $w_1(q_0)$, Tier 1 essentially determines q_0 by solving

$$\max_{q_0} \quad \tilde{\Pi}_1(q_0) = p(q_0)q_0 - \frac{\Theta^\beta}{N}q_0^2 - \tilde{C}_1(q_0; \Theta), \quad (1.3)$$

where $\tilde{C}_1(q_0; \Theta) = (2K_0 + K_1\Theta^{\delta_\theta})q_0^2$. Note that whereas the first and the third term in (1.3) represent the revenue and the production cost, respectively, which are also found in (1.2), the second term in (1.3) stands for the cost due to double marginalization. After solving (1.2) and (1.3), we obtain Lemma 1.1 for equilibrium prices and quantities in a supply chain with Tier l being the contract initiator for a given quality level Θ .

Lemma 1.1. *For quality Θ , if Tier l initiates the contract, then the equilibrium outcome for prices and quantities, $P_l(\Theta)$ and $Q_l(\Theta)$, are as follows:*

$$P_l(\Theta) = \left(2(l+1)\Theta^\beta + 2\Phi_l(\Theta)N\right) \left((2l+1) + 2\Theta^{-\beta}\Phi_l(\Theta)N\right)^{-1},$$

$$Q_l(\Theta) = N \left(2(l+1) + 2\Theta^{-\beta}\Phi_l(\Theta)N\right)^{-1},$$

where $\Phi_l(\Theta) = 2^l K_0 + 2^{|1-l|} K_1 \Theta^{\delta_\theta}$.

Corollary 1.1. *While $P_l(\Theta)$ is increasing in Θ , $Q_l(\Theta)$ is increasing then decreasing in Θ .*

The dependence of equilibrium outcomes, $(Q_l(\Theta), P_l(\Theta))$, on the contract initiator/leader position is driven by the *misalignment penalty* $\Phi_l(\Theta)$ that can be thought of as the severity of double marginalization associated with the quality when Tier l is the leader. It is the sum of the leader's direct production cost coefficient, K_0 for $l = 0$, and the other firm's production cost coefficient amplified by the distance from the leader, i.e., $2K_1\Theta^{\delta\theta}$. Thus, as $\Phi_l(\Theta)$ increases, the effective production cost increases implying that the equilibrium production quantity, firms' profits, and even social welfare decrease. Nevertheless, the impact of quality improvement has the same directional impact on the price and the quantity regardless of who is the contract leader. Corollary 1.1 shows that the optimal production quantity is non-monotone in quality. It is because quality improvement increases not only consumer's utility but also the price, creating two opposite forces for market coverage. At first, when the quality increases from a low level, the former outweighs the latter, resulting in more demand or broader market coverage. However, if the quality increases even further, a soaring price reduces market coverage. Hence, the improvement in the product quality has a mixed effect on the production quantity or market coverage.

The notion of quality-driven misalignment is related to the difference in production costs between a single vertically integrated firm and a multi-tiered supply chain incurring additional agency costs. Therefore, supply chains, regardless of the contract leader position, exhibit higher effective production costs relative to the vertically integrated case. Nevertheless, some contract leader positions may yield lower misalignment penalties resulting in lower effective production costs. The intrinsic magnitude of production cost coefficients $\{K_0, K_1\}$ and the product quality Θ from the development/investment decision determine the contract leader position with the lowest misalignment penalty. Note that the misalignment penalty

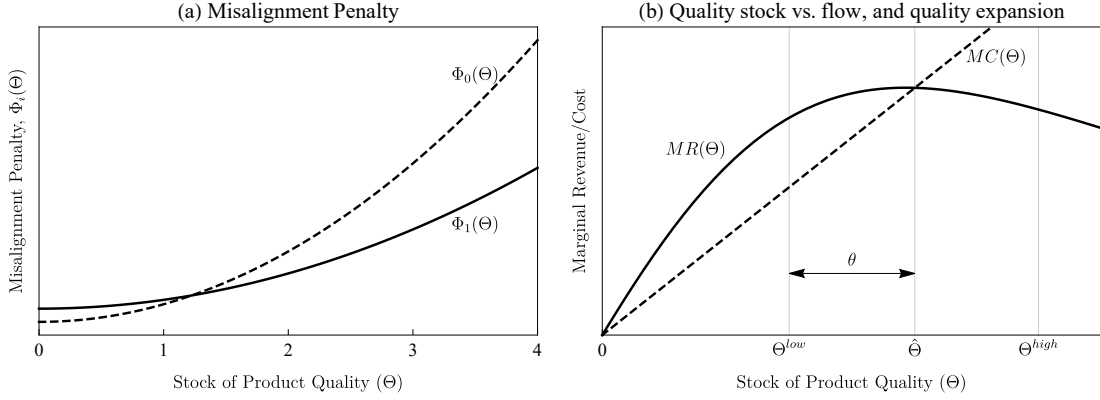


Figure 1.3: Misalignment Penalty and Quality Expansion ⁵

is increasing in Θ and the follower's production costs is amplified by $2^{|1-l|}$, where $|1-l|$ is the distance between the supplier (Tier 1) and the leader $l \in \{0, 1\}$. The downstream leader's penalty Φ_0 is smaller for low Θ but becomes larger for high Θ than the upstream leader's penalty Φ_1 as illustrated in Figure 1.3(a). That is, the contract leader minimizing $\Phi_l(\Theta)$ gravitates upstream to Tier 1 as the product quality improves. This dependence of leader position on product quality has significant implications (as discussed in the subsequent section) and comes out of a model that jointly considers qualities, quantities, and prices.

Next, we move on to the second stage and consider the investment decisions in product development and innovation to improve the quality, which is linked to how sales revenue is distributed. As the contract initiator would determine the contract detail in favor of itself, both the anchor investor and the non-anchor investor would prefer to be the contract initiator. In other words, the investor may or may not be the contract initiator unless firms in a supply chain strategically agree on a particular rule upfront. We investigate the incentives for the contract initiator of both the investor and the non-investor and derive the equilibrium result in the following proposition.

⁵Parameter values are $(K_0, K_1) = (3, 2)$, $N = 1$, $\beta = 1$, $\delta_\theta = 2$, and $\delta_D = 2$.

Proposition 1.1. Define $\Pi_{k|ij}$ as the profit of Tier k firm when Tier i is the innovation investor and Tier j is the contract initiator for $i, j, k \in \{0, 1\}$.

- (a) An investor prefers being the contract initiator to being the follower, i.e., $\Pi_{i|ii} \geq \Pi_{i|ij}$ for $i \neq j$.
- (b) A non-investor also prefers the investor to be the contract initiator if the development cost is not insignificant, i.e., $\Pi_{j|ii} \geq \Pi_{j|ij}$ for $i \neq j$.

Part (a) of Proposition 1.1 confirms that the investing firm is worse off if it does not get to lead the contracting process. Part (b) of Proposition 1.1 indicates that the firm not investing in innovation is willing (on its own interest) to cede the contract initiation/leadership to the investor (the exact conditions are derived in the Appendix). Thus, when development costs are significant, it is optimal for all parties to have the investment anchor and the contract initiator be the same firm. Furthermore, it is only realistic to expect that an industrial firm who invests and funds the component technologies asks something in return, in this case, the commitment to initiate the price-quantity contract, and the above result shows that the follower would find it in their best interest to agree to this arrangement. Based on this finding, we set the investment anchor to be the contract initiator, which simplifies the notation. Tier i firm's profit function when Tier j is the investment anchor and the contract initiator is expressed as follows.

$$\Pi_{i|j}(\hat{\Theta}_j) = \Pi_i(P_j(\hat{\Theta}_j), Q_j(\hat{\Theta}_j), w_j(\hat{\Theta}_j)) - \mathbb{1}_{\{i=j\}}\gamma(\hat{\Theta}_j^{\delta_D} - \Theta^{\delta_D}), \quad (1.4)$$

where $\mathbb{1}_{\{\cdot\}}$ is an indicator function. The first term is Tier i 's sales profit defined in (1.1) with P_j and Q_j in Lemma 1.1. The second term is development cost only incurred by the investment anchor. Then, the optimal product quality expansion under Tier i investment anchor can be obtained by comparing the solution from

the first order condition and the initial stock of quality (Lemma A.2 in the Appendix). Understanding the equilibrium quality, prices and quantities, we proceed to investigate the optimal investment anchor position/tier for normative objectives such as social welfare and market coverage followed by the equilibrium investment anchor position.

1.4.2 Optimal Investment Anchor for Welfare Objectives

We are able to characterize the equilibrium outcomes from investment to production to pricing for each investment anchor position. Before analyzing the investment anchor position in equilibrium, we first study how various normative metrics such as product quality, market coverage, and social welfare are related to the investment anchor position for different levels of development cost γ and the key component production cost K_1 . The normative investment anchor position can serve as a benchmark for the equilibrium investment anchor position (discussed in the next subsection), and help us to understand when there exist conflicts of interests between firms and a social planner. Specifically, in this subsection, we consider a social planner's choice of the investment anchor between the supplier and the manufacturer. All the decisions such as investment in R&D, price, and quantity are determined by both profit maximizing firms. This can be written as follows:

$$\begin{aligned} \arg \max_{i \in \{0,1\}} & f(\hat{\Theta}_i) \\ \text{s.t.} & \hat{\Theta}_i = \arg \max_{\Theta_i \geq \Theta} \Pi_{i|i}(\Theta_i), \end{aligned}$$

where $f(\cdot)$ is a normative objective function such as product quality ($\hat{\Theta}_i$), market coverage ($\rho(\hat{\Theta}_i)$), and social welfare (SW_i).⁶ The constraint implies that the optimal quality ($\hat{\Theta}_i$), characterized in Lemma A.2, is determined by the profit maximizing anchor firm Tier i , instead of the social planner. The planner only designates the position of the investment anchor in a supply chain.

The investment anchor's revenue is decreasing in the component production cost K_1 as captured by the inverse dependence on the misalignment penalty $\Phi_i(\Theta)$. Furthermore, the rate at which higher values of K_1 or higher product quality levels reduces the investment anchor's revenue is determined by the distance between the investment anchor i and Tier 1. Intuitively, the dependence on the distance between the investment anchor and the investment target (the supplier, or Tier 1) provides variation in the desirable investment anchor position as the development cost and/or the component production cost vary. We characterize the social planner's optimal investment anchor position in the following proposition.

Proposition 1.2. (a) *For moderately convex production costs at Tier 1, i.e., $\delta_\theta \in (1, 2\beta]$, there exists γ^{obj} , the pivotal development cost level, under (over) which Tier 1 (Tier 0) firm is the optimal investment anchor to maximize $obj \in \{\Theta, \rho, sw\}$, where each obj corresponds to the product quality, market coverage, and social welfare, respectively.*

(b) $\gamma^\rho \leq \gamma^\Theta$ and $\gamma^{sw} \leq \gamma^\Theta$.

(c) *As the upstream production costs K_1 increases, γ^{obj} also increases for $obj \in \{\Theta, \rho, sw\}$.*

Part (a) of Proposition 1.2 shows that for the low (high) development cost

⁶Social welfare is the sum of two firms' profits and consumer surplus. Specifically, social welfare under Tier i investment anchor can be expressed as $SW_i = \Pi_{i|i} + \Pi_{j|i} + CS$, where $CS = \Theta^\beta \int_{\underline{\alpha}}^1 (\alpha - \underline{\alpha}) d\alpha$.

(γ), the innovation anchor should be the upstream (downstream) firm to achieve a more normative objective function such as product quality, market coverage, and social welfare. The rationale is as follows. First, the downstream misalignment penalty is increasingly larger than the upstream penalty in the product quality (Θ) as illustrated in Figure 1.3(a). It implies that the supply chain occurs smaller misalignment penalty with the upstream innovation anchor. Next, it is evident that the low development cost results in higher Θ . Thus, the upstream firm is the optimal anchor for low γ . Figure 1.4 directly illustrates Proposition 1.2(a), the thresholds indicating the change of the investment anchor for the highest product quality γ^Θ in panel (a), for broader market coverage γ^ρ in panel (b), and for larger social welfare γ^{sw} in panel (c) with respect to the development cost γ , where the solid line is the result under Tier 1 being the investment anchor and the dashed line is under Tier 0 being the investment anchor. For instance, it would make sense, when the R&D costs are high, for a downstream manufacturer like Tesla to be actively anchoring the battery density improvement R&D (Fehrenbacher 2016; Lambert 2017), but if the R&D costs are cheaper, it would be viable and even desirable from a social welfare maximization perspective for the upstream firm Panasonic to be the R&D investment anchor.

Proposition 1.2(b) shows that the optimal investment anchor position for each objective may or may not be the same. In particular, when $\gamma < \gamma^\rho$, then the optimal investment anchor for product quality and market coverage are the Tier 1 supplier. Similarly, when $\gamma > \gamma^\Theta$, the Tier 0 manufacturer being the investment anchor achieves more of both objectives. However, if $\gamma^\rho < \gamma < \gamma^\Theta$, the optimal investment anchor positions differ from each other. While the supplier is preferred

⁷Parameter values are $(K_0, K_1) = (3, 2)$, $\delta_\theta = 2$, $\delta_D = 2$, $N = 1$ and $\beta = 1$. The solid line is the result for the case when Tier 1 is the investment anchor and the dashed line is the case when Tier 0 is the investment anchor.

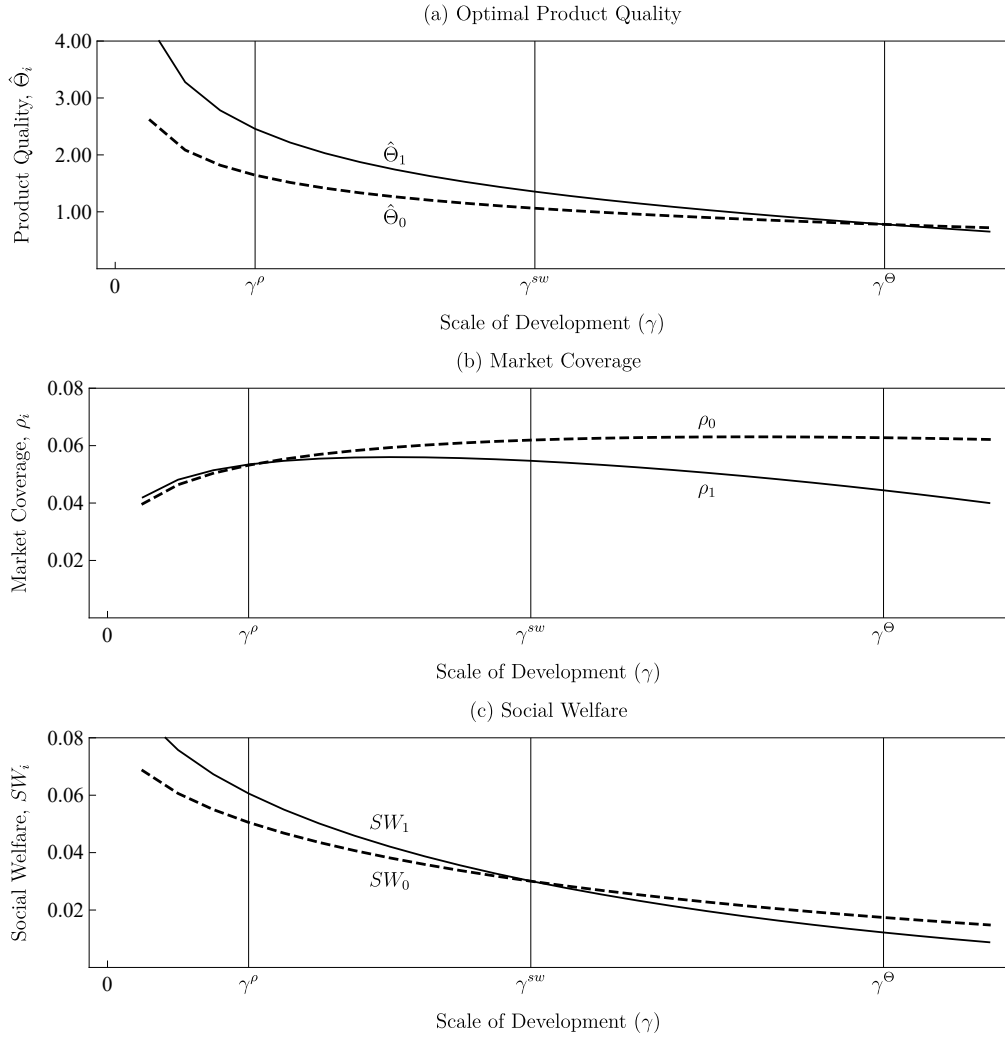


Figure 1.4: Threshold values of γ for optimal innovation investment anchor for various objectives. ⁷

for the higher quality product, the manufacturer is still optimal for market coverage as illustrated in Figure 1.4(a) and (b). Interestingly, our result indicates that the investment anchor for product quality does not always achieve more social welfare or broader market coverage, as a higher quality product may increase the consumer price substantially. For example, when γ is equal to γ^θ , the product quality is identical under each investment anchor position. The component price, however, is more expensive under Tier 1 being the investment anchor leading a higher consumer

price, resulting in the smaller market coverage. For Tier 1's anchoring to result in broader market coverage, Tier 1's investment in quality should be significantly greater than Tier 0's investment to compensate the higher component price. As γ decreases, the optimal quality difference between two investment anchor positions becomes increasingly larger. Hence, the development cost threshold for broader market coverage is less than that for the higher quality product. The relationship between product quality and social welfare can be similarly explained, which is depicted in Figure 1.4(a) and (c).

Finally, in part (c) of Proposition 1.2, we establish that Tier 1's anchoring is better preferred for high upstream production cost (large K_1) for all the objectives. The rationale is that a large value of K_1 is amplified in the misalignment penalty under the manufacturer being the investment anchor, making it more beneficial for the supplier to be the investment anchor.

1.4.3 Equilibrium Investment Anchor

After taking a normative stance on the question of who should be the investment anchor, we now characterize which firm will be the investment anchor in equilibrium. Note that, in our model setting, the supplier first identifies an R&D opportunity and should decide whether to be the anchor who can set the component price in return for R&D investment. If the supplier decides not to be the investment anchor, the manufacturer can decide whether to invest in the innovation by funding the supplier's R&D. First, the supplier solves the following

problem.

$$\begin{aligned} \arg \max_{i \in \{0,1\}} \quad & \Pi_{1|i}(\hat{\Theta}_i) \\ \text{s.t.} \quad & \hat{\Theta}_i = \arg \max_{\Theta_i \geq \Theta} \Pi_{i|i}(\Theta_i). \end{aligned}$$

We characterize the equilibrium investment anchor position with respect to the product development cost in the following proposition (proved in the Appendix).

Proposition 1.3. *For moderately convex production costs at Tier 1, i.e., $\delta_\theta \in (1, 2\beta]$, there exists the product development cost threshold γ^1 , under (over) which Tier 1 (Tier 0) firm is the investment anchor in equilibrium.*

Figure 1.5 illustrates the investment anchor in equilibrium for the varying product development cost. In panels (a) and (b) of the figure, a solid line represents a firm's profit when it is the investment anchor and a dashed line is the profit when the other firm is the investment anchor. Specifically, if $\gamma \leq \gamma^1$ or in Region (A) and (B), Tier 1 becomes the investment anchor in equilibrium and Tier 0 is better off by being the follower (non-anchor). Consequently, Tier 1's anchoring also maximizes the total supply chain profit.

However, when the product development cost is greater than γ^1 , Tier 1 does not want to be the investment anchor as its profit under the manufacturer being the investment anchor is greater. We remind that an investment anchor has a lead in price-quantity contracting and the component price increases in quality. Under Tier 0 investment anchor, although the Tier 1 supplier may be offered a cheaper price for its component, the firm does not need to invest in R&D. For large γ , the difference between two anchors' optimal qualities (investment) is relatively small, implying that the difference in the component prices is also not significant. That is,

⁸Parameter values are $(K_0, K_1) = (4, 1)$, $\beta = 1$, $N = 1$, $\delta_\theta = 1.2$, $\delta_D = 1.6$.

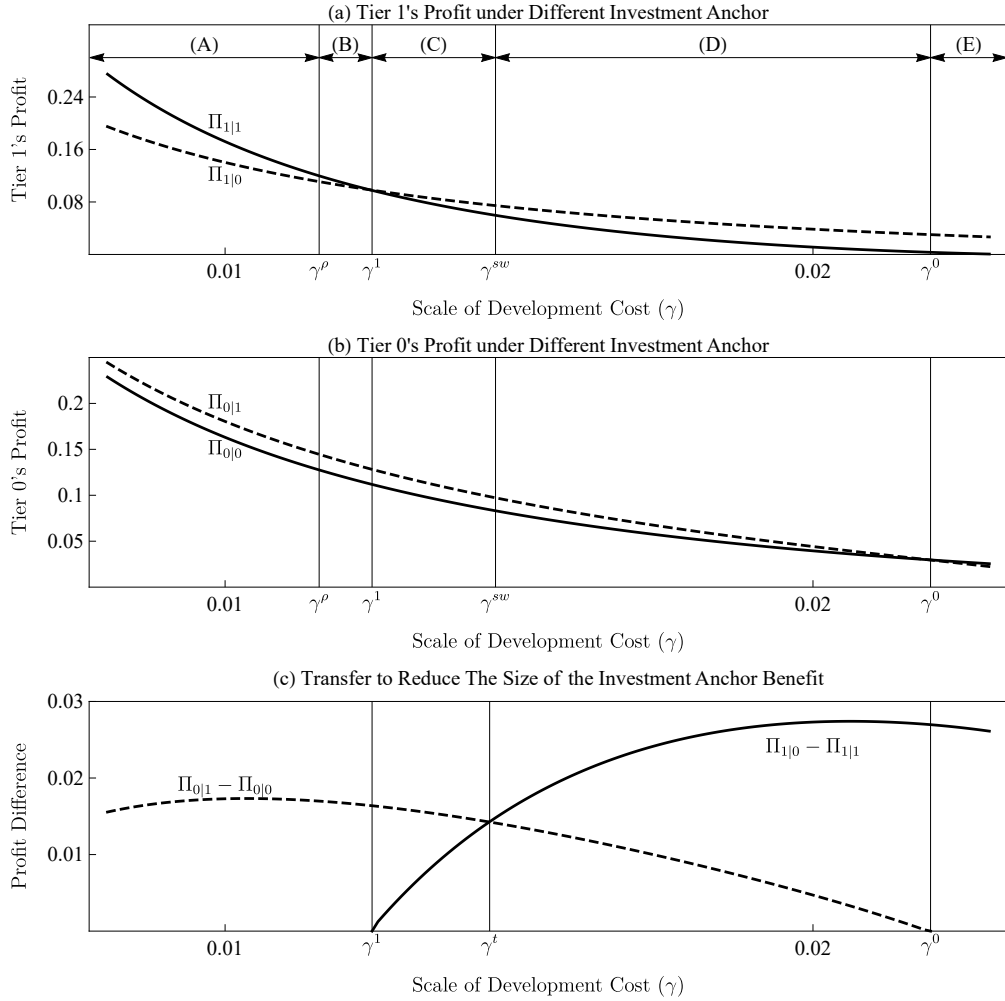


Figure 1.5: Optimal Innovation Investment Anchor: Firm's Profits ⁸

the Tier 1 supplier's saving from the investment by being the follower may outweigh the unit margin loss in component sales in this case.

Whereas Tier 0 will be the investment anchor if it is offered, the firm can be the anchor in Regions from (C) to (E) in equilibrium. Since the firm is still better off under Tier 1's anchoring for low development cost, $\gamma \leq \gamma^0$ or in Regions from (A) to (D), there are conflicts of interests in Regions (C) and (D).⁹ Note that if the development cost is more expensive than γ^0 or in Region (E), both firms

⁹If Tier 0 can first decide whether to be the investment anchor or not, the firm will be the anchor only in (E).

are better off under the downstream firm being the investment anchor. Therefore, when the development cost is either small or large, the position of the investment anchor in equilibrium does not create any conflict of interests between firms and also maximizes the supply chain profit.

Various misalignments may arise in intermediate regions which may be addressed with additional instruments or political interventions (e.g. transfer payment or subsidies). For example, in Region (C), Tier 0 becomes the investment anchor in equilibrium, which results in lower social welfare, so Tier 1 could be induced to invest.

1.5 Investment Anchor for Cost Reducing R&D

Thus far, we have explored the investment anchor position in a supply chain with quality increasing R&D opportunity. The other important type of innovation is the component cost-reducing R&D. To be consistent with the previous section, we examine which firm between the supplier (Tier 1) and the manufacturer (Tier 0) will be the investment anchor in equilibrium in the supply chain that has a cost reducing R&D opportunity for Tier 1's component; specifically, the production cost can be reduced by x with the investment of $\eta x/(K_1 - x)$, where η is the scale parameter for cost reduction R&D (Dasgupta and Stiglitz 1980; Bernstein and K ok 2009). This formulation ensures the convex increasing cost. Moreover, the investment cost equals zero if $x = 0$, and prevents an extreme case in which $x = K_1$. As is the case in quality increasing R&D, the Tier 1 supplier decides first whether to be the investment anchor or not. If the upstream supplier decides to be the investment anchor, she makes an investment and sets the component price. Otherwise, Tier 0 decides whether to make an investment and sets Tier 1's

component price. At first glance, cost reducing R&D seems to be an inverse of quality increasing R&D, but deeper examination reveals subtle differences, which result in contrasting insights.

First, we analyze the optimal price and quantity decisions. Consider the case in which Tier 0 is the investment anchor for given quality θ and cost reduction x . Tier-wise profit functions can be expressed similarly to (1.1) with K_1 replaced by $K_1 - x$. This modification is the same under the case in which Tier 1 is the investment anchor. Hence, the optimal prices and quantities under the case in which Tier l is the investment anchor can be characterized using Lemma 1.1 by substituting K_1 with $K_1 - x$. Next, the profit function including cost reduction R&D can be also written similarly to (1.4) by substituting $\gamma(\hat{\Theta}^{\delta_D} - \Theta^{\delta_D})$ with $\eta x / (K_1 - x)$. The following lemma characterizes the optimal investment in cost reduction R&D.

Lemma 1.2. *Tier l anchor's investment in cost reduction R&D is decreasing as scale of cost reduction (η) increases up to $\eta_l(\theta) = \frac{K_1 N^2 \theta^{2\beta + \delta_\theta}}{2^{l+1} (2^l K_0 N + 2^l \theta^\beta + 2^{1-l} K_1 N \theta^{\delta_\theta})^2}$. Afterwards, the investment anchor does not invest. Moreover, there exists $\bar{\theta}$ such that $\eta_0(\bar{\theta}) = \eta_1(\bar{\theta}) = \bar{\eta}$. If the given quality is less than $\bar{\theta}$ ($\theta \leq \bar{\theta}$), only Tier 0 invests for high η ($\eta_1(\theta) \leq \eta_0(\theta) \leq \bar{\eta}$). Otherwise, only Tier 1 invests for high η ($\bar{\eta} < \eta_0(\theta) < \eta_1(\theta)$).*

Lemma 1.2 shows that the cost reduction investment generally decreases as the R&D becomes more expensive but how it decreases depends on the component quality θ and the investment anchor tier l . When the quality is low (high), Tier 0 (Tier 1) firm can afford to invest more in the R&D even for high η . That is, each investment anchor may make a different decision even for whether to invest according to the component quality, let alone the amount of investment. To avoid trivial cases and provide clearer insights, we focus on the cases in which both tiers

as the investment anchor have the same decision regarding whether to invest, i.e. $\theta = \bar{\theta}$.

Proposition 1.4. *Consider a supply chain where Tier l is the investment anchor in the key component manufacturing cost reduction of which quality is $\bar{\theta}$.*

- (a) *The manufacturer (Tier 0) invests more in cost reduction R&D than the supplier (Tier 1).*
- (b) *The manufacturer (supplier) achieves broader market coverage when the R&D cost is low (high), i.e., $\eta \leq (>) \eta^\rho$.*
- (c) *The supplier is the unique investment anchor in equilibrium.*

Proposition 1.4(a) shows that Tier 0 invests in cost reduction more than Tier 1 regardless of the scale of cost reduction parameter η . This is because the way each investment anchor earns benefits from the R&D is different. Although the Tier 0 anchor sets a low component price to capture the R&D benefits, the Tier 1 anchor will not reduce the price as much. In other words, the market enjoys more benefits from the cost reduction if the manufacturer is the investment anchor.

Surprisingly, Proposition 1.4(b) reveals that Tier 0's increased investment in R&D does not always result in broader market coverage. Note that the misalignment penalty has two parts; one for Tier 0's manufacturing cost and the other for Tier 1's. An anchoring firm suffers from the penalty of non-anchor tier's manufacturing cost. For example, if Tier 0 is the anchor, it experiences the penalty of Tier 1's cost. However, when the R&D cost is low ($\eta \leq \eta^\rho$), Tier 0 achieve substantial cost reductions driving this penalty small and resulting in broader market coverage, which is illustrated in Figure 1.6(a). In contrast, for the case of high R&D cost, the

¹⁰Parameter values are $K_0 = 3, K_1 = 2, \delta_\theta = 1.5, \beta = 1, N = 1, \theta = 5.68$.

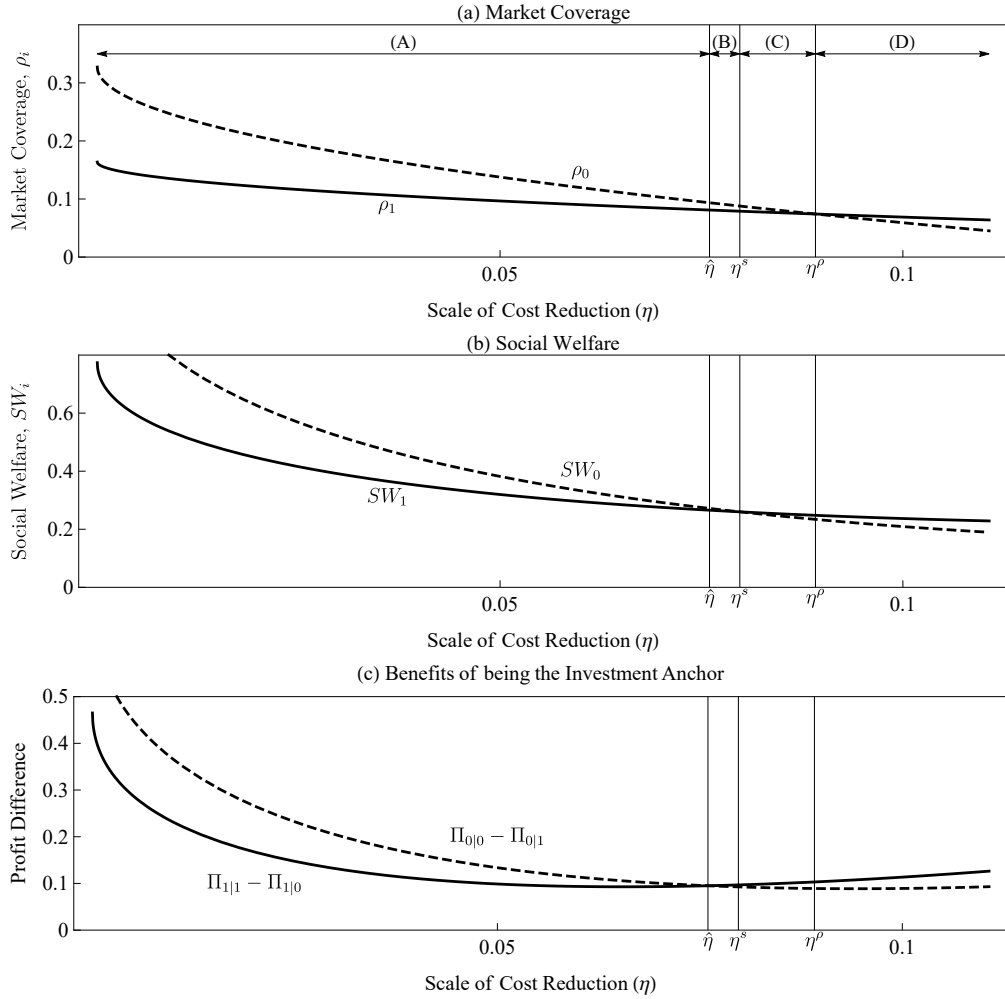


Figure 1.6: Market Coverage, Social Welfare, and Benefits of being the Investment Anchor under Cost Reduction R&D ¹⁰

penalty of Tier 1's cost remains significant as Tier 0's investment in cost reduction is small. Thus, the less market is covered under Tier 0 in spite of more investment. Likewise, Tier 0 (1) investment anchor creates more social welfare for low (high) η as depicted in Figure 1.6(b). This implies that there is also an optimal investment anchor position from normative perspectives under cost reduction R&D like quality improvement R&D in the previous section.

That being said, Proposition 1.4(c) shows that the supplier is the unique investment anchor in equilibrium, which is in sharp contrast to the case of quality

improvement R&D where the manufacturer can be the equilibrium investment anchor. Tier 1's profit as the follower may be substantially low because Tier 0 anchor sets a significantly low component price than the Tier 1 anchor. We note that the component price under Tier 0's anchoring $w_0(q) = 2(K_1 - x)q\theta^{\delta\theta}$ decreases as x increases. However, the corresponding price under Tier 1's anchoring $w_1(q) = \theta^\beta - 2q(K_0N + \theta^\beta)/N$ is not directly affected by x , but indirectly influenced via q . Figure 1.6(c) depicts the profit difference between being the investment anchor and the follower for each tier. The solid (dotted) line represents the benefit of being the investment anchor for Tier 1 (0). Notice that the solid line (Tier 1) is always greater than zero in η implying that Tier 1 chooses to be the investment anchor, which is stark difference from the result under quality improvement R&D case as given in Proposition 1.3.¹¹

This finding also further explicates the implication from prior research. Majumder and Srinivasan (2008) says "they (supply chain members) have a strong incentive to help other members reduce their cost because this helps all members in the chain." While cost reduction certainly increases the supply chain profits, it does not necessarily increase the profits of all firms. According to our result, even though a partner firm in a supply chain may be willing to invest in a focal firm's cost reduction R&D, the focal firm may want to deny the investment unless the cost reduction benefit is properly shared.

We should note that the supply chain manager or the policy maker may induce firms to have the optimal normative position of the investment anchor. For example, in Region (A) of Figure 1.6(a), Tier 1 may choose to forgo the option of being the investment anchor in exchange of a lump sum payment, which is feasible since the benefit of Tier 0 being the investment anchor is greater than

¹¹It also implies that Tier 0 will be the anchor, if the firm can move first instead of Tier 1.

Tier 1's. Moreover, Tier 1's such proposal should not be regulated, since the downstream investment anchor is socially preferred from the perspectives of both market coverage and social welfare. The middle regions (B) and (C) are delicate because the optimal normative investment anchor position is different depending on the normative objectives. In Region (D), the position of the investment anchor in normative perspectives and the equilibrium position are the same without any interventions. In a nutshell, while a wholesale price contract cannot align the equilibrium position of an investment anchor and the normative position under cost reduction R&D, a simple transfer payment can mostly align two seemingly confronting objectives.

Table 1.1: The Optimal Investment Anchor in Equilibrium ¹²

R&D Type	Low R&D cost	High R&D cost
Quality-Improvement	Supplier	Manufacturer
Cost-Reduction	Supplier (under-investment)	Supplier

Propositions 1.3 and 1.4 show that the investment anchor in equilibrium depends on the type of R&D. Table 1.1 contrasts these differences. When the R&D cost for quality-improvement is low, the supplier becomes the investment anchor in equilibrium to maximize its profit. If the R&D cost is high enough, the supplier is better off by being the follower, providing the manufacturer the option to be the investment anchor in equilibrium. In contrast, when the innovation is about cost reduction in the supplier's component, the supplier prefers to be the investment anchor regardless of the R&D cost, although it under-invests in the cost-reducing

¹²For low R&D cost for the cost-reduction case, the supplier is better off by being the investment anchor in spite of its under-investment compared to the case in which the manufacturer is the investment anchor.

innovation.

1.6 Model Extensions and Robustness Checks

We now verify the robustness of our results to other type of contracts such as revenue sharing contracts and other production cost structures like a concave production cost.

1.6.1 Revenue Sharing

We have so far assumed a wholesale price contract in the supply chain, which is simple and used in the literature as well as practice. However, there exist more efficient contracts that can reduce supply chain inefficiency. We expand our analysis to the case of revenue sharing contracts (Cachon and Lariviere 2005), examining the identity of the equilibrium investment anchor.

Suppose the supply chain parties share the total revenue between the investment anchor and the follower with λ and $1 - \lambda$, where $\lambda \in (0, 1)$ is given. To be consistent with the previous setup, the supplier decides whether to be the investment anchor or not first. If the supplier decides to be the investment anchor, it invests in the R&D. Otherwise, the manufacturer decides whether to invest in R&D or not. Subsequently, the investment anchor determines the wholesale price of the component. Each firm sets its own production quantity and the consumer price is determined by Tier 0. Once the revenue is realized, it is shared between the investment anchor and the follower according to the revenue sharing contract. We first analyze quality-improving R&D followed by discussing cost-reducing R&D.

Let us investigate the case where Tier 0 is the investment anchor. Tier 1 decides its production quantity (q_1) as follows given the investment anchor's

decisions.

$$\begin{aligned} \max_{q_1} \quad & \pi_{1|0}(q_1|w_0, p) = (1 - \lambda)pq_1 + w_0q_1 - K_1\Theta^{\delta\theta}q_1^2, \\ \text{s.t.} \quad & q_1 \leq q_0. \end{aligned}$$

The constraint means that the supplier will not produce more than the order quantity but may produce less if desired. The optimal production quantity without the constraint is $q_1(w) = (p(1 - \lambda) + w)/(2K_1\Theta^{\delta\theta})$. Under optimality, Tier 0 does not order more than q_1 as it should incur its own production cost ($K_0q_0^2$). Thus, we derive an inverse demand function $w_0(q_1) = 2K_1q_1\Theta^{\delta\theta} - p(1 - \lambda)$ from $q_1(w)$. Knowing this, Tier 0 investment anchor makes its decisions.

$$\begin{aligned} \max_{p, q_0} \quad & \pi_0(p, q_0) = \lambda pq_0 - wq_0 - K_0q_0^2, \\ \text{s.t.} \quad & q_0 = \min\{N(1 - p/\theta^\beta), q_1\}. \end{aligned}$$

We note that Tier 0's profit is $\pi_0(p, q_0) = p(q_0)q_0 - (K_0 + 2K_1\Theta^{\delta\theta})q_0^2$ after replacing w with $w_0(q_1)$ under optimality, which is Tier 0's profit under the wholesale price contract in (1.2). Therefore, the optimal quantity and price under revenue sharing are the same under wholesale price contract.

Next, consider the case in which Tier 1 is the investment anchor. For a wholesale price w , Tier 0 earns $(1 - \lambda)$ of the total revenue. Similar to the above analysis, Tier 0's optimal quantity implies an inverse demand function $w_1(q_0) = (1 - \lambda)(N - 2q_0)\Theta^\beta/N - 2K_0q_0$. Anticipating this, Tier 1 determines the optimal production quantity. Unlike Tier 0 investment anchor, Tier 1's optimal production quantity and profit increase in its share of revenue λ (the detailed expressions are given in Lemma A.3). Nevertheless, we show that Tier 1 can

be better off by being the follower and Tier 0 can be the investment anchor in equilibrium.

Proposition 1.5. *Consider a supply chain under a revenue sharing contract, where the innovation investment anchor determines the wholesale price and earns λ share of the revenue. For moderately convex production cost at Tier 1, i.e., $\delta_\theta \in (1, 2\beta]$, there exists a threshold γ_R^1 , under (over) which Tier 1 (Tier 0) firm is the investment anchor in equilibrium.*

Proposition 1.5 establishes that the equilibrium investment anchor can be either firm. Although revenue sharing can address double marginalization and improve supply chain efficiency, each firm seeking to maximize its own profit, instead of the whole supply chain, results in R&D underinvestment. Therefore, when the downstream production cost is high, Tier 1 chooses to be the follower to minimize the misalignment penalty. The proposition also implies that the supplier is the unique investment anchor under the cost reduction R&D, because Tier 1's profit as the investment anchor is greater under the revenue sharing contract and Tier 0's decision is not affected by revenue sharing. These findings show that our previous results with a simple wholesale price contract are robust with respect to other types of contracts.

1.6.2 Simultaneous Contracting

If one firm makes the whole investment in R&D and becomes the investment anchor, it seems reasonable for the anchor to ask for a contract leadership in return. Although we show that the investment anchor being the contract initiator is mutually beneficial for both firms in the supply chain (Proposition 1.1), the contracting can be processed with similar bargaining powers. A simultaneous

contracting may describe this scenario more plausibly than our sequential approach. On one hand, the new contracting scheme may improve the supply chain profit than that in a sequential setting by reducing (increasing) the leader's (follower's) profit. On the other hand, the reduced profit discourages the anchor to invest in R&D, subsequently lowering the supply chain profit. In this subsection, we explore how the different contracting process affects the investment anchor and the supply chain performance.

Let us consider the supply and the demand for the supplier's component to obtain the market clearing wholesale price. As we already study in Section 4.1, the supply function is $q_1(w) = w/2K_1\Theta^{\delta\theta}$ and the demand function is $q_0(w) = \frac{N(\theta^\beta - w)}{2(K_0N + \theta^\beta)}$. The equilibrium price is then determined at $q_1(w^*) = q_0(w^*)$. This leads to

$$w^* = \frac{K_1N\theta^{\beta+\delta\theta}}{K_0N + \theta^\beta + K_1N\theta^{\delta\theta}},$$

$$q^* = \frac{N\theta^\beta}{2(K_0N + \theta^\beta + K_1N\theta^{\delta\theta})}.$$

Indeed, q^* is equal to the optimal production quantity under the vertically integrated supply chain. Therefore, the supply chain profit from the simultaneous contracting is higher than the sequential case for a given quality level θ . Because this is obtained by eliminating the investment anchor's first mover advantage in the contracting stage, such an anchor may invest less in R&D, potentially leading the supply chain to be worse off. To investigate this possibility, we look at the investment in quality-improving R&D for the supplier expecting the simultaneous contracting. The firm's problem is as follows.

$$\max_{\theta} \pi_s(\theta) = -\gamma\theta^{\delta D} + \frac{K_1N^2\theta^{2\beta+\delta\theta}}{4(K_0N + \theta^\beta + K_1N\theta^{\delta\theta})^2}.$$

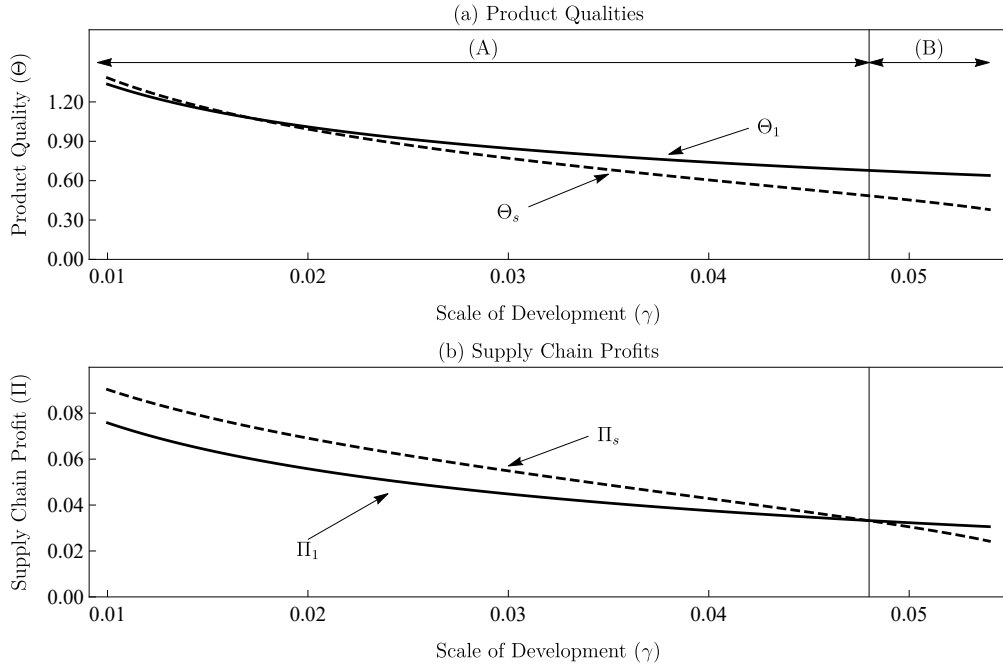


Figure 1.7: Product Qualities and Supply Chain Profits under Different Contracting Schemes ¹³

The following lemma shows that the supply chain may or may not be better off from the simultaneous contracting.

Lemma 1.3. *For moderately convex production and development costs at Tier 1, i.e., $\delta_\theta \in (1, 2\beta]$ and $\delta_D \in (1, 2\beta + \delta_\theta]$, the supply chain profit under the simultaneous procurement contract is larger (smaller) than that under the sequential contract when the development cost (γ) is small (large).*

When the development cost (γ) is low, the supplier can set high quality levels regardless of the contracting, implying that the difference between two quality levels is very small, as illustrated in Region (A) in Figure 1.7(a). Therefore, the supply chain is better off under the simultaneous contracting, which is described in 1.7(b) as the dashed line (Π_s), the supply chain profit under the simultaneous

¹³Parameter values are $K_0 = 0.8, K_1 = 1, \delta_\theta = 2, \delta_D = 3, \beta = 1, N = 1$. Θ_s and Π_s are the product quality and the supply chain profit under the simultaneous contracting. Similarly, Θ_1 and Π_1 are those under and the sequential contracting processes.

contracting, is above the solid line (Π_1), the supply chain profit under the sequential contracting, in Region (A). In contrast, for a large γ or in Region (B), the inability of being the contract initiator hurts the investment incentive significantly. As a result, the supply chain profit under the simultaneous contracting can be lower than that under the sequential contract. Thus, while the simultaneous contracting indeed increases the supply chain profit for small values of γ , it lowers the supply chain profit for large values of γ . Since the supplier is always worse off from the simultaneous contracting, an additional agreement between firms such as a lump-sum payment may be necessary for the contract to be agreed upon.

1.6.3 Investment Anchoring Under Concave Costs

We have considered the case of convex production costs to model the production ramp up challenges for innovative products as seen in industries ranging from small consumer electronics (Murai 2014; Lee 2015) to large electric vehicles (Maynard 2014; Kessler 2015; Hull 2017). However, the production costs may be concave in quantity in some industries as when there is economies of scale, and we now examine the role of investment anchoring in these situations.

Consider a general production cost $c(q)$, where $c(q)$ is weakly concave in the production quantity q . The supplier's profit function is $wq - c(q)$ for the wholesale price w . Suppose q' is ordered at $w = c(q')/q'$. If the firm produces q' , then its profit is zero. Producing more than q' is certainly not profitable because only q' is sold. Assume that the supplier produces $q^0 < q'$. Then, its profit is $\frac{c(q')}{q'}q^0 - c(q^0) < 0$ because $c(q)$ is concave or the production cost decreases less than the sales revenue, resulting in negative profits. The supplier's optimal decision is to produce q' . Therefore, if the downstream firm is the investment anchor and determines the component price, it can extract all the profit of the supplier. Consequently, Tier 1

prefers to be the investment anchor in order to have at least non-negative profits.

This observation ensures that if a quality improvement R&D opportunity does not result in convex production cost in quantity, being the investment anchor is always preferred. However, the improved product is expected to incur substantial production challenges, i.e., a convex production cost, the investment anchor can be the other firm, the manufacturer, different from the target R&D firm, the supplier.

1.7 Discussion and Conclusion

Product managers introducing innovative products are entrusted with the task of maximizing revenues and profits from their new products. A product manager's quest for revenues and profits can be hampered by the potential distortion of upfront investment in R&D in a supply chain. It is because the supplier, an upstream firm well positioned to invest in its own R&D, may under-invest in R&D but over-price its component due to concerns about the gains being appropriated by downstream firms. We study how new innovative products can be developed and financed in a supply chain, where a substantial upfront capital should be invested in R&D. Although this investment decision critically depends on who leads the investment in innovation and how accrued revenue is distributed, only the latter has drawn substantial attentions in the literature, typically assuming the investor is given. We propose an investment anchoring approach where the innovation investor is endogenously determined for either quality improvement or cost reduction R&D. To the best of our knowledge, this work breaks new ground in deeply examining and endogenizing innovation investor choice in a supply chain, a topic of growing importance as upstream technologies play a greater role in supply chains.

Investment anchoring helps supply chain partners offset distorted innovation

investments due to misalignment between partners. A downstream manufacturer that relies on an upstream supplier's R&D for quality improvement or cost reduction of the supplier's component would also find it optimal to go beyond the traditional approach of having the upstream supplier invest in R&D projects. Specifically, the two supply chain partners would conditionally agree for the downstream manufacturer to anchor or initiate the upstream R&D investment in return for greater investments by the supplier in the costly innovation project. Such an agreement could be enforced through an escrow-like arrangement by upstream suppliers who could then align incentives with downstream firms by investing and pricing their innovative products aggressively to expand unit sales, revenues, and profits. We characterize when this investment anchoring approach is beneficial for both firms resulting in an equilibrium outcome.

Our results have important and subtle implications for firms such as the electric car makers we discussed earlier in the paper. First, when the R&D cost for the innovation in the component (battery) quality is high, our analysis suggests that the downstream manufacturer should drive investment in core technology innovation. By doing so, both the supplier and the manufacturer are able to earn more profit and ensure broader market coverage (Fehrenbacher 2016; Lambert 2017). If the R&D cost is low, then the supplier being the investor is both viable and desirable for both firms. Second, this strategy is more relevant for quality-improving R&D rather than cost-reducing R&D, which refines managerial insights previously offered by Majumder and Srinivasan (2008). Although cost reduction increases the total supply chain profit, we show that it does not necessarily increase a firm's profit.

To maintain a keen focus on the investment anchor and to manage complexity, we formulate a stylized analytical model which may not have captured

the complexity of practice. First, we consider the innovation investment in a core component/technology such as the electric vehicle battery developed by the upstream supplier. In other industries, the primary quality-enhancing investment can be associated with other tiers of the supply chain, e.g., the final product quality can be affected primarily by the design of the end product, which is related to the investment in the downstream manufacturer. However, our analysis remains valid as long as there is a single primary investment target in a supply chain, regardless of its location, which determines the final product quality. Second, although we analyze a two-tier supply chain investing in an advanced/monopolistic technology, our analysis can be extended to a multi-tier supply chain or a supply network with a complex relationship. We concentrate on the simple linear supply chain case to derive primary first-order insights on the equilibrium investment anchor. Our analysis can be a building block to examine more complicated cases such as supply chain competition studied in Corbett and Karmarkar (2001). In closing, we believe that this paper takes a step forward to address the growing importance of product innovation in supply chains, by characterizing how innovation investment can be realized with anchoring to achieve greater profits and revenues in technology supply chains.

Chapter 1, in full, has been submitted as a manuscript to the journal Manufacturing & Service Operations Management and was co-authored with Junghee Lee, Vish Krishnan and Hyoduk Shin. The dissertation author was the primary investigator and author of this paper.

Chapter 2

Business Models for Technology-Intensive Supply Chains

Upstream technology and intellectual property play an increasingly critical role in emerging supply chains by endowing products with digital, data-networking, energy-storage and other sought-after capabilities. In such technology-intensive supply chains, intellectual property invented by an upstream firm must be embedded in a manufactured *subsystem* which is then integrated into a *full system* sold to end consumers. The technology providers face key business model decisions about how to monetize their innovation that we study in this paper. They typically monetize their decisions with a royalty-driven approach, which has gotten complicated in multi-lateral supply chains necessitating formal research attention. Moreover, they also consider forward integration into manufacturing to monetize their intellectual property. We characterize the appropriateness of different business model decisions for markets with varying levels of customer diversity and competitive intensity at

intermediate layers. Our key results show that a subsystem base royalty approach is the optimal business model when dealing with monopolistic intermediaries. However, it becomes increasingly optimal for the technology provider to adopt a full system base royalty business model when the intermediate supply chains face competition and the end-market customer diversity increases. We present conditions under which the technology provider may want to forward integrate. Our formulation and results have significant direct relevance to the prevailing heated global discussion on royalty base among technology providers, policymakers, and industry groups.

2.1 Introduction

Emerging technology and intellectual property, such as higher bandwidth wireless data-networking, efficient energy-storage, machine learning, and bio-analytics technologies endow numerous products from automobiles to machine tools to life sciences with sought-after capabilities. Incorporating these technologies allows downstream product development firms to enhance sales and profits. The technology in question is often the intellectual property of an upstream technology provider and it must be embedded in manufactured *subsystems* (like circuit boards or electro-mechanical components) before being integrated into finished products or *full systems* like smartphones, tablets, automobiles, and medical equipment. We refer to supply chains with such increased salience of upstream embedded technologies as Technology-Intensive Supply Chains (TISC). Clearly, a large fixed investment in R&D is needed to develop such innovations and those technology providers are keen to understand how their intellectual property can be monetized especially in more complex multi-lateral supply chain settings.

Technology providers conventionally monetize their intellectual properties

with a royalty-driven approach where they earn a percentage of sales of the product as royalty payment (Rostoker 1983; Goldscheider 1995; Jensen and Thursby 2001; Savva and Taneri 2015). The royalty-based monetization approach typically consists of a royalty rate and a royalty base, where the royalty payment per unit is the product of these two items. This business model (or monetization scheme) has become complicated in multi-lateral supply chains necessitating formal research attention. In a relatively simple supply chain, technology providers typically focus on setting the royalty rate because there is one clear royalty base. For example, when a drug-delivery firm licenses its extended drug delivery method to a pharmaceutical firm, the royalty base is the drug launched by the downstream pharmaceutical firm. However, in emerging manufacturing supply chains, more technologies are embedded in *subsystems* by specialized firms rather than being directly integrated into *full systems* before selling to consumers. This multi-tier supply chain structure results in more than one candidate for the royalty base, namely *subsystem* and *full system*, increasing the complexity of the technology monetization strategy. Interestingly, technology providers and even policymakers wonder (as seen in the example below) whether to set the royalty base on the intermediate subsystems or finished products, a topic on which we aim to focus in this paper and provide some useful guidance.

The practical significance of an innovator's business model dilemma is starkly illustrated by the smartphone industry driven by an upstream high-bandwidth data communication technology known as Long-Term Evolution (LTE). Upstream technology providers, such as Qualcomm and Ericsson, chose to charge royalties for the use of their innovations on the full system (smartphone) price rather than on the subsystem (LTE modem) price (Pettersson et al. 2015; Bartz and Nellis 2017). This royalty-based business model decision has attracted the attention

of non-profit expert groups and policymakers. The Institute of Electrical and Electronics Engineers (IEEE) amended its patent policy in 2015 to recommend the subsystem as the royalty base to their members. Even policymakers have weighed in some regions, such as China, the EU and Korea, promoting subsystem as the royalty base and penalizing technology providers implementing full system as the royalty base, asserting that it is detrimental to their markets (Mozur and Hardy 2015; Fairless and Clark 2015; Lee and Nellis 2016). However, technology providers, such as Qualcomm, have argued that the full system base royalty business model is more beneficial to markets, innovation, and aligning firm incentives¹. We formally study and characterize this issue of great industrial significance.

A second dilemma faced by technology providers is how to capture the gains accruing from their innovation. Specifically, the innovators concerned about appropriation of the benefits by downstream entities consider whether to forward integrate into the subsystem level. Such forward integration adds another dimension of complexity regarding manufacturing and competition of their subsystem as well as technology development and licensing, which should be jointly considered as a business model decision. It is useful to gain a fundamental understanding of the implications of these decisions for firm and supply chain profits as well as consumer and social welfare.

Our study aims to understand and resolve various issues that technology providers have faced while setting up their business model in a multi-lateral supply chain setting without irking downstream entities and policymakers. These include: (1) Which royalty base should be used as a part of the business model to maximize profits under different market and industry conditions such as in developed and developing countries? (2) What responses are expected from downstream

¹LTE/WiMax PATENT LICENSING STATEMENT (December 2008), <https://www.qualcomm.com/documents/ltewimax-patent-licensing-statement>

entities for the different business model decisions? (3) How should we reason with policymakers on the business model's implications on social welfare? (4) How should the technology provider set up its business model differently when it forward integrates into the subsystem? To answer these questions, we go beyond traditional two-tier price-quantity supply chains and incorporate product quality-enhancing innovations in a market of heterogeneous customers with differing abilities to pay for the product.

The contributions of this paper are multi-fold. To our best knowledge, this paper is the first work that formalizes a technology provider's royalty base decision in a three-tier technology intensive supply chain. We are able to formally address a real issue under varying degrees of competition and consumer heterogeneity, confronting the industry in general and technology providers and policymakers in particular; our analysis reveals that the optimal business model for each entity in TISC depends on the degree of competition in the intermediate layers of the supply chain and the end-market customer diversity. Specifically, we find that the optimality of the subsystem and full system base business models with monopolistic and competitive intermediaries. This is due to a fundamental underlying trade-off emanating from the royalty base between the incentives for downstream players to invest in quality improvements and the technology provider's investments that enhance differentiation and reduce cannibalization in the end products.

Next, we characterize that the optimal business model not only for a technology provider but also for other entities in TISC. A subsystem base business model (SSB) is optimal for the technology provider when dealing with monopolistic intermediaries. However, the provider finds it increasingly optimal to adopt a full system base business model (FSB) when the intermediate supply chains face competition and the customer heterogeneity increases. Similarly, other entities in TISC are

generally better off under FSB as the customer diversity increases, which provides a rationale for different stances of policymakers across countries.

Lastly, we provide the technology provider with the integrated business model from technology licensing to subsystem manufacturing. In general, the provider's integration into subsystem is mostly beneficial, it adds substantial (marginal) value to FSB (SSB). Interestingly, the technology provider's profit is affected by a subsystem competitor differently depending on end market customer diversity and the royalty base. For high customer diversity, the integrated provider is in fact generally better off with the competing supplier, but its profit decreases as the competitor's quality/capability increases regardless of business model, which is aligned with the previous findings (Conner 1995; Sun et al. 2004). To our surprise, for low customer diversity the SSB technology provider's profit is non-decreasing as the competitor's quality improves. In contrast, the FSB technology provider's profit can be decreasing and then increasing. This implies that a technology provider may be willing to help the competitor improve its quality but the willingness differs from business models, which enrich the managerial insights regarding competition in TISC.

Our analysis produces actionable insights for technology providers as well as policymakers. For instance, we are able to show that under a low degree of end market customer diversity, the upstream technology provider should implement SSB and it is compatible with the incentives of the rest of the supply chain. As customer diversity increases, the provider should choose FSB along with actively considering forward integration into the subsystem. At high-levels of customer diversity, the FSB approach is in alignment with the rest of the supply chain, but our results show that at intermediate levels of customer diversity/market inequality, transfer payments from the technology provider to downstream manufacturers may

be needed to achieve agreement on implementing the full system base approach. We also demarcate the optimality of the different royalty-based business models from the perspective of society as a whole, consumers, and downstream full system manufacturers, which not only provides a theoretical rationale to reason the recent litigations between firms and different stances across policymakers but also can be applied to reconcile the conflicts. Our formulation and results could have significant direct implications for the prevailing heated global discussion on royalty base among technology providers, national policymakers, and industry groups.

2.2 Literature Review

The primary focus of this paper is to examine the technology provider's business model decision and its impact on the rest of the supply chain as well as social welfare. Our work is chiefly related to three research streams: technology licensing, new product innovation/development, and business model innovation in supply chains.

Technology licensing literature has considered how to license technological innovations since Arrow (1962). Early literature classified technology licensing into two groups based on volume-independence, fixed-fee and royalty. Although initial results advocate fixed-fee licensing (Katz and Shapiro 1985, 1986; Kamien and Tauman 1986), royalty-based licensing approach has been widely used in practice (Rostoker 1983; Goldscheider 1995; Jensen and Thursby 2001). Follow-up studies have provided multiple reasons for the popularity of royalty licensing (Kulatilaka and Lin 2006; Savva and Taneri 2015). We refer the reader to Sen (2005) for a comprehensive review of the previous literature.

Being different from the straightforward fixed fee licensing, the royalty

licensing can be further divided contingent on whether it is related to licensee's product price (the royalty base price). If the royalty scheme is independent of the price, the royalty payment is simply a constant. Otherwise, it is the product of the royalty rate and the royalty base price. Whereas aforementioned papers model either type of royalties for simplicity or by implicitly assuming the equivalence, a stream of literature explicitly defines the former and the latter as *per unit* and *ad valorem*, respectively, and compares them in various settings such as risk sharing (Bousquet et al. 1998), Cournot duopoly (San Martín and Saracho 2010), and information asymmetry about the competitors' costs (Heywood et al. 2014). Llobet and Padilla (2016) independently tackle the royalty base controversy but in a two-tier setting by relating *per unit* and *ad valorem* to subsystem and full system bases. Their welfare analysis result shows that *ad valorem* (full system base) royalty tends to generate higher social surplus at stake of the downstream firm's profit. However, this approach neither precisely model the technology supply chain nor plausibly explain recent regulation moves across countries (Mozur and Hardy 2015; Lee and Nellis 2016).

Interestingly, the legal system treats the royalty base more importantly. There are *apportionment* and *entire market value* rules for the patent infringement damage calculation. If substantial evidence proves that the final product's (the full system's) demand was initially generated from the demand for the patented feature,² then the courts order to compensate the loss from patent infringement based on the entire market value rule,³ where the compensation is the product of a portion of the entire product price (the full system price) and its sales. Otherwise, the apportionment rule is applied, in which the compensation base is the smallest

²Mondis Technology, Ltd. v. LG Electronics, Inc., 2:07-CV-565-TJW-CE, (E.D.Tex. 2011)

³Lucent Technologies, Inc. v. Gateway, Inc., 580 F.3d 1301, 1336 (3d Cir. 2009)

component that infringed the patent.⁴ Since the two rules are for the patent infringement damage calculation ex-post, they are not readily applied to the technology provider's business model ex-ante. We differentiate ourselves from the previous literature by explicitly formalizing the royalty base in multi-lateral supply chains under varying competition in downstream firms and market conditions, which are important yet neglected considerations. By doing so, we find that both downstream firms and social surplus are affected by the royalty base but differently by competition and consumer heterogeneity, which better rationalizes the conflicts of interests between the technology provider and other entities and provides richer managerial insights.

We aim to study a technology provider's business model decision, specifically how the royalty base and the position in supply chain may vary based on market conditions (Bartz 2009; Mozur and Hardy 2015; Fairless and Clark 2015; Lee and Nellis 2016). Gabszewicz and Thisse (1979, 1980) model a market with consumers of different income levels but identical quality valuations. Mussa and Rosen (1978) assume consumers' different quality valuation, which has gained traction in the management science literature. Subsequent researchers have been able to derive more insights by modeling a market with discrete segments. Moorthy and Png (1992) and Villas-Boas (1998) study product line in a single firm and in a supply chain respectively, where the product quality is determined by its component quality. Krishnan and Gupta (2001) extend with an additional common quality component such as platform which needs one time investment. Krishnan and Zhu (2006) formalize fixed and variable cost intensive qualities with quality saturation. Most of these papers are focused on the product line design decisions of a vertically-integrated monopolist. Our paper uses a similar end market model to these papers

⁴Cornell University v. Hewlett-Packard Co. 609 F.Supp. 279 (N.D.N.Y. 2009)

but is sharply distinguished in that we consider a multi-tier supply chain driven by upstream intellectual property which determines key aspects of product quality.

This paper contributes to the emerging research stream on Business Model Innovation. Girotra and Netessine (2014) propose the definition of business model as “a set of key decisions that collectively determine how a business earns its revenue, incurs its costs, and manages its risks.” While our paper is not so broad, we still address key monetization dilemmas of innovative technology providers. Our paper is also related to Wang et al. (2017), who study a technology licensing problem where the technology can be licensed to either a decentralized supply chain with a designer and a producer or a centralized supply chain with an integrated device manufacturer. The innovator’s critical decision is to whom it licenses rather than how much to invest in technology R&D. Hu et al. (2017) take a look at the case where technologies are owned by downstream manufacturers rather than the upstream innovator. Their key business model decision is whether to open a proprietary technology to its competitor to spur a common supplier’s costly technology adoption. In contrast, a few paper analyze business model focusing on consumer’s psychological recognition. Orsdemir et al. (2016) study vertical integration and horizontal sourcing to ensure corporate social and environmental responsibility that affects consumer demand. Lim et al. (2015) compare business models regarding battery ownership of electric vehicle and the type of charging station to mitigate consumer’s psychological barriers such as resale and range anxieties of purchasing electric vehicle. They show that anxieties typically reduce adoption but this depends on electronic vehicle production cost. Our paper differs from these prior papers in its focus on technology investment and licensing business model decisions. Lee et al. (2018b) may be the closest one to our work in that they study both technology investment and multi-lateral supply chains but they still do

not consider upstream innovations that are licensed rather than assembled.

This paper contribute to aforementioned research streams by investigating a technology provider's business model in three-tier supply chains, which are increasingly common. We are differentiated from previous research in that the business model may include not only technology licensing (royalty and/or fixed fee) but also manufacturing strategies. We compare various combinations of business models which differ in their royalty bases under varying degree of downstream competition and consumer heterogeneity. Our work formalize that the upstream technology innovator's business model choices have significant impacts on not only its own profit but also the supply chain's profit and social surplus as discussed below.

2.3 The Model

We begin with a description of the model setting followed by decision sequence and formulation of a technology-intensive supply chain.

2.3.1 Model Description

Consider an upstream technology provider (TP) in a supply chain that invests and invents key capabilities which can be converted into intellectual property licensed to downstream production companies (Erat and Kavadias 2006; Wang et al. 2017; Lee et al. 2018b).⁵ The firm needs to make decisions about technology investment as well as business model decision on technology licensing. It could be a small start-up that lacks the resources to setup large manufacturing operations

⁵For the case where the technology is developed by a downstream firm, please see Wang (1998) for licensing to the competing manufacturer and Hu et al. (2017) for licensing to the upstream supplier.

initially, but could grow to become a large player capable of forward integration, i.e. subsystem production as discussed below. In this case, TP should set up a business model from technology investment/licensing to production. Examples include MIPS, ARM, and Qualcomm in semi-conductors and Alkermes with extended drug delivery technology in life sciences. The product or the full system in question sold to the consumer market (like a mobile phone or a medical device) is comprised of a technology core and a physical system with integrated hardware and software, which are termed as *technology* and *system*, respectively. The overall product quality is a combination of these two parts. Although the technology provides critical capability to products, it is of little value to consumers by itself without appropriate system integration. The product can be highly valuable only if both technology and system qualities are high (Altug and Ryzin 2013; Coad 2009), which is similar to the O-ring or inter-dependent production model in economics (Kremer 1993). For example, a smartphone with high bandwidth data networking technology is of limited use without a high resolution screen or a fast processor. This is conceptualized as a multiplicative combination of technology-driven and system qualities as follows. It is noteworthy that we use the term quality in a micro-economic sense (as a measure of capability) and our main results of the paper hold even with alternatives such an additive model of quality.

Assumption 1. The overall product quality (Q) is a multiplicative combination of technology-driven quality (T) and system quality (θ): $Q(T, \theta) = T\theta$.

We now turn to modeling the rest of the Technology Intensive Supply Chain (TISC), animated by the intellectual property-protected upstream technology of quality T . We model the case observed in practice (such as semiconductors, electronics, and even life sciences) that in the emergent stages of the technology, the technology provider focuses on achieving monopoly status by securing Intellectual Property

(IP) protection and relies on downstream subsystem suppliers to manufacture and incorporate it in a subsystem. This is in part due to resource constraints of the technology provider in the emergent stages; later in the life cycle of a technology, the provider may attempt to forward integrate into subsystem production. The subsystem in question must be integrated into the final products sold to consumers. To accurately describe such a multi-tier supply chain, we use Tiers 0, 1, and 2 from downstream to upstream. A tier number represents a proximity to the end market. Due to IP protection (offering monopoly rights), there is one technology provider in Tier 2 that develops the technology of quality T by investing $c_t T^{\delta_i}$ in R&D, where $\delta_i > 1$, to capture the increasingly difficult task of improving technology quality in a manner consistent with the microeconomics and operations literature (Jones and Mendelson 2011; Lee et al. 2018b).

This technology needs to be embedded into a specialized subsystem by expert suppliers before assembled into a full system by manufacturers. Although subsystem manufacturing can be outsourced to contract manufacturers, the design of subsystem (how to embed technology) should be provided as well, which often needs special workforce to decode and understand the technology (Wang et al. 2017). For example, there are specialized LTE modem suppliers such as MediaTek and Spreadtrum. Substantial capital investment for subsystem manufacturing leads us to assume limited number of such firms. We model that there can be at most two suppliers. Since the embedded technology is the primary determinant of the subsystem quality, there is little room for endogenous quality differentiation. We analyze the base model with the identical suppliers to provide clearest insights. Nevertheless, we extend the model by releasing the assumption to examine the impact of supplier asymmetry on business model in Section B.1 in the Appendix. After setting subsystem prices, subsystems are sold to full system manufacturers.

In Tier 0 (the full system tier closest to the end consumer), we model that there can be two manufacturers M_1 and M_2 to model the varying degrees of competition observed in industries such as smart phones and automobiles firms. Each full system manufacturer develops a subsystem into a full system with additional components referred to as *system*. Although they cannot alter the upstream technology (such as LTE), they can determine system qualities (θ) by incurring convex increasing unit production cost $c_f\theta^{\delta_m}$, where $\delta_m > 1$ (Mussa and Rosen 1978; Moorthy and Png 1992; Lee et al. 2018b), as well as the retail prices (p).

As a result, we have a general three-tier technology supply chain that consists of one technology provider developing IP-protected technology (Tier 2), supplier(s) embedding the technology into subsystems (Tier 1), and manufacturer(s) assembling subsystems with other components into full systems (Tier 0), where the number of firms in Tier 0 and 1 can vary. This three-tier supply chain is the simplest structure yet allows us to study a technology provider's business model decisions from R&D investment to licensing to manufacturing under varying degrees of competition in the subsystem and full system tiers and of consumer heterogeneity.

The above-mentioned product of quality (Q) is sold to a market which we model as follows. The market consists of low (l) and high (h) segments of consumers that value product qualities differently. Let v_l and $v_h (> v_l)$ be the valuations (willingness or ability to pay for a unit of quality) of each segment. The total size of the market is normalized to 1. We define $\alpha \in (0,1)$ as the portion of h segment. Thus, the market is fully characterized by two parameters $(v_h/v_l, \alpha)$, where v_h/v_l can be viewed as a measure of consumer heterogeneity or market inequality. To keep the focus on the supply chain and business model decisions, we adopt this discrete market approach which has been widely embraced in the management science literature to generate insights on firm's product line design decisions (Moorthy and

Png 1992; Villas-Boas 1998; Krishnan and Gupta 2001; Krishnan and Zhu 2006); A continuous market modeling approach has difficulty in deriving cleaner insights without resorting to simulation (Yurko 2011).

It is first evident that at most two different products can be sold by each firm as there are only two segments. If both manufacturers have two products, they compete in both segments earning zero profit. When only one product is sold, there are two cases depending on target segments of both firms. If the target segments are different, each manufacturer becomes a local monopoly and can earn positive profit. In contrast, a firm earns nothing by selling to the same segment. While we are interested in equilibrium outcomes, if there are multiple equilibria, we concentrate on a Pareto dominant equilibrium. When the system qualities are different, we let M_2 be the manufacturer producing a superior system without loss of generality. In addition, we model the industrial scenarios we have studied wherein the technology embedded in the product may generate network externalities to consumers - consumers in each segment may be impacted positively to a greater or lesser degree by the usage of the product across the two segments. This becomes particularly salient when the technology is related to communication or networking. Even non-communication technologies generate certain degree of network externalities due to the availability of support services and applications. To model these factors, we assume that a product may generate additional utility to its existing customers that is proportional to the current sales or demand of the product, D . We model the proportion of total utility increase by the product externalities as D^γ where $\gamma \geq 0$ can be interpreted as the degree of network externalities associated with the product. When γ is low, a consumer's utility is little affected by the sales volume. If it is high, her utility could vary significantly depending on sales. Our modeling of network externalities, that they are independent of product quality

and increase in sales, follows prior research (e.g., Conner 1995; Sun et al. 2004; Lee and Mendelson 2008). A type- x consumer's utilities for $x \in \{l, h\}$ can be written as:

$$U(Q, p | v_x, D) = v_x \cdot Q \cdot D^\gamma - p, \quad (2.1)$$

where p is the product price paid by consumer x , who buys at most one product that gives the highest non-negative utilities among the set offered.

2.3.2 Business Model for Technology Provider

We begin the business model analysis with volume-based royalty licensing only then introduce fixed fee. Technology licensors in many industries are committed to Fair, Reasonable, And Non-Discriminatory (FRAND) licensing. A provider can still determine details of licensing conditions but can neither restrict the number of licensees nor charge different royalty rates to different customers. To reflect this industrial reality, we make the following modeling assumption.

The technology provider offers the same royalty rate to licensees.

We define a business model for a technology provider (TP) as a collection of business decisions from technology development to licensing to manufacturing. Specifically, we refer to FSB (SSB) as a business model using the full (sub) system as the royalty base, where the R&D investment, the royalty rate, and the subsystem price when TP integrates into subsystem production, should be determined. As Figure 2.1 illustrates, it is the full system manufacturers (subsystem suppliers) that make royalty payment under FSB (SSB).

Each tier makes decisions sequentially from upstream to downstream or from Tier 2 to Tier 0. The sequence of events is based on our field studies in

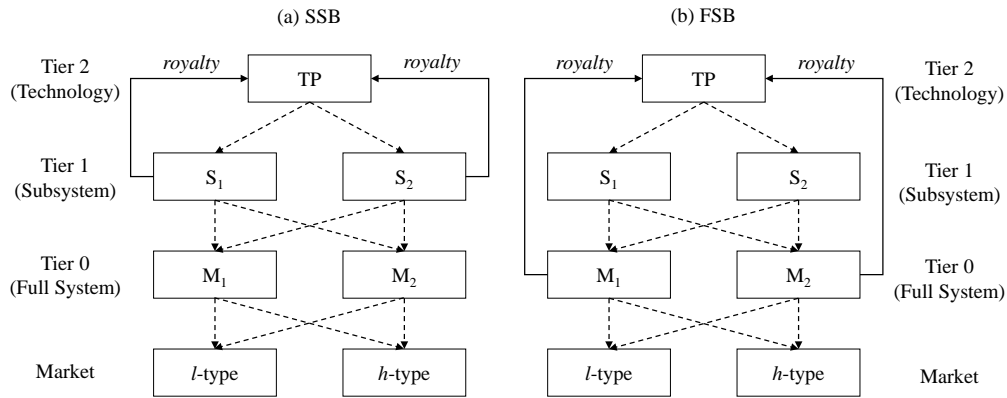


Figure 2.1: Subsystem Base Business Model (SSB) and Full System Base Business Model (FSB)

the electronics industry and is illustrated in Figure 2.2. In the initial stage, a technology provider in Tier 2 chooses a royalty base between sub and full systems. Then, it determines the investment in technology development and the royalty rate for technology licensing. For notational convenience, we use large (small) letters T (t) and R (r) to denote the technology quality and the royalty rate under FSB (SSB), respectively. Next, subsystem suppliers (S_1 and S_2) in Tier 1 decide their subsystem prices. In the final stage, full system manufacturers (M_1 and M_2) in Tier 0 determine which supplier subsystem to procure, the full system qualities, and the full system prices. We analyze this sequence to generate insights of business model decisions, assuming that all decisions are observable.

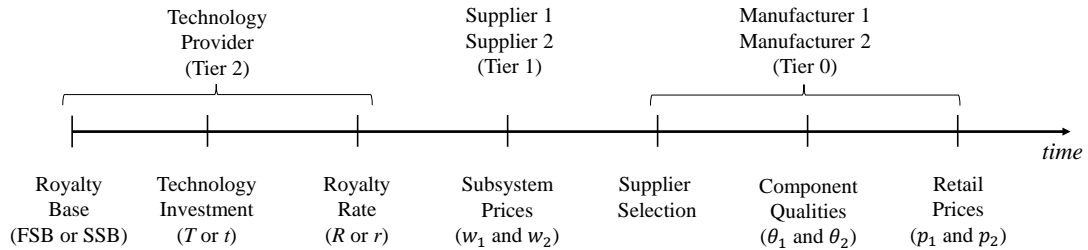


Figure 2.2: Decision Sequence

2.4 Analysis

To investigate the optimal business model for a technology provider (TP) under various supply chain structures and market conditions, we begin with the analysis of TP that focuses on R&D and does not manufacture the technology embedded subsystem, which will be relaxed in future sections. We also start analyzing the optimal business model in a three-tier monopoly supply chain as a benchmark, where there is only one firm at each tier in Section 2.4.1. Then, we investigate the competition impact on SSB and FSB followed by the comparison in Section 2.4.2. We conclude the section by introducing fixed fee into the business model in Section 2.4.3.

2.4.1 Business Models under Monopolistic Supplier and Manufacturer

Suppose that there is one firm in each tier. We examine the optimal business model for the technology provider (TP) by backward induction under SSB followed by FSB. Let us look at Tier 0, the full system manufacturer (M), which determines its product line strategy, the optimal system qualities, and prices. These decisions are analogous to prior work dealing with a monopolist's product line design (Moorthy and Png 1992). From this research stream, we learn that the consumer heterogeneity parameter is a critical factor influencing the manufacturer's decision. For example, M initially extends its product line to serve all segments, but shrinks it later to focus on the upper segment(s), as market inequality increases. We refer to these approaches as *Extension* and *Niche*. On top of the prior literature, product externalities can make another strategy, *Standard*, optimal, where one

standard product is sold to all segments.⁶ The manufacturer's profit function can be generally expressed as follows.

$$\pi_M(\theta_1, \theta_2, p_1, p_2|w) = \sum_{j=1}^2 (p_j - c_f \theta_j^{\delta_m} - w) D_j(\theta_j, p_j).$$

The profit function consists of up to two streams of profits depending on the product line. Notice that there are two types of variable costs. The manufacturer incurs not only the full system production cost ($c_f \theta_i^{\delta_m}$) but also the subsystem procurement cost (w). It implies that S can influence M 's decisions through w . For example, if w is high, M may not want to achieve either *Extension* or *Standard* and adopt *Niche* instead. Thus, S should set w carefully by examining M 's incentives related to each product line. The supplier's profit function can be written as follows.

$$\pi_S(w|t, r) = (w - rw - c_s) D_s(w).$$

We remind that S is responsible for royalty payment (rw) under SSB. The technology provider invests in R&D and earns the royalty payments. For brevity, we use subscript I for the technology provider who is the key innovator in this supply chain. Its profit function is:

$$\pi_I(t, r) = rw D_I(t, r) - c_t t^{\delta_i}. \quad (2.2)$$

Even though (2.2) is a simple form, maximizing it involves an interesting complexity.

It should anticipate the sequential responses of both Tier 0 and Tier 1. For TP

⁶The product line can be classified with respect to its market coverage. Namely, *Extension* and *Standard* fully cover the market but *Niche* partially does. While *Standard* can be equilibrium in this trilateral monopoly supply chain, it is not when there are multiple manufacturers. For such competitive environments, we use rather intuitive terms, Full and Partial, to refer to product line strategies.

to achieve a particular product line, it should induce S to set w accordingly by setting t and r so that S and M are better off under TP 's intended strategy than others. That is, TP needs to maximize its profit under the sequential deviation concern complicated by the technology externalities.

When the technology is licensed under FSB, M pays the royalties instead of S . For simplicity, we use the capital letters for profit (Π) and TP 's decisions (T , R). Each firm's profit function under FSB is expressed as follows.

$$\begin{aligned}\Pi_M(\theta_1, \theta_2, p_1, p_2|w) &= \sum_{j=1}^2 (p_j(1-R) - c_f\theta_j^{\delta_m} - w)D_j(\theta_j, p_j), \\ \Pi_S(w|T, R) &= (w - c_s)D_s(w), \\ \Pi_I(T, R) &= \sum_{j=1}^2 Rp_jD_j(\theta_j, p_j) - c_tT^{\delta_i}.\end{aligned}$$

It is worthwhile to mention that FSB has an adverse impact on M 's system quality investment (θ_i). This is because the royalty payment based on its full system prices prevents M from capturing all of the benefits generated from its system quality investment as part of the gains are transferred to TP . This adverse impact differentiates FSB from SSB and imposes another complexity on FSB TP 's optimal decision in addition to the sequential deviation issue, preventing us from fully characterizing the optimal product line strategy under different business models. Nevertheless, we characterize the optimal business model for a trilateral monopoly for a special case.

Proposition 2.1. *In a trilateral monopoly supply chain, SSB dominates FSB from the technology provider's perspective by inducing*

- (i) *Extension for low levels of market inequality with high enough network externalities* $\left(\frac{v_h}{v_l} \leq \frac{1}{\alpha} \text{ and } \gamma \geq \underline{\gamma}\right)$,

(ii) or, *Niche* for high levels of market inequality with moderate network externalities $\left(\frac{1}{\alpha^{1/2+\gamma}} \leq \frac{v_h}{v_l} \text{ and } \gamma \geq \frac{1}{2}\right)$,

where $\underline{\gamma}$ is characterized in the Appendix.

Proposition 2.1 shows the sufficient conditions for the optimality of SSB for *TP* in a trilateral monopoly setting. When consumer heterogeneity/market inequality is not high ($v_h/v_l \leq 1/\alpha$) and the technology externalities are above the threshold ($\gamma \geq \underline{\gamma}$), the *Niche* strategy is not a very attractive approach as it is more profitable to serve the entire market. Moreover, the *Standard* approach is dominated by *Extension*, which is more profitable via coordinated pricing. As a result, SSB *TP* is able to extract all of the surplus generated from downstream firms without being concerned about their desire to deviate from *Extension* strategy. Although FSB *TP* does not have the deviation concerns either, it discourages the manufacturer's quality investment leading SSB to dominate FSB for *TP*'s profit. Similarly, if the inequality is high enough, *TP* finds it optimal to partially cover the market. That is, *TP* charges a high royalty rate to force downstream firms to serve only *h* segment or to adopt *Niche*.

When market inequality becomes moderate, downstream firms are more tempted to deviate out of *Extension*. Because of the externalities, *TP* lowers the royalty rate to still induce them to cover the whole market via *Standard*, where *TP*'s profit is decreasing in market inequality. While it is challenging to characterize the optimal business model for moderate levels of market inequality, our numerical results show that SSB continues to outperform FSB (Figure 2.5(a)). That being said, as we will see in the next subsection, this result is reversed and FSB emerges as a viable and even dominant strategy when the intermediate supply chain tiers experience competition.

2.4.2 Business Models Under Symmetric Suppliers and Manufacturers

Subsystem Base Business Model:

Now let us consider a supply chain comprising of multiple firms at Tiers 0 and 1, where the royalty base is the subsystem. We begin with the case where there are two identical subsystem suppliers at Tier 1 to focus on full system competition in Tier 0.

Due to the competition between the symmetric suppliers S_1 and S_2 , manufacturers in Tier 0 are able to choose the lower price supplier and procure the subsystem at $w = \min(w_1, w_2)$, where w_i is S_i 's subsystem price. We apply backward induction for the remaining price and quality decisions. Manufacturer i (M_i) solves the following problem:

$$\begin{aligned} & \underset{p_i}{\text{maximize}} \quad \pi_i(p_i|p_j, \theta_i, \theta_j, t) = (p_i - c_f \theta_i^{\delta_m} - w) D_i(p_i|p_j, \theta_i, \theta_j, t) \\ & \text{subject to} \quad w \leq p_i - c_f \theta_i^{\delta_m}. \end{aligned} \quad (2.3)$$

Each Tier 0 manufacturer seeks to maximize the total profit, which is the unit profit of product i times its demand, D_i . The exogenous subsystem price w imposes the participation constraint (2.3). If w is high enough, manufacturers are forced to cover only h segment. Otherwise, they may cover the entire market. In Tier 1, a supplier sells a subsystem at w_i while incurring an exogenous manufacturing cost c_s and paying $r \cdot w_i$ to TP as a royalty payment. Its unit profit is $w_i(1 - r) - c_s$. The identical subsystem quality and cost assumption lead two suppliers to compete in price, resulting in $w_1 = w_2 = \frac{c_s}{1-r}$. In Tier 0, TP has two profit streams—royalty payments and sales. With respect to the royalty rate decision, TP essentially

should choose between the full coverage (both l and h segments) and the partial coverage (only h segment). TP has the same profit function to (2.2) in the trilateral monopoly case. Notice that the royalty profit increases in r . The optimal royalty rate is set at the highest value such that (2.3) is binding. Then, TP chooses the optimal t that equates marginal cost and revenue. After extensively analyzing the firm's decisions under SSB (Lemma B.1 in the Appendix), we state the main managerial insights as the following lemma.

Lemma 2.1. *The SSB profit-maximizing market coverage policy under competition is a threshold policy. If $\frac{v_h}{v_l} \leq \frac{\tilde{v}_h}{\tilde{v}_l}$, the market is fully covered. Otherwise, the market is partially covered, where $\frac{\tilde{v}_h}{\tilde{v}_l}$ is characterized in the Appendix.*

All proofs as well as the detailed equilibrium outcome expressions on the royalty rate, the technology quality, and TP 's profit are given in the Appendix. The lemma shows that the optimal market coverage policy is a threshold policy, in which Tier 0 and Tier 1 are integrated through SSB. When market inequality is low, TP covers the entire market by setting r such that M_1 's participation constraint is binding and TP 's profit is independent of market inequality. If the inequality is high enough, TP increases r to induce both manufacturers to compete for h segment. Therefore, M_1 's profit ends up with zero under SSB, which is not necessarily the case under FSB.

Full System Base Business Model:

Consider the business model where royalty is charged on the full system prices. Being similar to that under SSB, M_i 's profit function is:

$$\Pi_i(p_i|p_j, \theta_i, \theta_j, T, R) = (p_i(1 - R) - c_f \theta_i^{\delta_m} - w) D_i(p_i|p_j, \theta_i, \theta_j, T, R).$$

We remind that a full system manufacturer only internalizes $1 - R$ of its price p_i due to the royalty payment ($p_i R$) under FSB, which negatively affects the system quality decision (θ_i) and may lower the retail price in equilibrium. After analyzing Tier 0 manufacturers' optimal decisions in Lemma B.2 in the Appendix, we obtain that not only the manufacturer's quality but also its prices decrease in the royalty rate. It implies that TP may set a lower royalty rate under FSB than SSB to incentivize the full system manufacturer. The competition between symmetric suppliers in Tier 1 drives the equilibrium subsystem price to the manufacturing cost, c_s . Anticipating the responses in Tier 0 and 1, TP determines the technology quality T and the royalty rate R . In doing so, the technology provider can resort to full market coverage or partial coverage, which we now examine separately.

To achieve full coverage, TP must ensure that both the low-end (M_1) as well as high-end (M_2) manufacturers find it incentive compatible to enter the each segment, in which there are two different full systems sold at different prices. The technology provider should determine the technology quality and the royalty rate considering that it earns different per unit royalty payments from manufacturers. In this FSB full coverage case, TP solves the following problem.

$$\begin{aligned} & \underset{T,R}{\text{maximize}} \quad \Pi_I^f(T, R) = R(p_1^f(T, R)(1 - \alpha) + p_2^f(T, R)\alpha) - c_t T^{\delta_i} \\ & \text{subject to} \quad 0 \leq p_1^f(T, R)(1 - R) - c_f \theta_1(T, R)^{\delta_m} - c_s. \end{aligned} \quad (2.4)$$

(2.4) is M_1 's participation constraint. Whereas binding M_1 's participation condition is optimal for SSB full coverage, FSB's adverse impact on downstream quality may or may not make (2.4) binding optimal. The complex expressions for optimal decisions are stated in Lemma B.3 in the Appendix.

Turning to the partial coverage case, we can show that it is dominated by

the full coverage option for all but extreme cases of dominant h segment. Notice that to achieve partial coverage case, TP must induce both manufacturers in Tier 0 to forego l segment and to sell their full systems to h segment by setting the royalty rate and the technology quality. Therefore, TP solves the following problem for partial coverage.

$$\begin{aligned} & \underset{T,R}{\text{maximize}} && \Pi_I^p(T, R) = -c_t T^{\delta_i} + R p^p(T, R) \\ & \text{subject to} && c_s > v_l \theta_1(T, R) T(1 - R) - c_f \theta_1(T, R)^{\delta_m}, \end{aligned} \quad (2.5)$$

$$c_s \leq v_h \alpha^\gamma \theta_2^p T(1 - R) - c_f (\theta_2^p)^{\delta_m}. \quad (2.6)$$

(2.5) assures a manufacturer's deviation to l segment is not profitable and (2.6) guarantees that the concentration on h segment is profitable. We make two observations in TP 's problem. Like SSB, manufacturer's competition for the same segment causes the full system price to be set at the cost. However, a royalty rate which is sufficiently high to satisfy (2.5) and (2.6) may discourage downstream quality investment significantly, which curtails the manufacturers' costs and TP 's royalty profits in turn (Lemma B.4 in the Appendix). As a result, partial coverage is dominated by the full coverage under FSB in all but the extreme parameter ranges of high-segment customers. We now formally state this optimal FSB decision and market coverage result.

Lemma 2.2. *The FSB profit-maximizing market coverage policy under competition involves full coverage for all but the extreme proportion of h segment customers. While the optimal technology quality is monotone increasing, the optimal royalty rate is not monotone increasing in market inequality.*

Lemma 2.2 has two interesting implications. First, it shows that the techno-

⁷Parameter values are $\delta_m = 2, \delta_i = 3, \alpha = 0.2, c_s = 0.35, c_t = 0.5, c_f = 0.25, \gamma = 1$, and $v_l = 1$.

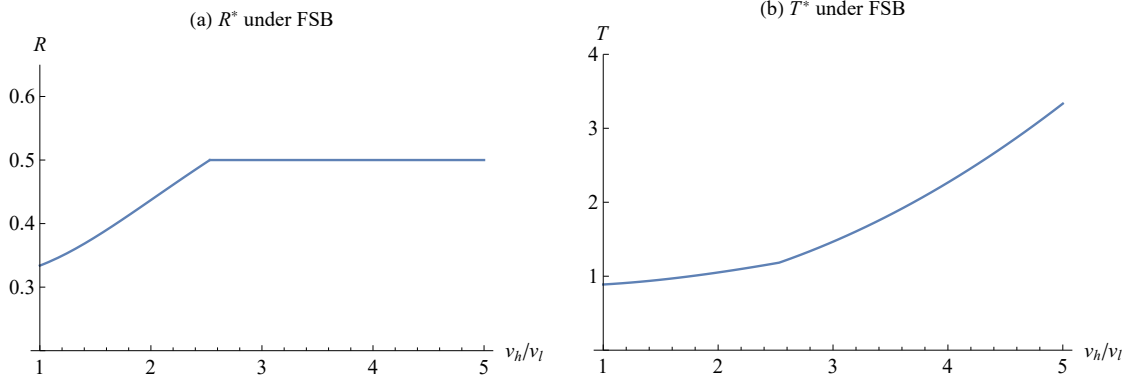


Figure 2.3: The optimal royalty rate (R^*) and the optimal technology quality (T^*) under FSB Full coverage ⁷

logy provider under FSB adopts the full coverage in most markets with small to reasonably large h segment⁸ and for even high market inequality, which is in sharp contrast to the partial coverage under SSB (Lemma 2.1). Next, as a result, the equilibrium royalty rate is determined as stated in Lemma B.3 in the Appendix, resulting in the royalty rate is not monotone increasing in market inequality. Instead, it converges to a constant. When the royalty rate is increasing in low market inequality, M_1 's participation condition (2.4) is binding like SSB. However, for high inequality, it is optimal not to bind (2.4). This is because a high royalty rate that extracts all the profits of M_1 may substantially reduce the high-end manufacturer's (M_2 's) royalty payment since the high royalty rate also discourage M_2 's system quality investment and retail price. Figure 2.3(a) and (b) illustrate that the optimal royalty rate converges to a constant but the optimal technology quality is increasing in market inequality.

The comparison of optimal market coverage policies between SSB and FSB suggests that the technology provider should understand that the market coverage

⁸The partial coverage can be optimal only within a range of market inequality if α is close to 1 as shown in the proof of Lemma 2.2.

⁹n/a means TP 's participation condition is not satisfied.

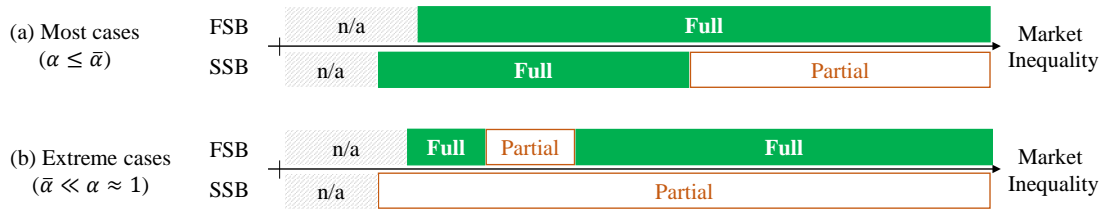


Figure 2.4: Technology Provider's Market Coverage Comparison between FSB and SSB ⁹

decision can widely vary depending on the royalty base, which is illustrated in Figure 2.4. The varying market coverage under different royalty bases generates a new insight for policymakers. If the market coverage is the first priority and modifying regulation takes considerable time and effort, allowing FSB may be the robust decision.

Optimal Business Model:

We have investigated TP 's optimal investment in technology development and optimal royalty rate under each business model. Based on these findings, we study the optimal business models for TP as well as other entities in the supply chain. First of all, when the proportion of h segment (α) is dominantly large, SSB partial coverage is clearly optimal as we discussed in Section 2.4.1.¹⁰ In contrast, when α is small or moderate, the market is fully covered with different business models depending on market inequality. For the meaningful business model comparison, we focus on the latter case hereafter, which is most real-world markets and an optimal business model is defined by each entity in the supply chain as the one generating more profits or surpluses.

From the above analysis, it is clear that TP 's profit under SSB is constant

¹⁰We derived the threshold portion of h segment $\bar{\alpha}$ in Lemma B.5 in the Appendix such that for $\alpha \leq \bar{\alpha}$ the market is fully covered under both business models.

as market inequality (v_h/v_l) increases,¹¹ because the per unit royalty payment is constrained by M_1 's price or l segment's valuation (v_l). In contrast, FSB enables TP to receive a higher per unit royalty payment from M_2 , leading TP 's profit under FSB to increase in market inequality. Clearly, TP prefers to adopt FSB as market inequality increases, but we find that policymakers,¹² consumers, and even high-end manufacturers can prefer the FSB approach at increasing levels of market inequality. We now discuss the implication of these business models for different parties including different supply chain firms, consumers and policymakers in the following proposition.

Proposition 2.2. *In a trilateral supply chain under downstream competition and contingent on TP developing its technology (conditions provided in the Appendix), SSB is attractive at low level of market inequality, but FSB dominates SSB for each of the supply chain entities as market inequality increases in the following order: Low-end manufacturer (M_1)–Technology Provider (TP)–Policymakers–Consumers–High-end manufacturer (M_2).*

Proposition 2.2 shows that the competition among supply chain entities can have a significant impact on the business model preference of each entity. Loosely speaking, the technology provider prefers the SSB with no competition but prefers the FSB approach under competition. For $\gamma = 1$ and $\alpha = 1/2$, Proposition 2.1.(i) and 2.1.(ii) indicate that SSB is optimal for $v_h/v_l \leq 2$ and $v_h/v_l > 2.83$ in a trilateral monopoly setting. In contrast, the characterization in the Proposition 2.2 implies that FSB is already optimal for $v_h/v_l \geq 2$. Figure 2.5 clearly contrasts this, where FSB (SSB) is optimal in the (un)colored region. While the uncolored region dominates in Figure 2.5(a), the colored region is substantially larger in Figure

¹¹We fix v_l and let v_h vary when it comes to market inequality v_h/v_l .

¹²Since the market is fully covered regardless of business models, policymakers' objective function is the social welfare, which is the sum of all the profits and consumer surplus.

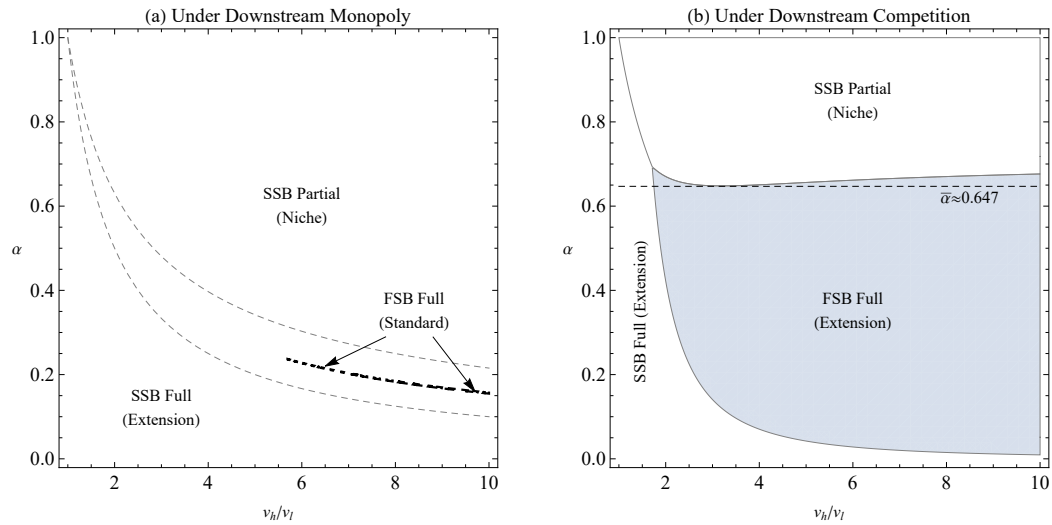


Figure 2.5: Technology Provider's Optimal Business Model in v_h/v_l and α Under Varying Downstream Competition ¹³

2.5(b). This is because FSB enables the technology provider to earn different per unit royalty payment with a single royalty rate from manufacturers where their full system prices are different. As market inequality becomes higher, M_2 's full system price also increases, leading TP to be increasingly better off under FSB.

Interestingly, other entities in the supply chain are also generally better off under FSB for increasing levels of market inequality, as FSB TP invests more in technology R&D while slowly increasing the royalty rate. In addition, there is an order of preference shift from SSB to FSB in the supply chain. Whereas TP prefers FSB even with low market inequality, M_2 prefers FSB only at high enough market inequality when M_2 can sell superior enough full systems thanks to higher quality technology ($TP-M_2$). Meanwhile, M_1 weakly prefers FSB since it can earn strictly positive profit under FSB (M_1-TP). Although consumers do not pay royalties directly, their products are negatively affected by the royalty rate under FSB. To garner more surpluses, consumers need some good technology but

¹³Parameter values are $\delta_m = 2$, $\delta_i = 3$, $c_s = 0.2$, $c_t = 0.4$, $c_f = 0.25$, $\gamma = 1$, and $v_l = 1$.

not as good as M_2 needs (*Consumer– M_2*). Social surplus, policymakers’ objective, is the aggregate of all entities’ profits and surpluses. FSB is socially preferable if the technology investment under FSB is large enough. TP ’s contribution to social surplus makes FSB socially optimal even though consumers are not better off yet (*Policymakers–Consumers*). Table 2.1 summarizes how each entity’s business model preference shifts as market inequality increases.

Table 2.1: Optimal Business Model For Each Entity In Market Inequality ¹⁴

Business Model	Market Inequality (v_h/v_l)				
	Low	→			High
SSB	TP	PM	PM	Consumer	M_2
	PM	Consumer	Consumer	Consumer	M_2
FSB	M_1	M_1	M_1	M_1	M_1
		TP	TP	TP	TP
			PM	PM	PM
				Consumer	Consumer
					M_2

Whereas TP can theoretically implement its preferred business model ignoring other firms, such a monopolistic behavior may cause various conflicts of interests. Anticipating or having such an issue, not only TP but also other entity may propose a reconciliation scheme. In the most likely conflict between TP and M_2 , if TP earns more profits by changing its business model from SSB to FSB ($\Pi_I - \pi_I$) than M_2 ’s loss ($\Pi_2 - \pi_2$), TP may arrange a lump-sum payment to M_2 and vice versa. We characterize this reconciliation scheme with a lump-sum payment in the following proposition.

¹⁴PM means Policymakers. M_1 and M_2 are the low-end and the high-end manufacturers, respectively.

Proposition 2.3. *When market inequality is low, SSB can be adopted by M_2 subsidizing TP . Otherwise, FSB can be implemented by TP subsidizing M_2 .¹⁵*

Figure 2.6 illustrates TP 's additional profit under FSB ($\Pi_I - \pi_I$) with the solid line and M_2 's additional profit under SSB ($\pi_2 - \Pi_2$) with the dashed line. If the solid line is below (above) zero, SSB (FSB) is preferable for TP . Similarly, when the dashed line is below (above) zero, FSB (SSB) is preferable for M_2 . As Table 2.1 shows, both firms prefer SSB and FSB in region (A) and (D) or low and high market inequalities, respectively. In region (B) and (C), TP prefers FSB but M_2 is better off under SSB. Since TP 's gain from FSB is larger than M_2 's gain from SSB in region (C), TP can make M_2 indifferent under FSB by giving a lump-sum payment. In region (B), M_2 may have TP adopt SSB by making a similar one time payment to make TP indifferent. The payment may be cash (Mozur and Hardy 2015) or in-kind engineering and design services (Shrout 2018). Although the actual amount of the payment is likely to be determined by many factors such as bargaining power of the different entities¹⁶, the amount will increase (e.g., the solid line in $[v_1, v_2]$) and then decrease (e.g., the dotted line in $[v_2, v_3]$) in market inequality. The approach presented in Proposition 2.3 can be extended to resolve a conflict between any entities in TISC.

Our results provides a theoretical rationale to reason technology provider's business model choices, various conflicts and regulatory moves. Proposition 2.2 shows that market inequality is a key factor for the business model choice. In practice, the ratio between the prices of a high-end and low-end full systems can be

¹⁵A sufficient condition for a special case is characterized in the proof in the Appendix.

¹⁶For instance, if M_2 has greater bargaining power, v_2 will become greater and Region (B) larger - this can be seen with a proportion parameter $\eta \in (0, 1]$ that M_2 must compensate for TP 's loss. As η decreases, M_2 's bargaining power increases. For $\eta = 1$, M_2 should pay TP 's whole loss because of SSB, i.e., the solid line in Region (B). However, for $\eta < 1$, M_2 needs to pay TP 's partial loss pushing the solid line downward with the dotted line unchanged. Thus, Region (B) is expanded and SSB will be more likely to be observed. The same logic can be applied to TP .

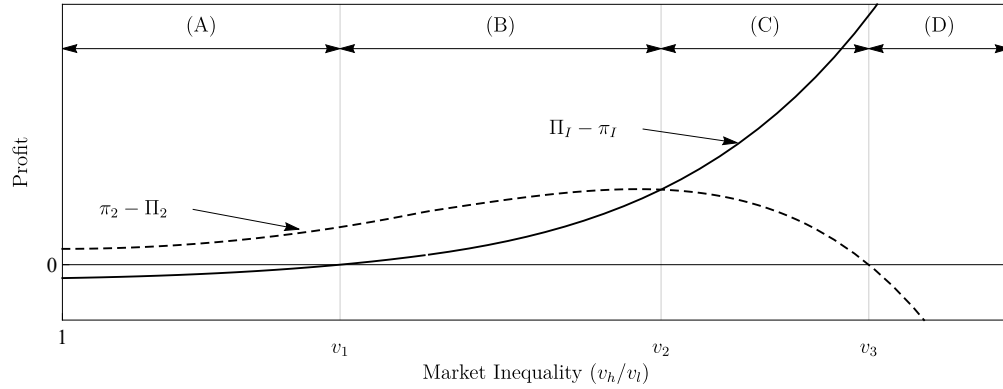


Figure 2.6: Profit Differences of TP and M_2 under FSB and SSB

a reasonable proxy for market inequality. This price ratio in PC market (2 to 4)¹⁷ tends to be smaller than the ratio in smartphone market (greater than 10, Elmer-DeWitt 2013). Being consistent to our result, technologies relevant for PC is often licensed under SSB (e.g., Random-access Memory technology of Rambus)¹⁸ but communication technologies for smartphone such as LTE are licensed under FSB. The proposition also implies that TP and M_2 are most likely to have the conflict of interests among entities in TISC (e.g., Pettersson et al. 2015; Bartz and Nellis 2017; Greenwald 2017). When it comes to regulation, policymakers across countries may prefer different business models depending on their economy structures. Recently, Qualcomm was fined in China and Korea for its FSB practice (Mozur and Hardy 2015; Lee and Nellis 2016). The smartphone industry in Korea relies more on the high-end manufacturers than China. That is, the policymakers in such an economy lean more toward to M_2 by regulating FSB. Interestingly, the decision in China may not seem consistent as FSB may be more beneficial to the economy consisting of more low-end manufacturers. Nevertheless, it is also explained by replacing

¹⁷<https://technology.ihc.com/415044/mainstream-and-value-pcs-rule-over-high-end-performance-models>

¹⁸<http://www.nasdaq.com/article/rambus-rmbs-sk-hynix-amend-patent-licensing-deal-analyst-blog-cm488913>

M_2 with policymakers in Proposition 2.3. Although the National Development and Reform Commission (NDRC) of China had accused Qualcomm of its FSB, the agency allowed the company to maintain FSB after the settlement with \$975 million fine. In the next section, we continue investigating the technology business model by accommodating another common licensing mechanism, a fixed fee.

2.4.3 Fixed Fee and Royalty Rate Licensing

We have investigated the technology provider's business model where the technology is licensed by means of royalty. A fixed fee is another major licensing mechanism. It is known to mitigate double marginalization but is lacking of demand risk sharing. When demand is certain and segmented like in our setup, a fixed fee does not have these trade-offs. To show clearer insights by adding a fixed fee, we analyze the base case supply chain with identical suppliers where the technology can be licensed via not only a royalty rate but also a fixed fee. We note that TP adopting SSB can extract all the profits of suppliers under either full or partial coverage with only a royalty rate, implying that a fixed fee is redundant under SSB. Instead, it may improve FSB TP 's profit since a fixed fee does not impose negative effects on system quality in the downstream but at the same time enables TP to extract additional profit. Hence, we focus on investigating the impact of a fixed fee on FSB.

We analyze the full coverage case and then consider the partial coverage followed by the comparison. A manufacturer i 's (M_i 's) profit with the fixed fee W is:

$$\Pi_i(\theta_i, p_i) = \underbrace{(p_i(1 - R) - c_f\theta_i^2 - c_s)}_{B_i} D_i - W,$$

where B_i is M_i 's profit before paying the fixed fee W . Then, TP 's problem is written as follows.

$$\begin{aligned} & \underset{T,R}{\text{maximize}} && \Pi_I(T,R) = -c_t T^3 + R(p_1(1-\alpha) + p_2\alpha) + 2W \\ & \text{subject to} && 0 \leq B_1, \\ & && W = \min\{B_1, B_2\}. \end{aligned}$$

The first constraint is M_1 's participation constraint. The next constraint is for the fixed fee, implying that it can be one of four amounts, i.e. $W \in \{0, B_1 < B_2, B_2 < B_1, B_1 = B_2\}$. First, if the participation constraint is binding, the fixed fee is zero and redundant for TP . Second, B_1 is likely to be W when h segment is large. In the opposite case, B_2 constrains W . The last case is when two manufacturer's profits before paying the fixed fee are equal. With the characterization of optimal decisions for each fixed fee case in Lemma B.6, we obtain the following proposition.

Proposition 2.4. *Consider a trilateral supply chain with identical suppliers and manufacturers where the technology is licensed with a fixed fee and a royalty rate.*

- (i) *SSB is still optimal at low market inequality, but FSB dominates SSB as market inequality increases for all segment sizes except the identical size ($\alpha = 1/2$) in the following order: Technology Provider (TP)–Policymakers–Consumers–High-end manufacturer (M_2).*
- (ii) *Low-end manufacturer's is better off under FSB in an interval of market inequality.*
- (iii) *The optimal royalty rate may not be increasing in market inequality.*

Proposition 2.4.(i) shows that SSB (FSB) is still optimal for all entities except M_1 when market inequality is low (high). We remind that whereas the

royalty rate in SSB is constrained by a smaller margin of manufacturers, fixed fee in FSB is limited by a smaller sales profit of manufacturers. If market inequality and α are small, both manufacturers' margins are about the same but their sales profits are much different, where SSB can perform better than FSB with fixed fee for TP 's profit. When two market sizes are equal ($\alpha = 1/2$), the sales profit difference is negligible for low market inequality, resulting in FSB's dominance as a special case. Consequently, the business model preferences of most entities are preserved with the additional licensing instrument, a fixed fee.

Proposition 2.4.(ii) reveals that M_1 strictly prefers FSB when market inequality is intermediate. It is because the fixed fee is determined by a smaller sales profit of M_1 and M_2 . We remind that M_1 earns zero regardless of business models even without a fixed fee for low market inequality. In the opposite case, M_1 's sales profit constrains the fixed fee implying that its profit under FSB is indifferent from SSB. When market inequality is intermediate, TP sets a low royalty rate to mitigate FSB's adverse impact on full system quality and captures all of M_2 's profit with a fixed fee, leading M_1 to be profitable. Indeed, Proposition 2.4.(iii) shows that the optimal royalty rate should be lowered in market inequality when it is intermediate. Now let us consider the partial coverage case. By charging a high fixed fee and zero royalty rate, FSB TP can extract as much as SSB TP can. However, FSB is more restrictive to prevent a manufacturer's deviation incentive to full coverage, since the fixed fee does not affect the manufacturer's margin directly as SSB does. Thus, SSB still outperforms FSB for the partial coverage.

In summary, the optimal royalty base and the other structural results on the comparative attractiveness of the FSB and SSB of the earlier section are not affected much by the addition of a fixed fee. While the fixed fee brings additional profits to FSB TP , we find that SSB is still optimal for TP for low market inequality and

FSB continues to become more attractive at increasing levels of market inequality.

2.5 Business Model Adaptation and Forward Integration

We now further generalize the analysis of FSB and SSB to the case when the subsystem suppliers in Tier 1 are asymmetric with cost-quality gaps. As the suppliers may earn profit, either technology providers or full system manufacturers can be motivated to integrate into subsystem production.¹⁹ We refer to each integration as *forward* and *backward integrations*, respectively. In particular, forward integration is increasingly relevant in practice as a technology provider can do so relatively easily compared to a manufacturer thanks to the provider's superior knowledge regarding the technology as the originator. In this section, we study how the forward-integrated technology provider should modify its business model and go to market approach, where the subsystem competition strategy is a new element in the business model. Backward integration is studied in the following section.

We first outline the asymmetry and describe the model setting. While the embedded technology determines the most quality of the subsystem, each subsystem may differ in quality due to exogenous factors such as understanding of technology, reputation, brand, and service (Conner 1995). We normalize the superior subsystem's quality 1 and define $\beta \in (0, 1)$ as the inferior subsystem's relative quality, letting S_2 be the superior quality supplier without loss of generality. We also define c_1 and c_2 as the manufacturing cost of each supplier with $c_1 < c_2$. For ease of exposition, we adopt the common convention of quadratic system quality

¹⁹If there are symmetric suppliers, they are engaged in Bertrand price competition and earn zero profit. The forward integration into either of a supplier does not help TP to attain more values created from the downstream.

cost ($\delta_m = 2$, e.g. Moorthy and Png 1992; Mussa and Rosen 1978; Krishnan and Zhu 2006) and linear technology externalities in users ($\gamma = 1$, e.g. Lee and Mendelson 2008; Conner 1995; Sun et al. 2004) and put a mild convex increasing technology cost assumption of $\delta_i = 3$ to avoid trivial/corner cases.^{20 21} When TP produces a subsystem, we model its subsystem as the superior one because of TP 's inherently better understanding of the technology as the originator. Facing a competing supplier (S_1) with inferior quality ($\beta < 1$), there are four competition strategies available. First, TP can behave as the monopoly despite of the competing supplier (S_1). Second, TP may deter S_1 from entering by setting a low subsystem price, which is termed as *Deter*. Next, it can share the market; in this strategy, TP sells to M_2 for h segment, and S_1 sells to M_1 for l segment. This strategy is referred to as *Share*. Lastly, it can forego the market; specifically, TP chooses not to produce subsystem at all and relies on S_1 's production, which is called as *Forego*. When α is very large, the optimal business model is to use SSB and partially cover the market by deterring the competitor to enter, which is rather straightforward. Thus, we concentrate on the case in which α is small to moderately large where the market is fully covered by either SSB or FSB.

2.5.1 Subsystem Base Business Model for the Integrated Technology Provider

Under SSB, TP can control S_1 's price via the royalty rate. Its main decision is whether to license the technology or not. If TP does not want to license, TP

²⁰In Section 2.4, we obtain a mild convexity condition between δ_m and δ_i , namely $k = \delta_i \delta_m - \delta_i - \delta_m > 0$. If $\delta_m = 2$, then $\delta_i > 2$ for $k > 0$. By assuming $\delta_i = 3$, we have the simplest model for more complex cases.

²¹Under these environments, the non-integrated TP finds FSB (SSB) generally optimal when β or market inequality are high (low). It is because the heterogeneous subsystems in quality enable TP to receive different unit royalties under not only FSB but also SSB. We refer the readers to the Appendix B.1 for the analysis and detailed discussion.

can adopt *Deter* by charging a very high royalty rate, for example $r = 1$. We note that the resulting profit is the same to the monopoly profit since there is no deterrence cost. Hence, we treat *Deter* and *Monopoly* in the same manner. Otherwise, there are two outcomes of licensing from *Share* and *Forego*. After deriving the optimal decisions for each strategy in Lemma B.7 in the Appendix, we characterize the optimal business model for the forward-integrated technology provider in the following lemma.

Lemma 2.3. *Consider a trilateral supply chain where the technology provider produces the superior subsystem under SSB. Its competition strategy shift in β for market inequality is as follows.*

$$\begin{cases} \text{Monopoly} - \text{Forego} & \text{if } v_h/v_l \leq v_h^{s1}/v_l, \\ \text{Monopoly} - \text{Share} - \text{Forego} & \text{otherwise,} \end{cases}$$

where v_h^{s1} is characterized in the Appendix. Moreover, when $v_h/v_l < 1/\sqrt{\alpha}$, the technology provider's equilibrium profit is weakly increasing in β .

Lemma 2.3 shows *TP*'s optimal competition strategy with respect to market inequality and the quality of the competing supplier (β). When *TP*'s competitive advantage is clear (low β), *Deter* is optimal and *TP*'s profit is not affected by β . In the opposite case of high β , *TP* relies on the competitor's production, i.e. *Forego*, where its profit is increasing in β . When market inequality is low or, equivalently, *l* segment is more important, *TP* maximizes its profit by providing one subsystem to the market. Hence, the optimal strategy shifts from *Monopoly* to *Forego* and *TP*'s profit is weakly increasing in β . In contrast, for high market inequality, *TP* wants to maximize quality differentiation between full systems with different subsystems if the competing subsystem's quality is intermediate. That is, *TP* shares the market

with S_1 , where TP sells to M_2 and S_1 does to M_1 . At first glance, TP 's profit may decrease in β , because it should lower its subsystem price for M_2 not to buy from S_1 . Although this reduces TP 's subsystem sales profit, the royalty profits from S_1 increases in β . Therefore, if market inequality is small enough ($v_h/v_l < 1/\sqrt{\alpha}$), the royalty profit gain is more than the sales profit loss, leading TP 's profit to increase as its competitor has better quality. The lemma implies that TP is generally better off with a stronger competitor for low market inequality. As we will see in the next subsection, TP 's profit in β becomes more nuanced under FSB.

2.5.2 Full System Base Business Model for the Integrated Technology Provider

Next, we consider the integrated technology provider under FSB. Its investment, royalty rate, and pricing decisions under FSB are more complicated because it can be optimal for TP to leave some profits to the low-end manufacturer (M_1). The optimal decisions under each strategy are characterized in Lemma B.8 in the Appendix. The complex representation of profit function under *Share* hinders us from comparing profits across the strategies. Nevertheless, we characterize sufficient conditions for strategies to be optimal.

Lemma 2.4. *Consider a trilateral supply chain where the technology provider produces the superior subsystem under FSB. Its competition strategy becomes:*

- (i) *For small enough β , Monopoly is optimal.*
- (ii) *For large enough β and low market inequality, Forego is optimal*
- (iii) *For intermediate β and low market inequality, Deter can be optimal and TP 's profit decreases in β .*

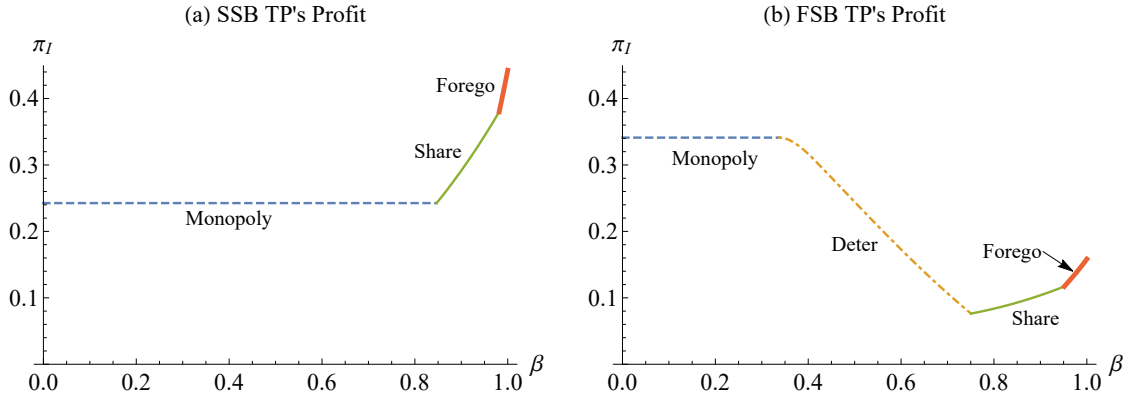


Figure 2.7: Technology Provider's Profits in β under SSB and FSB for Low Market Inequality ²²

Lemma 2.4.(i) and (ii) imply that the equilibrium competition strategy under FSB shifts similarly to that under SSB. While the same rationales under SSB can be applied to *Monopoly*, *Share*, and *Forego* under FSB, *Deter* is distinguished from *Monopoly* under FSB. We remind that *TP* does not have a direct business transaction with the subsystem competitor (S_1) under FSB. To deter S_1 's entry, *TP* must reduce its own subsystem price, where the price reduction increases in β . That is, *TP* incurs the deterrence cost, resulting in the decreasing profit in β . When *TP* cannot afford the deterrence cost, i.e. β is high enough, *TP* shares or forgoes the market. Figure 2.7 contrasts *TP*'s profit under different business models for low market inequality, where each line type represents each strategy.

Figure 2.7(a) illustrates SSB *TP*'s profit. When β is small, *TP* becomes a natural monopoly as the dotted constant line shows. For high β , *TP*'s profit is increasing in β even under *Share* since the royalty profit increase from M_1 is more than the sales profit loss from M_2 thanks to low market inequality. When β is very high, *TP* relies on S_1 for low production cost. In contrast, Figure 2.7(b) shows that although FSB *TP* suffers from deterring (dot-dashed line), it can be optimal when S_1

²²Parameters are $\alpha = 0.2, c_1 = 0.15, c_2 = 0.35, c_t = 0.5, c_f = 0.25, v_l = 1$, and $v_h = 1.8$.

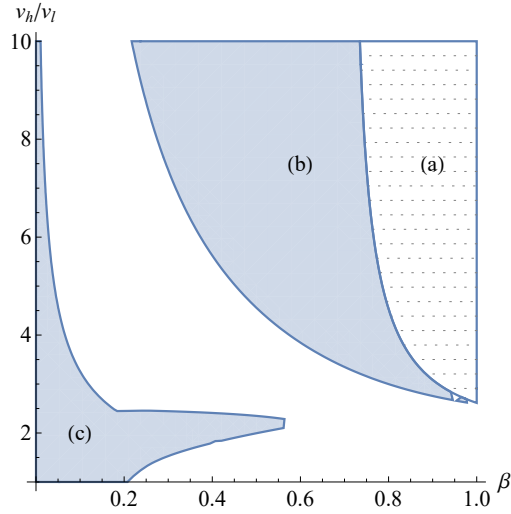


Figure 2.8: Value of Subsystem Manufacturing Integration for FSB Technology Provider ²³

is too weak to share. This reveals that for low market inequality the FSB technology provider generally prefers a weaker competitor. However, if the competitor is either intermediate or strong, TP may prefer a stronger competitor, which is a sharp contrast to SSB TP 's monotonic preference for a stronger competitor. With these results, we obtain the optimal business model for the integrated technology provider in the following proposition.

Proposition 2.5. *Consider a trilateral supply chain where the technology provider produces the superior subsystem. For low market inequality, the technology provider's optimal business model shifts from FSB to SSB in β . Otherwise, it changes from FSB, SSB, to FSB in β .*

Proposition 2.5 shows that TP 's subsystem integration increases the value of FSB substantially as the integration generates an additional revenue stream, i.e., sales revenue from manufacturers. Figure 2.8 illustrates this insight. Region

²³Parameter values are $\alpha = 0.2, c_s = 0.15, c_2 = 0.25, c_f = 0.2$, and $c_t = 0.5$. (a) is the region where TP prefers FSB without subsystem integration. (b) is the additional regions where TP prefers FSB from subsystem integration. (c) is the region where TP prefers FSB because of the two revenue streams.

(a) is where FSB is preferred by the non-integrated TP when market inequality and β are high. The integration lowers the thresholds of market inequality and β for the preference of FSB over SSB, and results in an additional FSB preferred region (b). We notice that the regions of (a) and (b) forms a convex region, which is resulted from the asymmetric subsystem quality. Since SSB also enable TP to earn different unit royalties, a higher market inequality level is required for FSB to be optimal. Thus, the trade-off found in the base model, FSB's price differentiation benefit with negative impact on downstream quality, also applies to the asymmetric suppliers even with the forward-integrated technology provider if β is reasonably high. This implies that the FSB preference order between entities shown in the base model (Proposition 2.2) still holds. Interestingly, the integrated TP finds FSB optimal in region (c) despite low market inequality, in which the non-integrated TP dominantly prefers SSB. Whereas TP can be a natural monopoly for low β regardless of the business models, only FSB TP has the additional subsystem sales revenue in addition to the royalty profit. We remind that SSB TP has only the subsystem sales since it does not license to the competing supplier in this region. In short, the additional revenue stream of FSB leads TP to prefer FSB under the forward integration for small β regardless of market inequality.

2.6 Extensions: Manufacturer Backward Integration and Competition in Technology Provision

Thus far, we have focused on a monopolistic technology provider and analyzed its business model decisions, including royalty base and forward integration

decisions with limited attention on downstream supply chain entities. While this is reasonable given the patent law-driven monopoly position enjoyed by technology providers, we now extend our analysis to consider other scenarios where technology providers face competition and a downstream full system manufacturer may be able to backward integrate and produce subsystems. We also analyze the case where such forward and backward integration efforts may entail a substantial integration cost.

2.6.1 Backward Integration

We consider the case where full system manufacturers also can produce subsystems by themselves, potentially to lower their procurement cost and increase their profits. The resulting supply chain can be either two-tier or three-tier depending on the capabilities of subsystem suppliers and full-system manufacturers. For example, when the subsystem suppliers are identical, the backward integration results in a two-tier supply chain and the question of royalty base does not arise. Even when the suppliers' qualities are asymmetric but each manufacturer integrates with each supplier, the resulting supply chain is also two-tier. A two-tier supply chain is trivial, as there is no choice of royalty base. Hence, we focus on a three-tier supply chain as a result of backward integration consisting of one TP , one supplier and two manufacturers (who produce both subsystem and full system).

The interesting case arises when manufacturers can only integrate with an inferior supplier.²⁴ It is also reasonable since to embed a technology into a subsystem properly requires not only manufacturing capability but also design capability (Wang et al. 2017). A manufacturer is hardly better at designing the

²⁴If both manufacturers can integrate with a superior supplier, they may not procure from an inferior supplier at all, resulting in a two-tier supply chain.

subsystem than the expert supplier. We show that the manufacturers may or may not be better off from the integration depending on TP 's business model in the following proposition.

Proposition 2.6. *Suppose that full system manufacturers integrate into the inferior subsystem supplier. Although both manufacturers are weakly better off from integration under FSB, the high-end manufacturer (M_2) can be worse off under SSB for high market inequality.*

Proposition 2.6 provides a managerial insight that the backward-integration should be carefully considered under SSB. The rationale is as follows. As M_2 can use an alternative subsystem at a very low cost thanks to the integration, S_2 should substantially lower its price to sell its subsystem to M_2 . However, this also reduces SSB TP 's royalty profits and technology investment. Therefore, the backward-integrated M_2 faces the trade-off between the procurement cost reduction and the downgraded technology quality. The latter dominates the former as market inequality increases. In contrast, the integration is beneficial to manufacturers under FSB since the technology provider still has the price differentiation benefit and the manufacturers earn the procurement cost reduction from backward integration.

2.6.2 Integration Cost

Thus far we have analyzed forward and backward integrations without explicitly considering integration costs. When integration is costly, it becomes more ambiguous and challenging to pursue. We specifically consider the case where TP first decides whether to integrate into S_2 (owing to its superior technical knowledge), and the manufacturers determine whether to integrate into S_1 (due to the lack of sophisticated design knowledge). In addition, we focus on more

interesting competition scenarios where β is moderate to large, since FSB with forward integration is optimal for small β due to the trivial competition (Proposition 2.5).

For low market inequality, we remind that TP adopts SSB. When β is high enough or the subsystem quality difference is small, TP simply chooses not to produce subsystem at all (*Forego* in Lemma 2.3). However, when β is moderate, TP is better off by selling the superior subsystem (*Deter* or *Share* in Lemma 2.3) and the costly forward integration into S_2 can be profitable. In all cases, the manufacturers do not backward integrate because the surplus from the integration is easily extracted under SSB.

For high market inequality, TP implements FSB. Being similar to the above, forward integration is not profitable for high β . When β or the subsystem quality difference is moderate, TP may pursue costly integration. Both manufacturers may backward integrate to lower procurement cost. However, the mechanism is different. While a low-end manufacturer directly lowers the subsystem procurement cost, a high-end manufacturer indirectly induces S_2 to lower its price.²⁵ Table 2.2 summarizes our discussion.

Table 2.2: TP’s Business Model with Forward Integration and Manufacturers’ Backward Integration with Integration Cost ²⁶

S_1 ’s Subsystem Quality (β)	Market Inequality (v_h/v_l)	
	low	high
moderate	SSB & FI	FSB & FI, B1
high	SSB	FSB, B1

²⁵Interestingly, the high-end manufacturer does not integrate into S_2 either for high β even though it can. It is because the procurement cost saving is less than the integration cost inferred by the fact that the leader of the game, TP , chooses not to integrate (Lemma B.9). As a result, S_2 is likely to remain independently in this case.

²⁶FI represents the forward integration and B1 does the backward integration into the inferior

2.6.3 Multiple Technology Providers

We now turn to the case of two technology providers, which may be substitutable or complementary to each other. We analyze the substitutable technologies followed by the complementary ones.

Suppose there are two identical technology providers that can develop substitutable technologies. To facilitate the discussion, we model that there are two identical suppliers and their production cost is not affected by the technology quality. In the symmetric equilibrium, all providers compete to get both market segments and end up with zero profit. In the more interesting asymmetric equilibrium, each TP has one segment, resulting in two three-tier local monopolistic supply chains (e.g. $TP_1 - S_1 - M_1$ vs. $TP_2 - S_2 - M_2$). According to Proposition 2.1, SSB is likely to be the optimal business model for the technology providers. With this conjecture, we proceed to discuss the complementary case before presenting the result.

In the case of complementary technologies, there are two identical technology providers (TP_1 and TP_2) providing equally important technologies (T_1 and T_2). The full system quality can be expressed as $Q = \theta T_1^{1/2} T_2^{1/2}$. When both providers adopt either FSB or SSB, the analysis with the single technology provider in Section 2.4.2 can be easily applied and the managerial insight remains valid. That is, when market inequality is high (low) enough, FSB (SSB) is the equilibrium business model. Nevertheless, for intermediate market inequality, it may be optimal that one TP implements FSB but the other TP adopts SSB. Thus, various combinations of business models can be observed in equilibrium. The following proposition compares the optimal business models under multiple technology providers with different natures of technologies.

supplier.

Proposition 2.7. *With two technology providers making business model choices between SSB and FSB (and conditional on supply chain cost being low enough compared to market inequality as characterized in the Appendix B.2),*

(i) For substitutable technologies, the optimal business models are (SSB, SSB).

(ii) For complementary technologies, the optimal business model shifts from (SSB, SSB) to (FSB, FSB) as market inequality increases.

Proposition 2.7.(i) states the case for the substitutable technologies. Each *TP* establishes a monopolistic three-tier supply chain, where FSB's price differentiation benefit is limited. In contrast, Proposition 2.7.(ii) extends our results to the complementary technology case and may explain why complementary LTE wireless technology providers such as Qualcomm and Ericsson adopt FSB for their business model.

2.7 Managerial Insights and Implications

Upstream technologies play an increasingly important role in modern supply chains, and business model decisions can be vital to the smooth functioning of the focal supply chain. While technology licensing issues have been studied in the context of a single firm, a complex supply chain structure raises several new challenges for technology providers (*TPs*). First, there are multiple royalty bases for licensing with different implications for consumer welfare and firm performance. The debate on what the royalty base should be has swirled worldwide across firms, non-profit expert groups, and even policymakers. In addition, growing *TPs* can forward integrate and produce technology subsystems with the emergence of capable OEMs. These developments offer a rich set of application-driven questions studied in this paper.

The contributions of this paper are threefold. First, to our best knowledge, this paper is the first work that formalizes a technology provider's royalty base business models, SSB and FSB, in a three-tier supply chain. FSB offers *TP* the opportunity to achieve greater product and price differentiation and would lead to more investment in technology R&D. At the same time, it discourages the downstream firms' full system quality investment – trade-offs which are core to the choice of business models. Second, we are able to formally address a real issue confronting the industry in general and technology providers and policymakers in particular; our analysis provides the optimal business model for each entity in TISC under varying degrees of competition and market inequality. A supply chain aligning business model is viable at extreme levels of market inequality - SSB at low market inequality and FSB at high market inequality are preferred for all supply chain entities. When the market inequality is at intermediate levels, we expect to see FSB when *TP* are more powerful and SSB when high-end manufacturers are more powerful. Third, we characterize a unified business model for the integrated *TP* including decisions from technology development and licensing to subsystem manufacturing under competition. For high market inequality, *TP* is generally better off by having an inferior competitor in both business models, which is aligned with the previous findings (Conner 1995; Sun et al. 2004). In contrast, for low market inequality, *TP* may be worse off depending on the competitor's quality and the business model. To our surprise, the FSB technology provider can be more profitable with a high quality competitor than with an intermediate quality competitor. This implies that *TP* may be willing to enhance the competitor's quality and enriches the previous managerial insights regarding competition in technology supply chain. We also examine other interesting scenarios of manufacturer's backward integration and multiple technology providers.

Our model and analysis offers some predictions that can be empirically examined. First, a sub-system based business model aligns with low levels of market inequality and full system based business model is preferred at high levels of market inequality. At intermediate levels of market inequality, we can expect to see disagreements to surface among supply chain players, unless one of the entities plays a dominant role. When the technology is relatively new and highly capable driving the supply chain and creating powerful technology providers, a full system based approach is likely to be the norm. However, a sub system based business model may be favored when the higher end downstream manufacturers control the supply chain. To achieve agreement and alignment among equal partners, technology providers may resort to transfer payment (cash or in-kind services) to downstream manufacturers that would make them choose the full system business model.

This paper offers a number of actionable insights for technology providers, policymakers, and downstream manufacturers. The technology provider should try to shift its business model from SSB to FSB, as market inequality increases. Moreover, *TP* adopting FSB should more seriously consider the forward integration into subsystem or achieve agreement with downstream parties with transfer payment. Policymakers/social planners who desire to promote technology investment (as in countries that want to maintain a technology lead) should encourage full-system base approach, while progressive economies that operate under lower market inequality (as in Scandinavian countries) may promote the subsystem based approach. Finally, downstream manufacturers with advanced capabilities should strive for the subsystem-based approach (with negotiations or transfer payments) to maximize their own profitability. These results speak directly to the structure and functioning of global technology-intensive supply chains.

Chapter 2, in full, has been submitted as a manuscript to the journal Management Science and was co-authored by Junghee Lee, Vish Krishnan and Hyoduk Shin. The dissertation author was the primary investigator and author of this paper.

Chapter 3

Does Competition Help Drug Shortage Recovery?

There are ongoing shortages of generic drugs in the U.S., which critically threaten public healthcare. As the drug manufacturing industry becomes more consolidated, a manufacturing issue in a single firm can lead to a nationwide shortage. Furthermore, such manufacturing issue driven shortages are more than 70% of all shortages. While the FDA and patients advocate that increasing competition may mitigate the drug shortage, manufacturing firms seriously challenge the idea. Using historical drug shortage data recovery and competition level, we reconcile both perspectives and provide better insights.

3.1 Introduction

The U.S. has been experiencing persistent drug shortages since early 2000, posing a significant threat to public health. Some shortages due to natural disaster or sudden increased demand are somewhat unavoidable. Unfortunately, more than

70% of shortages is driven by the manufacturing issues such as contamination in manufacturing lines or shutdowns of manufacturing facilities (U.S. Government Accountability Office 2014). Moreover, American Society of Health-System Pharmacists (ASHP) reports that the number of new drug shortages had rapidly increased from 2006 to 2010 (Figure 3.1). To mitigate the impacts of increasing drug shortages, the U.S. government issued Executive Order 13588 – Reducing Prescription Drug Shortages on October 31, 2011, which was enacted in the Food and Drug Administration Safety and Innovation Act (FDASIA) on July 9, 2012.

These interventions endowed the Food and Drug Administration (FDA) with two main authorities (U.S. Food and Drug Administration 2013). First, all the drug manufacturers are required to notify the FDA of any interruption in manufacturing. This mandatory reporting enables the FDA to prevent or mitigate shortages. In addition, the FDA publicizes this information so that health care providers and patients can be better prepared. Second, the FDA can expedite reviews of drug approval applications and manufacturing facility inspections that could mitigate shortages. The underlying principles are rather straightforward; earlier notification leads to better preparation and unmet demand is more likely to be satisfied by increasing competition with more drug manufacturers. Figure 3.1 illustrates that the number of new drug shortages had decreased from 2011 to 2013, implying that the interventions may be effective. That being said, the drug shortage is persistent and many doctors are still forced to ration some critical drugs (Fink 2016).

We conjecture that the interventions' limited effect may be due to unintended or underestimated consequences. When a drug shortage occurs because of a manufacturing issue at one firm, the shortage can be mostly resolved by the firm's solving the issue internally, the competitors' increasing supply, or the new entrants¹.

¹Temporary importation is also an option but rarely adopted since foreign manufacturing facilities are not often FDA-approved. For drug shortages occurred in 2010 and 2011, only 5% of

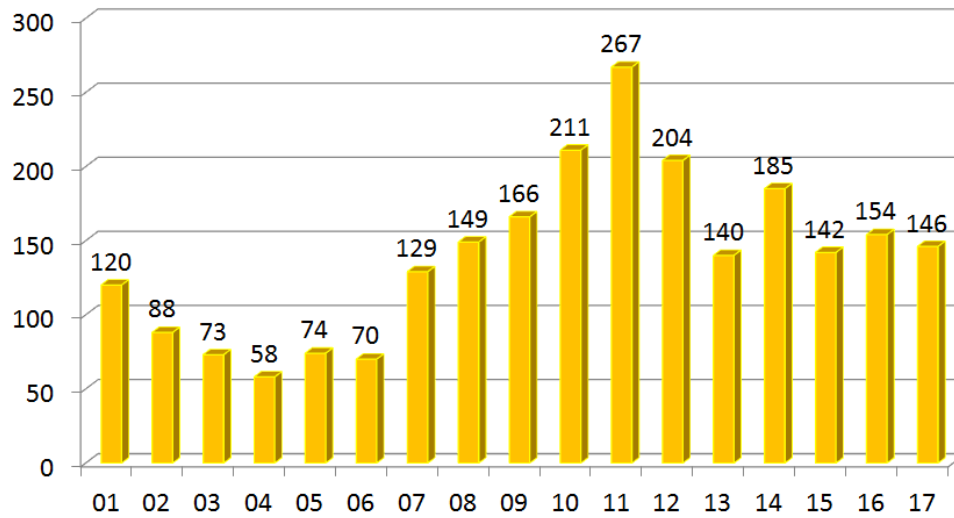


Figure 3.1: New Shortages by Year

The FDA’s approach to increase competition has two opposite forces regarding drug shortages. While it encourages the latter two options, it discourages the first option since the profit of the incumbent facing the manufacturing problem will be reduced (Scott Morton 1999). Thus, the effectiveness of increasing competition on mitigating the drug shortage duration is contingent on which effect is stronger.

In this paper, we pose the following questions: (1) Does competition help drug shortage recovery universally? (2) If not, when does competition mitigate or aggravate drug shortage recovery? Using a unique drug shortage history data between 2010 and 2015, we find that the competition effect on drug shortage recovery may not be monotonic contrary to popular belief. Specifically, the non-monotonic effect appears for a more profitable drug and for the competition level change from a monopoly to a duopoly. When a drug is less profitable, our result shows a monotonic competition effect. Namely, the drug shortage recovery time is decreasing as the competition level increases. To address endogeneity concerns regarding the competition level, we employ coarsened exact matching (CEM), drugs were approved for importation (U.S. Food and Drug Administration 2011)

which provides a quasi-experimental setting. Furthermore, we provide a theory that plausibly explains the empirical results based on analytical models.

Our contribution are three-fold. To our best knowledge, this is the first paper that clearly shows the empirical relationship between a firm's recovery time and competition. While there is ample theoretical literature about supply chain recovery, few papers provide empirical results mostly due to the difficulty of observing a firm's recovery (Jain et al. 2016). By exploiting direct observations of drug recovery times in the dataset, we provide unequivocal empirical results. Next, we develop a new theory that competition influences not only firm's profitability but also recovery complexity. While it is well understood that a firm's profit decreases in competition, it is often neglected that the firm's volume also decreases in competition. The latter is important in the context of manufacturing system recovery since it is likely to be easier to fix a smaller scale manufacturing line than a larger one. Last, our results generate an actionable recommendation to policymakers based on the subtle effect of competition on drug recovery time. When competition already exists (e.g., a duopoly or an oligopoly), then increasing competition further will mitigate the drug shortage. However, if there is no competition, policymakers strive to increase the competition level high enough (e.g., from a monopoly to an oligopoly). Otherwise, a monopoly may be better than a duopoly for some profitable drugs.

3.2 Literature Review

The main research question of this paper is to examine the empirical relationship between competition and a firm's recovery time under the context of recent drug shortages. This paper is multi-disciplinary by nature across operations management, health, and economics.

The drug manufacturing industry has various unique features. Because drugs are medically necessary product, the FDA plays a critical role in preventing and mitigating drug shortages. While the agency identified the issue in early 2000 (Jensen et al. 2002), the drug shortages started increasing in 2006 and peaked in 2011 (Fox et al. 2014). More than 70% of shortages is driven by the manufacturing issues such as contamination in manufacturing lines or shutdowns of manufacturing facilities (U.S. Government Accountability Office 2014). Such shortages can be avoided by investing in spare capacity or preventive facility maintenance. However, if the profit margin is low, firms may be reluctant to expend their resources. Yurukoglu et al. (2017) argues that the steady drug shortage increase is due to an unintended consequence of the reimbursement policy change in Medicare under the Medicare Modernization Act in 2003. They assert that reduced margin under the new regulation leads manufacturers to invest less in reliability and quality in their manufacturing facilities. However, reversing the implemented policy is a extremely sensitive political agenda. The U.S. government issued Executive Order 13588 in 2011 followed by the Food and Drug Administration Safety and Innovation Act (FDASIA) in 2012 to mitigate the issue. These interventions officially allow the FDA to expedite the required review processes of drugs in short supply. The drug shortages has been somewhat decreased recently but still persistent (Fink 2016), implying limited effectiveness of the interventions.

Increasing competition in the drug manufacturing industry may bring various effects. On the one hand, it is generally beneficial for health care providers and patients. Competitive pressure induces manufacturers to build more spare capacity (Kim and Scott Morton 2015) and reduces the drug price (Reiffen and Ward 2005; Berndt et al. 2007). Upon the occurrence of a drug shortage, more firms can provide the drug instead of the disrupted firm and resolve the shortage sooner. On

the other hand, intense competition may reduce profit (Scott Morton 1999) and incentive to recover from it (Jain et al. 2016). Therefore, increasing competition may prolong the recovery process.

In the medical drug context, there is a strand of empirical literature examining the effect of competition on brand drug price (Frank and Salkever 1997; Bhattacharya and Vogt 2003; Wiggins and Maness 2004), generic drug price (Reiffen and Ward 2005; Berndt et al. 2007), and firm's market share (Grabowski and Vernon 1992). However, few papers explore the relationship between competition and drug shortages. One exception is Berndt et al. (2017), which provides a descriptive analysis of drug shortages during 2004 and 2016.

In operations management, there are many works that study recovery from disruption under various competitive settings. That being said, most works are aimed to provide generally applicable results by abstracting some unique feature of the drug manufacturing industry (Iyer et al. 2005; Hu et al. 2013; Kim and Tomlin 2013). Recently, Kim and Scott Morton (2015) study how the different price regulations affect the capacity decisions of two competing firms and Jia and Zhao (2017) propose better procurement contracts to mitigate the drug shortages. However, they do not explicitly consider the varying degree of competition. Our paper complements the previous theoretical works by providing empirically validated results. Jain et al. (2016) may be the closest one to our work in that they also study the supply chain recovery time with respect to sourcing strategies such as supplier diversification and supplier concentration. They empirically show that the supplier concentration is associated with faster recovery from supply interruptions. Because they cannot observe the supply chain recovery directly, they develop a supply chain recovery estimator, which is inherently less accurate. This paper elucidates the empirical literature in operations management regarding the relationship between

competition and a firm's recovery. We assert that our result is clearer and more accurate due to the direct observation of recovery.

3.3 Hypothesis Development

When a supply chain manages to satisfy demand with little excess capacity, even one supplier's manufacturing failures may lead to a large scale supply-demand mismatch, namely shortage (Jensen and Rappaport 2010; Woodcock and Wosinska 2013). The shortage can be resolved by either the competitors' capacity expansions or the disrupted firm's recovery, which often requires capital investment and takes non-ignorable time. It may seem natural to propose increasing competition as a shortage mitigation strategy for health care providers and patients. At the same time, it imposes adverse impacts on drug manufacturers by reducing their margins.

Consider a firm that cannot provide a drug to the market because of manufacturing disruption. The recovery from the disruption does not happen by itself without any resources. The disrupted firm should spend resources on the recovery process. How much to invest is evidently one of the most critical questions as it is closely related to the recovery completion time. Although the actual completion time is uncertain, it is likely the case that more investment such as overtime and using more efficient equipment would expedite the recovery process, which has been commonly adopted in the literature (Iyer et al. 2005; Kim and Tomlin 2013). Intuitively, a disrupted firm is likely to expend less resources as its expected profit from the recovery decreases. It is well established that a firm's profit decreases in the competition level. Increasing competition often leads to non-increasing margin and quantity sold, resulting in decreasing profit (Scott Morton 1999). Specifically, Reiffen and Ward (2005) estimate that the average wholesale

price decreases in the competition level, using drug price data between the late 1980s and the early 1990s. The FDA also confirms a similar pattern with more recent data between 1999 and 2004. By relating a firm's decreasing profit with its investment decision in recovery process, we establish the following hypothesis.

Hypothesis 3.1. *A firm's recovery time will increase in the competition intensity.*

When firms are competing with homogeneous goods, one firm may be enough to motivate fierce price competition (e.g., Bertrand competition). However, Bresnahan and Reiss (1991) assert that the effect of competition is more gradual than a theory predicts. By studying six different industries, they show that the marginal competition effect decreases in the number of entering firms implying convex decreasing profit. More recent studies estimate that the average drug price decreases in a convex manner as the number of entrants increases (Reiffen and Ward 2005; Wiggins and Maness 2004). Thus, a competition level change from a monopoly to a duopoly is likely to reduce a firm's profit most and to increase a firm's recovery time most, resulting in the following hypothesis.

Hypothesis 3.2. *The increase in a firm's recovery time will be highest when the competition level changes from a monopoly to a duopoly.*

The recovery time change by the competition level may also differ across the profitability of drugs. While it is evident that a high profit drug's recovery time is likely to be shorter than a low profit drug's, the marginal effect of competition on recovery time is less straightforward. Suppose there is a single firm selling a brand drug. We call this firm as the brand monopoly. When there is a generic entrant, the entrant often captures a relatively large market share soon (Grabowski and Vernon 1992) and the brand monopoly's profit may decrease substantially. Now, consider a single firm selling a generic drug. To distinguish this firm with the brand

monopoly, we call it as the generic monopoly. Since a brand drug is known to be more profitable, the generic monopoly's profit is likely to be lower than that of the brand monopoly (Wiggins and Maness 2004). Upon the entrance of another generic firm, the generic monopoly's profit would also decrease. Aronsson et al. (2001) shows that the higher the price of the original product relative to the average price of the generic substitutes, the larger the decrease of market share of the original product. Therefore, the profit decrease in the generic monopoly is likely to be less than that of the brand monopoly. This leads to the next hypothesis.

Hypothesis 3.3. *While a brand drug's recovery time is shorter than a generic drug's recovery time, the recovery time increase due to the competition level change is more salient in a brand drug.*

3.4 Empirical Evidence on the Link Between Competition and Recovery Time

In this section, we explain four distinct data sets followed by the empirical results. The recovery time exhibits substantial heterogeneity. Some of this variation in a monopoly and a duopoly is in line with our hypothesis about the negative effect of competition on recovery time. However, our result also shows the opposite effect for a oligopoly.

3.4.1 Data

Four distinct data sources are used to construct our data set. We first describe each data source and then explain how we construct and define the variables for empirical testing.

The most important data is about the history of each drug shortage. There are two institutions that track and provide drug shortage information. One is the U.S. Food and Drug Administration (FDA). While the agency provides the current status of each shortage via its website², the historical data is not accessible. For this reason, many researchers have relied on the drug shortage data from University of Utah Drug Information Service (UUDIS) (e.g., Woodcock and Wosinska 2013; Fox et al. 2014; U.S. Government Accountability Office 2014; Yurukoglu et al. 2017). We obtained the drug shortage and recovery history data from UUDIS between 2010 and 2015.

The next data set used is the FDA's Orange Book (Approved Drug Products with Therapeutic Equivalence Evaluations) for route of administration and application number. While there are various routes, injectable drugs require more sophisticated manufacturing processes (Jensen and Rappaport 2010; Kaiser 2011). Since the manufacturing process complexity is likely to be related to the recovery process complexity, we conjecture that route of administration has an implication on the recovery process. The application number is a combination of the application type and a serial number. By looking at the application type, we can distinguish whether a drug was approved as either an original drug or a generic one. As the profitability of a drug is not directly observed, the application type is used as a proxy for profitability³. The other two sources are EvaluatePharm for the therapeutic categories of drugs and Compustat for manufacturers' financial information.

The raw data consists of about 30,000 MS-word document files for 733 drug shortages between 2001 and 2016. We limit our analysis to the resolved drug shortages between 2010 and 2015 for two reasons. First, the documents

²<https://www.fda.gov/Drugs/DrugSafety/DrugShortages/default.htm>

³There are commercial databases tracking the volume and the revenue of drugs. These information can be useful to estimate the average price of drugs. Nonetheless, cost is necessary to estimate the profit, which is not revealed.

Table 3.1: Dependent and Independent Variable Descriptions

Variable	Description
<i>diff</i>	days to recovery
<i>CompNum</i>	The number of competitors
<i>CompType</i>	The type of competition depending on the number of competitors
<i>year</i>	Year when a shortage occurred
<i>IsInjection</i>	1 if a drug is injectable. 0 otherwise.
<i>IsBrand</i>	1 if a drug is sold under a brand name. 0 otherwise.
<i>IsPublic</i>	1 if a manufacturer is a public firm. 0 otherwise.

created before 2010 are lacking of important information such as NDC and available products, which hinders us to track the drug shortage history and construct the competition type. Second, we can also avoid censoring problems. We match the remaining drug shortages with other three data sources. This leaves us with a final data set of 367 drugs and 2815 NDCs. We provide a list of variables and their descriptions in Table 3.1 and summary statistics in Table 3.2.

While most of variables in Table 3.1 are directly retrieved from the data sources, *CompType* was constructed by the authors to deliver clear insights. The main focus of the paper is to investigate the effect of competition on the drug shortage recovery time. Although the number of competitors (*CompNum*) can be generally regarded as the competition intensity, using *CompNum* itself is less meaningful for two reasons. First, it is theoretically well understood how the effects of a monopoly and a duopoly on the firm's recovery from disruption differ (Kim and Tomlin 2013; Kim and Scott Morton 2015). However, the effects of different level of oligopolies are much less clearer. In an empirical context, idiosyncratic factors of 10 manufacturers may explain most heterogeneities in the dependent variable. Second, the idea of increasing competition was motivated by drugs with fewer manufacturers such as a monopoly and a duopoly. Thus, comparing the effects of monopoly and duopoly on drug recovery is more relevant in both academia and practice. To achieve our object without sacrificing the data, we created a

Table 3.2: Descriptive Statistics

Statistic	N	Mean	St. Dev.	Min	Max
<i>diff</i>	5,504	192.351	233.916	0	1,869
<i>CompNum</i>	5,504	3.701	2.917	0	15
<i>year</i>	5,504	2,012.706	1.492	2,010	2,015
<i>IsInjection</i>	5,504	0.729	0.445	0	1
<i>IsBrand</i>	5,504	0.343	0.475	0	1
<i>IsPublic</i>	5,504	0.776	0.417	0	1

new variable *CompType* by aggregating *CompNum*. *Monopoly* (*Duopoly*) indicates the case where *CompNum* is equal to 0 (1). *Oligo1* means that there are 2 to 4 competitors. *Oligo2* is defined when there are more than 4 competitors.

3.4.2 Empirical Result

We have a scalar dependent variable y_i , days-to-recovery of a drug shortage i , and a vector of covariates \mathbf{x}_i that contains the number of competitors, drug's clinical characteristics, and manufacturer's business characteristics⁴. To accommodate the non-negativity of the dependent variable, we model it as

$$y_i = \exp\{\mathbf{x}_i' \boldsymbol{\beta}\} \times \epsilon_i, \quad (3.1)$$

where $\boldsymbol{\beta}$ is a vector of the coefficients of covariates \mathbf{x}_i . The link function $\exp(\cdot)$ guarantees non-negativity of the dependent variable (days). By taking the logarithm, the model can be easily analyzed in the linear regression framework. We regress \logdiff ($\triangleq \log(y_i)$) on the competition type by adding different control variables and present the results in Table 3.3.

⁴One remark is that we does not specify the time index t for a drug shortage even though our observations are collected over the past several years. This might be a strong assumption if there are many drug shortages repeatedly occurred systematically. Our data shows that it is rather innocuous because more than 91% of shortages happened only once. The most frequent repeated shortage is three times but its proportion is less than 1%.

Table 3.3: Empirical Results

	<i>Dependent variable:</i>			
	log(days to recover)			
	(1)	(2)	(3)	(4)
Duopoly	0.425*** (0.070)	0.241*** (0.059)	0.363*** (0.074)	0.428*** (0.080)
Oligo1	0.037 (0.058)	0.063 (0.053)	0.107* (0.064)	0.156** (0.072)
Oligo2	-0.317*** (0.058)	-0.006 (0.058)	0.244*** (0.091)	0.138 (0.099)
Duopoly:Generic			-0.364*** (0.131)	-0.442*** (0.136)
Oligo1:Generic			-0.228* (0.118)	-0.247* (0.126)
Oligo2:Generic			-0.480*** (0.134)	-0.386*** (0.143)
Generic		0.092*** (0.033)	0.372*** (0.112)	0.357*** (0.118)
IsInjection		0.019 (0.035)	0.010 (0.035)	-0.104* (0.062)
Year	No	Yes	Yes	Yes
Therapeutic Category	No	Yes	Yes	Yes
Firm Control	No	Yes	Yes	Yes
Firm fixed effect	No	No	No	Yes
Observations	5,504	5,504	5,504	5,504
R ²	0.040	0.372	0.374	0.446

Note: *p<0.1; **p<0.05; ***p<0.01

Model (1) is the base model where the competition type is the only independent variable. We note that the coefficient of *Duopoly* is positive and significant. This implies that the recovery time under duopoly is 53% ($= \exp(0.425) - 1$) longer than that under a monopoly keeping all else equal. This is plausible to the economic principle that firm's profit decreases in competition, leading to longer recovery time in competition. In sharp contrast to this expectation, the coefficient of *Oligo1* is not significantly different from that of *Monopoly* but that of *Oligo2* is significantly less than that of *Monopoly*. This result suggests that the effect of competition on the drug shortage recovery time is non-monotonic. Specifically, for competition

to mitigate the drug shortage duration, the competition should be intense enough (e.g., *Oligo2*). Otherwise, less intensive competition such as a duopoly may prolong the drug shortage.

We test this non-monotonic effect by adding more control variables in Model (2). We include three indicator variables such as whether a drug is sold under a brand name, whether a drug is injectable, and whether a manufacturer is a public firm. In addition, *Year* when a shortage occurred and *Therapeutic Category* (e.g., Cardiovascular and Oncology) are added to control unobserved year specific heterogeneities and drug's clinical traits based on its target therapeutic area, respectively. As the effect sizes of the competition type generally become smaller, their managerial implications remain unchanged, rejecting Hypothesis 1. For Hypothesis 2, we compare the coefficient change in the competition level. As our base competition level is *Monopoly*, the coefficient of *Duopoly* is the difference due to the change from *Monopoly* to *Duopoly*, i.e., $0.246=0.246-0$. Similarly, the difference due to the change from *Duopoly* to *Oligo1* can be computed by subtracting the coefficient of *Duopoly* from that of *Oligo1*. Because the coefficient of *Oligo1* is not significant, comparing the difference $0.185 (=0.246-0.061)$ from *Duopoly* to *Oligo1* to that from *Monopoly* to *Duopoly* (0.246) is less meaningful. So is the change from *Oligo1* to *Oligo2*. However, the absolute difference is decreasing as the competition intensity increases in favor of Hypothesis 2. Interestingly, this result remains unchanged and becomes significant in Model (3) as we introduce more controls. The positive coefficient of *Generic* confirms our intuition that a less profitable drug is recovered later. The effect of manufacturing complexity (*Injectable*) on the recovery time are not significant but directionally in line with our intuition.

In Model (3), we introduce an interaction between the competition type

and whether a drug is sold under a brand name to test that the competition effect differs across profitability. All the coefficients of the interaction terms are negative as we conjecture in Hypothesis 3. To our surprise, the interaction effect reveals an unexpected nuanced result. The effect of competition on the recovery time differs across profitability. For a profitable drug (not *Generic*), the competition leads to an overall non-monotonic recovery pattern similar to Model (2) but turns out to prolong the recovery time compared to *Monopoly*. In sharp contrast, for a less profitable drug (*Generic*), the competition results in not only a monotonic pattern but also the shorter recovery time. This result is also robust in Model (4) after controlling for firm fixed effects. Our analysis generates an interesting insight. Increasing competition may not be a panacea for expediting recovery of all drugs. When policymakers strive to influence the competition level, they should carefully consider the profitability of products.

3.5 Theoretical Model: n -firm Recovery Competition

We have so far discussed our empirical findings to validate our hypotheses based on the existing theories. In this section, we provide a theoretical model to understand our empirical findings. Suppose that Firm i sells a drug with $n - 1$ competing firms. Let $P(n)$ denote i 's profit per unit time when it operates normally. We assume that $P(n)$ is decreasing in n (Scott Morton 1999). If a manufacturing disruption occurs at i , then the firm cannot produce any drug and earns nothing. The disruption can be recovered through costly recovery effort. It is reasonable to assume that more effort is likely to shorten the recovery time (Iyer et al. 2005; Kim and Tomlin 2013). We use t_i for a random recovery time of which probability

density function is $f(\cdot|\lambda_i)$, where λ_i is recovery effort. Specifically, we assume that higher effort results in shorter recovery time on average, i.e. $E[t_i|\lambda_1] < E[t_i|\lambda_2]$ for $\lambda_1 > \lambda_2$. During i 's disruption period, one of $n - 1$ competitors can steal i 's market share via capacity expansion. Similar to the recovery time, the capacity expansion time is also random and can be expedited on average by investing more. If i recovers before capacity expansion of $n - 1$ firms, i can preserve its market share and earns $P(n)$ upon recovery. Otherwise, i loses the market and earns nothing. Thus, i must decide how much to invest in recovery effort considering its effect on the recovery time and strategic behaviors of its competitors.

We use subscript i and $-i$ to denote Firm i and firms other than i . For example, λ_i is i 's recovery investment and λ_{-i} is a vector of $n - 1$ firms' capacity investments. For the concise expression, we define $t_c(n - 1) = \min\{t_{-i}\}$ as the earliest capacity expansion time of $n - 1$ competitors. Then, Firm i 's problem can be formulated as follows.

$$\max_{\lambda_i} \pi_i(\lambda_i|\lambda_{-i}) = \int_0^\infty \int_0^{t_c(n-1)} \int_{t_i}^\infty P(n)e^{-rt} dt f(t_i|\lambda_i) dt_i f(t_c(n-1)|\lambda_{-i}) dt_c(n-1) - k(n)\lambda_i, \quad (3.2)$$

where r is the interest rate and $k(n)$ is a recovery cost coefficient. We notice that the recovery cost is a function of n because the recovery complexity is affected by the manufacturing scale, which is determined by n . Nevertheless, we do not impose any functional assumptions. After deriving the result under a most general set up, we discuss how the result changes depending on functional assumptions on $k(n)$.

To facilitate analysis, we assume that the recovery and capacity expansion times follows exponential distribution (Kim and Tomlin 2013) and the cost coefficient

of recovery and capacity expansion are the same⁵. We derive the optimal recovery investment for a firm competing with $n - 1$ competitors in the following proposition.

Proposition 3.1. *When a manufacturing disruption occurs at Firm i competing with $n - 1$ competitors for $n \geq 2$, i 's optimal recovery investment is*

$$\lambda_i^*(n) = \frac{(n-1)P(n) + \sqrt{(n-1)^2P(n)^2 + 4k(n)nP(n)r^2}}{2k(n)rn^2} - r.$$

We note that the coefficients of $P(n)$ in λ_i^* are positive, implying monotonically decreasing $\lambda_i^*(n)$ or the monotonically increasing recovery time in $P(n)$. If $k(n)$ is invariant, the competing firm's optimal investment is decreasing in the number of competitors.

Next, we consider the monopoly's case. As the monopoly does not have any competitor, its problem can be reduced by replacing $t_c(0) = \infty$ in (3.2), resulting in the simple optimal decision $\lambda_i^*(1) = \sqrt{\frac{P(1)}{k(1)}} - r$. Now we can compare the recovery times under varying competition levels. In contrast to a monopoly and a duopoly, there are numerous cases in oligopolies. As our empirical result is directional, we focus on a oligopoly with three firms. To ensure a firm's entry, we let $P(1) = k(1)r^2P$, where $P > 1$. By comparing the optimal investments under different scenarios, we obtain the following proposition.

Proposition 3.2. *Let $P(1) = k(1)r^2P$ and $P(n) = P(1)\theta_{1n}$ for $P > 1$. Define T_n as the expected recovery time under n firm competition. Then, there exists $\bar{\theta}_{nm}$ such that $T_n \leq T_m$ for $\theta \leq \bar{\theta}_{nm}$ and $T_n > T_m$ for $\theta > \bar{\theta}_{nm}$.*

The proposition implies that if a firm's profit decreases more than a threshold, its investment becomes smaller resulting in the longer recovery time. While the

⁵Our model can directly accommodate asymmetric cost parameters. However, this does not provide additional insights.

intuition is rather clear, the result allows us to explore the profit and the recovery complexity conditions that reproduce our empirical findings. Let us first focus on the profit condition by assuming $k(n) = k$.

Corollary 3.1. *Suppose $k(n)$ is invariant in n . If $\theta_{12} < \frac{(1-2\sqrt{P})^2}{P^{3/2}}$ and $\theta_{13} > \frac{(2-3\sqrt{P})^2}{P(-1+2\sqrt{P})}$, then T_n increases then decreases in n . However, $3P(3) > 2P(2)$.*

When the recovery complexity is constant in manufacturing scale, certain profit decreases due to competition can reproduce our non-monotonic empirical result. That said, such profit conditions imply that the total industry profit under the oligopoly ($3P(3)$) is greater than that under the duopoly ($2P(2)$), which is implausible to the standard economic result of decreasing $n \cdot P(n)$. Thus, the corollary deduces that $k(n)$ is indeed a function of n . Moreover, it should be decreasing in n considering decreasing $n \cdot P(n)$. The assumption of decreasing recovery complexity in competition is reasonable. Increasing competition naturally reduces not only one firm's market share but also its manufacturing scale. It is conceivable that fixing an issue in a smaller scale is easier than in a larger scale. The non-monotonic recovery time may be due to varying recovery complexities in addition to varying profit across each competition intensity. As we are lacking of a proxy of such complexity, we are not able to test our conjecture. That being said, we assert in the following section that our result is robust under a more sophisticated test and alternative explanations cannot explain our non-monotonicity.

3.6 Discussion

We have tested our hypotheses and developed a theoretical model that can plausibly reproduce the non-monotonic result. In this section, we first verify our result with a more robust methodology to endogeneity, coarsened exact matching.

Then, we discuss alternative explanations.

3.6.1 Robustness Check

Our main independent variable is the competition type. As the variable was not randomly assigned, our result is exposed to endogeneity bias. There are two main causes for endogeneity; self-selection and omitted variables. While a firm can determine whether to produce a drug that affects competition, self-selection is not likely to bias the result. Typically, a firm can produce a drug long after it decided to do so because of the FDA's unpredictable review process that may often take a couple of years. Moreover, while the firm may observe the current number of competitors in the market, it does not know how many firms are being reviewed by the FDA for entry. As a result, self-selection has limited impact on the current competition type. That being said, we do recognize that omitted variable bias is a concern. For example, a drug's profitability may influence the firm's entry decision and recovery decision. Historical price information of drugs would be useful to control profitability, if the observation interval is granular enough and cost is assumed to be similar. However, we are lacking of price data.

To test robustness of the results with the current data set, we utilize coarsened exact matching (CEM). In general, matching is a nonparametric method to balance the treated and the control groups. Among various matching techniques, CEM utilizes the researcher's ex-ante knowledge to control potential confounding factors. For example, profitability can be a confounding factor in our empirical analysis. Although we cannot directly observe the information, it is reasonable to assume that whether a drug is sold under a brand name, a drug's therapeutic category, whether a firm is public, and sales period (year) influence a drug's profitability other than the competition type. Because our observations are not

Table 3.4: Regression and CEM Results

	<i>Dependent variable:</i>			
	log(days to recover)			
	Model 1	Model 1 (CEM)	Model 2	Model 2 (CEM)
	(1)	(2)	(3)	(4)
Duopoly	0.245*** (0.059)	0.452*** (0.101)	0.370*** (0.073)	0.715*** (0.124)
Oligopoly	0.035 (0.051)	0.076 (0.080)	0.123** (0.061)	0.235** (0.096)
Duopoly:Generic			-0.370*** (0.130)	-0.893*** (0.198)
Oligopoly:Generic			-0.294** (0.115)	-0.538*** (0.163)
Generic	0.129*** (0.032)	0.041 (0.068)	0.409*** (0.110)	0.614*** (0.150)
Year	Yes	Yes	Yes	Yes
Firm Control	Yes	Yes	Yes	Yes
Therapeutic Category	Yes	Yes	Yes	Yes
Observations	5,504	1,653	5,504	1,653
R ²	0.363	0.383	0.364	0.393

well distributed across 15 different therapeutic categories with respect to 4 different competition types, we consolidate *Oligo1* and *Oligo2* as *Oligopoly*. We present results from regression and CEM with the consolidated competition type in Table 3.4.

The coefficients in Column (1) and Column (3) assure that the regression result from oligopoly consolidation does not alter the previous non-monotonic pattern found in Table 3.3. The CEM result are presented in Column (2) and Column (4). Each confirms that the regression result is also consistent with the corresponding CEM result. We notice that the CEM result is more salient with a much smaller sample because unmatched observations are dropped in the matching process.

3.6.2 Alternative Explanations

We have shown that varying recovery complexity due to manufacturing scale can be a plausible reason for our empirical results. There are three alternative explanations that seem related to our results, which we discuss respectively.

Cooperative Strategy

We recognize that the recovery time increase from *Monopoly* to *Duopoly* can be due to a strategic long-term relationship. It is well known that grim trigger is an equilibrium strategy in a repeated prisoner's dilemma, where two players start by cooperating and continue to do so as long as they have cooperated previously. In our *Duopoly* context, grim trigger is not to expand capacity as fast as a competitor can. Instead, the competitor gives the disrupted firm enough time for recovery because the competitor will receive enough time when it has a disruption. As there are more firms, such a cooperative relationship is less likely to be kept and firms fiercely compete, resulting in the smaller recovery time than that under *Duopoly*. In short, a strong effect of a cooperative strategy under a duopoly may explain the non-monotonic result.

Nevertheless, the cooperative strategy is not likely to hold in our context. We remind that a brand drug's recovery time increases from *Monopoly* to *Duopoly* instead of a generic drug. This implies that a brand drug company faces a generic competitor under the duopoly. It is hardly conceivable that a generic competitor would wait for a brand firm's recovery for the brand firm's future reciprocal waiting.

Risk-averse Decision Maker

It is widely accepted that a firm is risk-neutral and hence trying to maximize the expected profit. Nevertheless, the decision maker is an individual and may be

risk-averse. Then, his objective function can be different from (3.2), which may drive the non-monotonic recovery time. To test this conjecture, we verify whether the competition effect differ across public and private firms. While public firms are well diversified and perceived as risk-neutral, private firms may not be. However, our result indicates that the interaction effect is not significant, suggesting both types of firms make the same decision with respect to competition.

Moral Hazard

Related to a previous alternative explanation, an individual decision maker may want to avoid blame for a drug shortage from the public. When there are more firms, he can avoid blame by waiting for competitors' capacity expansions. However, this cannot explain the decreasing recovery time for further competition intensity increase from a duopoly to an oligopoly. Moreover, the ASHP and the FDA release the shortage information about which manufacturer's product is in short supply on their websites. The decision maker may not be able to hide from the public.

3.7 Conclusion

Drug shortages are regarded as a new normal in the U.S. While preventing drug shortages is important, mitigating them upon occurrence is also essential to public health. As one of the mitigation strategies, increasing competition in a drug market has been perceived. On the one hand, it motivates normal firms that do not have manufacturing disruption to expand capacity. On the other hand, it reduces the incentive of firms experiencing disruption to fix the disruption.

This paper empirically investigates whether competition helps drug shortage

recovery using a unique drug shortage history data between 2010 and 2015. First, we find that the competition effect on drug shortage recovery is not monotonic. Specifically, the recovery time increases then decreases on average as the competition intensity increases. This is contrary to popular belief that reduced profit due to increasing competition may prolong the recovery time. We provide a new theory that can explain this non-monotonic recovery pattern with recovery complexity. Increasing competition reduces not only profit but also market share of a firm, which in turn results in a smaller manufacturing scale. We assert that recovering a smaller scale manufacturing facility is easier than a larger scale facility. In short, increasing competition may prolong and shorten the recovery time through reduced profit and reduced recovery complexity. If the profit is more severely reduced than the recovery complexity, then the recovery time can increase in competition. Otherwise, the recovery time decreases.

We support this theory by investigating how competition affects the recovery time of drugs with different profitability. It is well known that a brand drug is more profitable than its generic version. Moreover, once a generic drug enters, it substantially hurts the brand drug's profit. According to our theory, the brand drug's recovery time should increase more than the generic drug's. Our results not only confirms the theory but also shows that the generic drug's recovery time may be even monotonically decreasing in competition. To address endogeneity concerns regarding the competition level, we employ coarsened exact matching (CEM), which provides a quasi-experimental setting and controls potential confounding factors. The consistent results from CEM show the robustness of our results.

Our contribution is three folds. First, to our best knowledge, this is the first paper that clearly shows the empirical relationship between the drug shortage recovery time and supply chain competition. While there is ample theoretical literature

about firm's recovery from disruption, few papers provide empirical validations of theories. We provide more nuanced results and elucidate the competition impact on a firm's recovery incentive. Next, we develop a new theory that competition influences not only firm's profitability but also recovery complexity. While it is well understood that a firm's profit decreases in competition, it is often neglected that the firm's volume also decreases in competition. The latter is important in the context of manufacturing system recovery since it is likely to be easier to fix a smaller scale manufacturing line than a larger one. Lastly, our results recommend that policymakers recognize the subtle effect of competition on drug recovery time and carefully choose which drug applications or facility inspections to expedite. When competition already exists (e.g., a duopoly or an oligopoly), then increasing competition further will mitigate the drug shortage. However, if there is no competition, they strive to increase the competition level high enough (e.g., from a monopoly to an oligopoly). Otherwise, a monopoly may be better than a duopoly for some profitable drugs.

Chapter 3, in part, is currently being prepared for submission for publication and was co-authored with Junghee Lee, Vish Krishnan and Hyoduk Shin. The dissertation author was the primary investigator and author of this paper.

Summary and Conclusions

Technology plays an increasingly critical role in various supply chains by endowing products with sought-after capabilities. For these supply chains to perform, both the creation and the reliable supply of technology are necessary. The current dissertation provides two model-based theories and an empirical validation of technology supply chains. First, it shows how firms in a technology supply chain can productize their innovation and serve lower ends of the market while maximizing profit. Second, it establishes how technologies can be monetized in a supply chain with powerful intermediaries and complementary capabilities. Third, this work shows that sufficient competition in a supply chain is necessary to provide an innovative product to the market in a reliable manner.

Appendix A

Proofs for Chapter 1

Proof of Result 1.1. Suppose that a component quality is Θ and costs kq^2 to produce q units. For the retail price p , the consumer demand is $D(p) = N(1 - p/\Theta^\beta)$. Consider a vertically integrated firm. Its profit function is $p \cdot D(p) - kD(p)^2$. It is straightforward to see that the optimal price is $\frac{\Theta^\beta}{2} \frac{2kN + \Theta^\beta}{kN + \Theta^\beta}$ and the market coverage $\frac{N\Theta^\beta}{2kN + 2\Theta^\beta}$. The resulting revenue and profit are $\frac{N\Theta^{2\beta}}{4} \frac{2kN + \Theta^\beta}{(kN + \Theta^\beta)^2}$ and $\frac{1}{4} \frac{N\Theta^{2\beta}}{kN + \Theta^\beta}$, respectively. For a decentralized case, there is a supplier that produces and sells the component at some wholesale price w . Suppose that the supplier first sets w and the manufacturer responds with p . It is also clear to see that the retail price ($\frac{\Theta^\beta}{2} \frac{2kN + 3\Theta^\beta}{kN + 2\Theta^\beta}$) is set higher, resulting in the smaller demand ($\frac{N\Theta^\beta}{2kN + 4\Theta^\beta}$), smaller supply chain revenue ($\frac{N\Theta^{2\beta}}{4} \frac{2kN + 3\Theta^\beta}{(kN + 2\Theta^\beta)^2}$), and smaller supply chain profit $\frac{N\Theta^{2\beta}}{4} \frac{kN + 3\Theta^\beta}{(kN + 2\Theta^\beta)^2}$ due to double marginalization. Thus, the supply chain has less incentive in R&D investment than the vertically integrated firm. \square

Proof of Result 1.2. We suppose the same setup in the Proof of Result 1. To maximize revenue, the vertically integrated firm only considers $p \cdot D(p)$ and sets $p = \Theta^\beta/2$. In the supply chain setting, the manufacturer's revenue is the same to the integrated firm's revenue. So are the pricing decision ($\Theta^\beta/2$) and the market

coverage ($N/2$), which is larger than the integrated firm's profit maximizing market coverage ($\frac{N\Theta^\beta}{2kN+2\Theta^\beta}$). \square

Lemma A.1. *The optimal quantity and price of the vertically integrated firm that conducts R&D and manufactures the critical component and the final product are as follows. For a given quality Θ ,*

$$Q(\Theta) = \frac{N\Theta^\beta}{2(K_0N + \Theta^\beta + K_1N\Theta^{\delta_\theta})},$$

$$P(\Theta) = \Theta^\beta - \frac{\Theta^{2\beta}}{2(K_0N + \Theta^\beta + K_1N\Theta^{\delta_\theta})}.$$

Proof of Lemma A.1. For a given quality Θ , the integrated firm's profit function is written as follows.

$$\Pi(Q, P) = P(Q)Q - (K_0 + K_1\Theta^{\delta_\theta})Q^2,$$

where $P(Q) = (1 - Q/N)\Theta^\beta$. The first order condition with respect to Q gives the optimal quantity, market coverage, $Q(\Theta)$. $P(\Theta)$ follows from $P(Q)$. Then, the optimal quality can be obtained by solving the following problem.

$$\max_{\Theta} \Pi(Q(\Theta), P(\Theta)) - \gamma\Theta^{\theta_D} = \frac{N\Theta^{2\beta}}{4(K_0N + \Theta^\beta + K_1N\Theta^{\delta_\theta})} - \gamma\Theta^{\theta_D}.$$

For this problem to be concave, $\delta_D > 2\beta - \delta_\theta$, which is satisfied from the assumptions $\beta \leq 1$, $\delta_\theta > 1$, and $\delta_D > 1$. Thus, the first order condition with respect to Θ gives the optimal quality. \square

Proof of Lemma 1.1. Equilibrium price and quantity are obtained by reducing tier-wise profit expressions into a single contract leader's profit expression by iteratively applying marginalization operation presented in Majumder and Srinivasan 2008.

First, in the case of Tier 0 contract leadership, the leaf node Tier 1's profit expression can be written as

$$\Pi_1(q_1; w_0) = w_0 q_1 - \Theta^{\delta_\theta} K_1 q_1^2. \quad (\text{A.1})$$

Tier 1 optimally responds to wholesale price offer of w_0 by maximizing Π_1 above with respect to q_1 which leads to $q_1(w_0) = w_0 (2K_1 \Theta^{\delta_\theta})^{-1}$. Tier 0 faces the inverse factor demand of the form $w_0(q_1) = (2K_1 \Theta^{\delta_\theta}) q_1$. Substituting $w_0(q_1)$ into $\Pi_0(p, q_0, w_0)$ and using the optimally binding quantity constraint $q_0 = q_1$, we have

$$\Pi_0(p, q) = pq - \Phi_0(\Theta) q^{\delta_q} \quad \text{s.t.} \quad N(1 - \frac{p}{\Theta^\beta}) \geq q, \quad (\text{A.2})$$

where $\Phi_0(\Theta) = K_0 + 2K_1 \Theta^{\delta_\theta}$. By optimizing (A.2) over p and q , it follows that

$$\begin{aligned} P_0(\Theta) &= (2 + 2\Theta^{-\beta} \Phi_0(\Theta) N)^{-1} (\Theta^\beta + 2\Phi_0(\Theta) N), \\ Q_0(\Theta) &= N (2 + 2\Theta^{-\beta} \Phi_0(\Theta) N)^{-1}, \end{aligned} \quad (\text{A.3})$$

which completes the proof for the case of Tier 0 contract leadership. For the other remaining cases, by following the similar steps, we obtain the equilibrium outcomes as stated in Lemma 1.1. \square

Proof of Proposition 1.1. Let $\Pi_{k|ij}$ denote as the profit of Tier k firm when Tier i is the investor and Tier j is the contract initiator. For part (a), we want to prove that $\Pi_{1|11} \geq \Pi_{1|10}$ and $\Pi_{0|00} \geq \Pi_{0|01}$. Consider Tier 1's case first ($k = 1$). Assume that Tier 1 that are both the investor and the initiator mimics the quality decision $\hat{\Theta}$ of Tier 1 that is only the investor. The former clearly makes an suboptimal

decision. According to Lemma 1.1, the profit functions can be written as follows.

$$\Pi_{1|11} = \frac{N\hat{\Theta}^{2\beta}}{8K_0N + 8\hat{\Theta}^\beta + 4K_1N\hat{\Theta}^{\delta_\theta}} - \gamma\hat{\Theta}^{\delta_D},$$

$$\Pi_{1|10} = \frac{4K_1N^2\hat{\Theta}^{2\beta+\delta_\theta}}{4(K_0N + \hat{\Theta}^\beta + 2K_1N\hat{\Theta}^{\delta_\theta})^2} - \gamma\hat{\Theta}^{\delta_D}.$$

After some algebra, the sign of $\Pi_{1|11} - \Pi_{1|10}$ becomes equivalent to $3K_1^2N^2\hat{\Theta}^{\delta_\theta} + 2K_1N\hat{\Theta}^{\delta_\theta}$

$(K_0N + \hat{\Theta}^\beta) + (K_0N + \hat{\Theta}^\beta)^2 > 0$, which shows $\Pi_{1|11} \geq \Pi_{1|10}$. Similarly, $\Pi_{0|00} \geq \Pi_{0|01}$ can be shown.

For part (b), the profit comparison includes the incentive of the opportunistic strategy, where the non-investor is the contract initiator, which requires the closed form solution for quality. Because of this reason, we consider a special case of $\beta = 1$, $\delta_\theta = 2$ and $\delta_D = 2$. We will prove that there exists $\hat{\gamma}$ over which $\Pi_{1|00} \geq \Pi_{1|01}$. Similarly, there also exists $\tilde{\gamma}$ over which $\Pi_{0|11} \geq \Pi_{0|10}$.

We define Θ_{ij} for the optimal quality when Tier i is the investor and Tier j is the contract initiator. There are three cases to consider to examine whether the opportunistic behavior is an equilibrium strategy. With our notation, we want to find a condition such that $\Pi_{1|00} \geq \Pi_{1|01}$. To have these comparison, we obtain the optimal quality decisions for each case. According to Lemma 1.1 and A.2, Θ_{00} and Θ_{01} solve the following first order conditions, respectively.

$$\frac{N(2K_0N + \Theta_{00})}{8(K_0N + \Theta_{00} + 2K_1N\Theta_{00}^2)^2} = \gamma \quad (\text{A.4})$$

$$\frac{N(2K_0N + \Theta_{01})(2K_0N + \Theta_{01}(2 - K_1N\Theta_{01}))}{8(2K_0N + \Theta_{01}(2 + K_1N\Theta_{01}))^3} = \gamma \quad (\text{A.5})$$

One can easily verify that the left hand side of (A.4) decrease in Θ . Consider (A.5). The denominator is clearly increasing in Θ . By differentiating the numerator, we

obtain $2K_0N(3 - 2\Theta K_1N) + \Theta(4 - 3\Theta K_1N)$. It is straightforward to verify that this quadratic equation is concave and has two solutions, which are both negative. That is, the numerator is decreasing for $\Theta > 0$. Thus, (A.5) is decreasing. Since all three left hand sides are decreasing, they have the maximum value when $\Theta = 0$. This is equivalent to say that there are threshold values of γ for each case under which the optimal quality level is greater than zero but over which there is no investment. Let us denote such thresholds as $\hat{\gamma}_{ij}$. Then, $\hat{\gamma}_{01} = 1/16K_0 < \hat{\gamma}_{00} = 1/4K_0$. Hence, if $\gamma > \hat{\gamma}_{01}$, $\Pi_{1|01} = 0 \leq \Pi_{1|00}$. Being opportunistic is not an equilibrium strategy for the supplier when $\gamma \geq \hat{\gamma}_{01}$. Similarly, one can also prove the existence of the threshold over which the manufacturer is worse off by being opportunistic. \square

Lemma A.2. Define $\hat{\Theta}_i$ as the optimal quality level for Tier i investment anchor to expand, i.e., $\hat{\Theta}_i \triangleq \arg \max_{\Theta_i \geq \Theta} \Pi_{i|i}(\Theta_i)$. Then, $\hat{\Theta}_i = \min\{\Theta_i, \Theta\}$, where Θ_i is the solution of $\beta\Theta_i^{\beta-1}Q_i(\Theta_i) + \Theta_i^\beta Q'_i(\Theta_i) = 2\gamma\delta_D\Theta_i^{\delta_D-1}$ and Θ is the initial stock of product quality.

Proof of Lemma A.2. Using the equilibrium quantity in Lemma 1.1, we can simplify the investor's profit function before the investment is made. Since the quality does not affect the expression, we let $Q_i(\Theta_i) = Q_i$ to simplify the notation. After substituting $p(Q_0)$ and $\tilde{C}_0(Q_0, \Theta_0)$ with $(1 - Q_0/N)\Theta^\beta$ and $\Phi_0(\Theta_0)Q_0^2$, (1.2) is written as

$$\begin{aligned} \tilde{\Pi}_0(Q_0|\Theta_0) &= Q_0\Theta_0^\beta - \frac{\Theta_0^\beta}{N}Q_0^2 - \Phi_0(\Theta_0)Q_0^2 \\ &= \left(\Theta_0^\beta - \frac{\Theta_0^\beta + N\Phi_0(\Theta_0)}{N}Q_0 \right) Q_0 \\ &= \frac{\Theta_0^\beta}{2}Q_0 \end{aligned}$$

Thus, the profit function with the development cost can be written as

$$\hat{\Pi}_0(\Theta_0) = \frac{\Theta_0^\beta}{2} Q_0(\Theta_0) - \gamma(\Theta_0^{\delta_D} - \Theta^{\delta_D}),$$

which gives the first order condition $\beta\Theta_0^{\beta-1}Q_0(\Theta_0) + \Theta_0^\beta Q_0'(\Theta_0) = 2\gamma\delta_D\Theta_0^{\delta_D-1}$. Similarly, one can verify that $\tilde{\Pi}_1(Q_1|\Theta_1) = \Theta_1^\beta Q_1(\Theta_1)/2 - \gamma(\Theta_1^{\delta_D} - \Theta^{\delta_D})$ using Lemma 1.1. \square

Claim A.1. *If $R(\hat{\Theta})$ is a supply chain revenue associated with new expanded product quality $\hat{\Theta}$ such that $\hat{\Theta} \geq \Theta$, i.e., new stock of quality weakly exceeds the previous stock of quality Θ , and development cost of raising product quality level from Θ to $\hat{\Theta}$ is $C(\hat{\Theta}, \Theta) = \gamma \cdot \max\{\hat{\Theta}^{\delta_D} - \Theta^{\delta_D}, 0\}$, then*

$$\arg \max_{\hat{\Theta}} \left\{ R(\hat{\Theta}) - C(\hat{\Theta}, \Theta) \right\} = \max \left\{ \arg \max_{\hat{\Theta}} \left\{ R(\hat{\Theta}) - C(\hat{\Theta}, 0) \right\}, \Theta \right\} \quad (\text{A.6})$$

s.t. $\hat{\Theta} \geq \Theta$ *s.t.* $\hat{\Theta} \geq 0$

Proof of Claim 1. On the left-hand side of (A.6) $C(\hat{\Theta}, \Theta) = \gamma\hat{\Theta}^{\delta_D}$ since maximization is constrained to $\hat{\Theta} \geq \Theta$. Further, on the right-hand side of (A.6) $C(\hat{\Theta}, 0) = \gamma\hat{\Theta}^{\delta_D}$ since $\hat{\Theta} \geq 0$. Therefore, maximization problems with respect to $\hat{\Theta}$ on both sides of (A.6) have the same objective function. However, on the right-hand side the maximand of unconstrained problem, $\hat{\Theta}^*$, may be less than initial stock of quality, i.e., $\hat{\Theta}^* \leq \Theta$, which is corrected for by an additional $\max\{\cdot\}$ operator such that $\max\{\hat{\Theta}^*, \Theta\} \geq \Theta$. Hence, expression (A.6) holds. \square

Remark A.1. *Claim A.1 establishes basis for a convenient proof technique for results in this paper that are dependent on the initial stock of quality Θ . If marginal revenue and marginal cost expressions depend only on $\hat{\Theta}$ then it suffices to examine optimal product quality expansion outcomes conditional on $\Theta = 0$, i.e., unconstrained*

optimization $\hat{\Theta} \geq 0$, which can be revised as indicated in (A.6) for $\Theta > 0$. Figure 1.3(b) provides further intuition.

Proof of Proposition 1.2. For the proof of **(a)**, we show the existences of γ^Θ , γ^ρ , and γ^{sw} sequentially.

1. $\exists \gamma^\Theta$.

According to Lemma 1.1 and A.2, the marginal revenue of Leader i can be written as

$$\begin{aligned} MR_i(\Theta_i) &= (\beta\Theta_i^{\beta-1}Q_i + \Theta_i Q'_i) \\ &= Q_i(\Theta)^2 g_i(\Theta), \end{aligned} \tag{A.7}$$

where $g_i(\Theta) = (2^{i+1}\beta K_0 + 2^i\beta\frac{\Theta^\beta}{N} + 2^{1-i}K_1(2\beta - \delta_\theta)\Theta^{\delta_\theta})\Theta^{-1}$. If some Θ^{MR} solves $MR_0(\Theta^{MR}) = MR_1(\Theta^{MR})$, then Θ^{MR} also solves $h(\Theta) = \frac{Q_1(\Theta)^2}{Q_0(\Theta)^2} - \frac{g_0(\Theta)}{g_1(\Theta)} = 0$. Specifically,

$$h(\Theta) = \left(\frac{2K_0N + 2\Theta^\beta + K_1N\Theta^{\delta_\theta}}{K_0N + \Theta^\beta + 2K_1N\Theta^{\delta_\theta}} \right)^2 - \frac{2K_0N\beta + \beta\Theta^\beta + 2K_1N(2\beta - \delta_\theta)\Theta^{\delta_\theta}}{4K_0N\beta + 2\beta\Theta^\beta + K_1N(2\beta - \delta_\theta)\Theta^{\delta_\theta}}. \tag{A.8}$$

Notice that $h(0) > 0$ and $\lim_{\Theta \rightarrow \infty} h(\Theta) < 0$. Moreover,

$$\begin{aligned} h'(\Theta) &= \frac{3}{2}K_1N\Theta^{\delta_\theta-1} \left(-\frac{6(K_0N + \Theta^\beta)(K_0N\delta_\theta + (\delta_\theta - \beta)\Theta^\beta)^3}{K_0N + \Theta^\beta + 2K_1N\Theta^{\delta_\theta}} \right. \\ &\quad - \frac{2K_0N\delta_\theta + 2(\delta_\theta - \beta)\Theta^\beta}{K_0N + \Theta^\beta + 2K_1N\Theta^{\delta_\theta}} \\ &\quad \left. - \frac{2\beta(2\beta - \delta_\theta)(2K_0N\delta_\theta + (\delta_\theta - \beta)\Theta^\beta)}{(4K_0N\beta + 2\beta\Theta^\beta + K_1N(2\beta - \delta_\theta)\Theta^{\delta_\theta})^2} \right) < 0. \end{aligned}$$

Therefore, there exists a unique Θ^{MR} . Let γ^Θ be the solution of $\Theta_0(\gamma) = \Theta_1(\gamma) = \Theta^{MR}$. If $\Theta > \Theta^{MR}$, then $MR_1(\Theta) > MR_0(\Theta)$ and $\Theta_1 > \Theta_0$, which holds for $\gamma < \gamma^\Theta$ since the optimal quality decreases in γ . Otherwise, $\Theta_0 \geq \Theta_1$.

2. $\exists \gamma^\rho$.

We start with proving the following claim.

Claim A.2. *Let Θ^Q and Θ^{MR} be the solution of $Q_0(\Theta) = Q_1(\Theta)$ and $MR_0(\Theta) = MR_1(\Theta)$. Then, $\Theta^{MR} \in (0, \Theta^Q)$.*

Proof of Claim A.2. We showed that for $\Theta > \Theta^{MR}$, $\frac{g_1(\Theta)}{g_0(\Theta)} > \frac{Q_0^2(\Theta)}{Q_1^2(\Theta)}$. Furthermore, by definition, $\frac{Q_0(\Theta^Q)}{Q_1(\Theta^Q)} = 1$ holds, and

$$\frac{g_1(\Theta^Q)}{g_0(\Theta^Q)} - 1 = \frac{(\delta_\theta - \beta)\Theta^\beta + N\delta_\theta K_0}{2\beta N K_0 + \beta\Theta^\beta + 2N(2\beta - \delta_\theta)K_1\Theta^{\delta_\theta}} > 0, \quad (\text{A.9})$$

where $\Theta = \Theta^Q$ i.e., $\frac{g_1(\Theta^Q)}{g_0(\Theta^Q)} > \frac{Q_0^2(\Theta^Q)}{Q_1^2(\Theta^Q)}$ also holds. Thus, $\Theta^{MR} < \Theta^Q$.

□

According to Lemma 1.1,

$$Q'_0(\Theta) = \frac{K_0\beta - 2K_1(\delta_\theta - \beta)\Theta^{\delta_\theta}}{(K_0N + \Theta^\beta + 2K_1N\Theta^{\delta_\theta})^2} \frac{N^2}{2\Theta^{1-\beta}}, \quad (\text{A.10})$$

$$Q'_1(\Theta) = \frac{2K_0\beta - K_1(\delta_\theta - \beta)\Theta^{\delta_\theta}}{(2K_0N + 2\Theta^\beta + K_1N\Theta^{\delta_\theta})^2} \frac{N^2}{2\Theta^{1-\beta}}. \quad (\text{A.11})$$

They reveal three important properties. First, $Q_i(\Theta)$ increases from 0 then decreases to 0, i.e., unimodal, in Θ . Second, when Q_i increases, it is concave. Third, Q_0 has the maximum earlier than Q_1 . In addition, $Q_0(\Theta) = Q_1(\Theta)$ has the unique solution Θ^Q for $\Theta > 0$ since $\lim_{\Theta \rightarrow 0} \frac{Q_0(\Theta_0)}{Q_1(\Theta_0)} = 2$, $\lim_{\Theta \rightarrow \infty} \frac{Q_0(\Theta_0)}{Q_1(\Theta_0)} = 1/2$,

and $\frac{Q_0(\Theta_0)}{Q_1(\Theta_0)}$ is decreasing as shown below.

$$\frac{\partial}{\partial \Theta_0} \left(\frac{Q_0(\Theta)}{Q_1(\Theta)} \right) = -3K_1N\Theta^{\delta_\theta-1} \frac{K_0N\delta_\theta + (\delta_\theta - \beta)\Theta^\beta}{(K_0N + \Theta^\beta + 2K_1N\Theta^{\delta_\theta})^2} < 0.$$

Concave increasing Q_i and $Q'_0(0) > Q'_1(0)$ implies that Q_0 must be decreasing in $\Theta > \Theta^Q$.

Notice that $Q_1(\Theta_1)$ is the optimal decision instead of $Q_1(\Theta_0)$, where $\Theta_1 > \Theta_0$ for $\Theta_i > \Theta^{MR}$ according to Claim A.2 $\Theta^{MR} < \Theta^Q$. One can construct an interval $[\gamma_0^Q, \bar{\gamma}]$ such that $\Theta_0(\bar{\gamma}) = \Theta^Q - \epsilon$ for arbitrarily small $\epsilon > 0$ and $\Theta_0(\gamma_0^Q) = \Theta^Q$. If $Q_1(\Theta_0)$ is increasing as γ decreases from $\bar{\gamma}$ to γ_0^Q or equivalently as Θ_0 increases from $\Theta^Q - \epsilon$ to Θ^Q , $Q_1(\Theta_1)$ is also increasing but $Q_1(\Theta_1) < Q_1(\Theta_0)$. Thus, the cross point $\Theta^\rho \geq \Theta^Q$. Similarly, when $Q_1(\Theta_0)$ is decreasing as γ decreases in the same interval, $Q_1(\Theta_1)$ is decreasing but $Q_1(\Theta_1) > Q_1(\Theta_0)$ and $\Theta^\rho < \Theta^Q$. Therefore, there exists a unique γ^ρ such that $Q^\rho = Q_0(\gamma^\rho) = Q_1(\gamma^\rho)$. This also proves that $\gamma^\rho < \gamma^\Theta$ since $Q_0(\Theta_0(\gamma)) > Q_1(\Theta_1(\gamma))$ for $\gamma > \gamma^\rho$ and $Q_0(\Theta_0(\gamma^\Theta)) > Q_1(\Theta_1(\gamma^\Theta))$.

3. $\exists \gamma^{sw}$.

The social welfare is the sum of two firms' profits and the consumer surplus. Suppose Tier 1 mimics Tier 0's quality decision, i.e., $\Theta_1 = \Theta_0 = \theta$. If we let $X = K_0N + \theta^\beta$ and $Y = K_1N\theta^{\delta_\theta}$, the social welfare under different leaderships can be written

$$\begin{aligned} \Pi_0^{ss} &= N\theta^{2\beta} \frac{2X + 6Y + N\theta^\beta}{8(X + 2Y)^2} - \gamma\theta^{\delta_d}, \\ \Pi_1^{ss} &= N\theta^{2\beta} \frac{6X + 2Y + N\theta^\beta}{8(2X + Y)^2} - \gamma\theta^{\delta_d}. \end{aligned}$$

Furthermore, let $X = aY$ for $a \neq 0$. Then, the comparison is equivalent to

$$\Pi_1^{ss} - \Pi_0^{ss} = \left(\frac{6a+2}{(2a+1)^2} - \frac{2a+6}{(a+2)^2} \right) \frac{1}{Y} + N\theta^{2\beta} \left(\frac{1}{(2a+1)^2} - \frac{1}{(a+2)^2} \right).$$

One can verify that $a < 1$ or $X < Y$ is necessary for $\Pi_1^{ss} < \Pi_0^{ss}$. Since $\delta^\theta > \beta$, $X < Y$ for large enough θ or low enough γ . Moreover, θ is suboptimal for Tier 1. Hence, there still exists γ^{sw} with the optimal quality decision Θ_1 .

We prove part **(b)**. For $\gamma^\rho < \gamma^\Theta$, we already proved while proving $\exists \gamma^\rho$. We also showed that when Tier 1 mimics Tier 0, the social welfare under Tier 1 leadership is greater if $X < Y$. Claim A.3 below shows that $X \geq Y$ at $\gamma = \gamma^\Theta$. For $X < Y$, θ should be large enough or γ is low enough, i.e., $\gamma < \gamma^\Theta$. Thus, $\gamma^{sw} < \gamma^\Theta$.

Claim A.3. $X \geq Y$ at $\gamma = \gamma^\Theta$, where $X = NK_0 + \theta^\beta$ and $Y = NK_1\theta^{\delta\theta}$.

Proof of Claim A.3. At $\gamma = \gamma^\Theta$, the marginal revenue of the leaders are equal, i.e., $MR_0(\theta) = MR_1(\theta)$. Assume that the denominator of $MR_0(\theta)$ is larger than that of $MR_1(\theta)$, which can be expressed

$$\begin{aligned} NK_0 + \theta^\beta + 2NK_1\theta^{\delta\theta} &> 2NK_0 + 2\theta^\beta + NK_1\theta^{\delta\theta} \\ &\equiv NK_1\theta^{\delta\theta} > NK_0 + \theta^\beta. \end{aligned} \tag{A.12}$$

Then, the numerator of $MR_0(\theta)$ must be larger than that of $MR_1(\theta)$.

$$\begin{aligned} 2\beta NK_0 + \beta\theta^\beta + 2(2\beta - \delta_\theta)NK_1\theta^{\delta\theta} &> 4\beta NK_0 + 2\beta\theta^\beta + (2\beta - \delta_\theta)NK_1\theta^{\delta\theta} \\ (2\beta - \delta_\theta)NK_1\theta^{\delta\theta} &> 2\beta NK_0 + \beta\theta^\beta. \end{aligned} \tag{A.13}$$

After multiplying $(2\beta - \delta_\theta)$ at (A.12) and relating it to (A.13), we have

$$\begin{aligned} (2\beta - \delta_\theta)NK_0 + (2\beta - \delta_\theta)\theta^\beta &> 2\beta NK_0 + \beta\theta^\beta \\ &\equiv -\delta_\theta NK_0 + (\beta - \delta_\theta)\theta^\beta > 0. \end{aligned} \quad (\text{A.14})$$

However, (A.14) does not hold since $\beta \leq 1 < \delta_\theta$ by assumption. \square

For the proof of part (c), we prove that γ^Θ increases in K_1 first. Subsequently, we show that γ^ρ and γ^{sw} also increases in K_1 . Note that $MR_i(\theta)$ is decreasing in K_1 since the degree of K_1 in the denominator is higher than that in the numerator. Moreover, $MR_i(0)$ is not affected by K_1 . Since $MR_0(0) > MR_1(0)$ and MR_i is decreasing in K_1 , if MR_0 is decreasing faster than MR_1 , γ^Θ is increasing in K_1 , where γ^Θ is defined where $MR_0(\theta) = MR_1(\theta)$. Thus, we want to prove $\partial MR_0/\partial K_1 < \partial MR_1/\partial K_1$, which is equivalent to $\frac{\partial MR_0}{\partial K_1}/\frac{\partial MR_1}{\partial K_1} > 1$.

$$\begin{aligned} \frac{\partial MR_0}{\partial K_1}/\frac{\partial MR_1}{\partial K_1} &= \left(\frac{2NK_0 + 2\theta^\beta + NK_1\theta^{\delta_\theta}}{NK_0 + \theta^\beta + 2NK_1\theta^{\delta_\theta}} \right)^3 \\ &\cdot \frac{2(2\beta + \delta_\theta)NK_0 + 2\delta_\theta\theta^\beta + 4NK_1(2\beta - \delta_\theta)\theta^{\delta_\theta}}{2(2\beta + \delta_\theta)NK_0 + 2\delta_\theta\theta^\beta + NK_1(2\beta - \delta_\theta)\theta^{\delta_\theta}}. \end{aligned}$$

The second fraction is clearly greater than 1. The first fraction is greater than 1 by Claim A.3. Therefore, γ^Θ increases in K_1 .

Next, recall that we established existence of γ^ρ on an interval $(\gamma_0^Q, \gamma^\Theta)$, where $Q_0(\Theta_0(\gamma_0^Q)) = Q_1(\Theta_0(\gamma_0^Q))$ and $\Theta_0(\gamma^\Theta) = \Theta_1(\gamma^\Theta)$. For $Q_0(\Theta_0(\gamma_0^Q)) = Q_1(\Theta_0(\gamma_0^Q))$, $NK_0 + \Theta_0(\gamma_0^Q)^\beta = NK_1\Theta_0(\gamma_0^Q)^{\delta_\theta}$. Applying Implicit function theorem, we obtain $\Theta_0(\gamma_0^Q)$ decreases in K_1 , which is equivalent to γ_0^Q increases in K_1 . Hence, γ^ρ is interior to the interval where both endpoints are strictly increasing in K_1 . For every K_1 we construct $\Delta K_1 > 0$ such that $\gamma_0^Q(K_1 + \Delta K_1) = \gamma^\Theta(K_1)$, which guarantees that $\gamma_0^Q(K_1 + \Delta K_1) > \gamma_0^Q(K_1)$. Similarly, it can be proved that γ^{sw} increases in

K_1 . □

Proof of Proposition 1.3. We want to show if Tier 1 wants Tier 0 to be the investment anchor. First, consider Tier 0's incentive compatibility. If Tier 0 does not take the anchoring offer, no investment is made. So is its profit. Next, Tier 1 should be better off by being the follower. These can be expressed as

$$0 \leq V_{0|0}(\gamma), \quad (\text{A.15})$$

$$V_{1|1}(\gamma) \leq V_{1|0}(\gamma), \quad (\text{A.16})$$

where $V_{i|j}(\gamma)$ is Tier i 's optimal value function with respect to γ under Tier j 's anchoring. Since the leader's profit is decreasing in γ , there exists $\bar{\gamma}_0$ and $\bar{\gamma}_1$ such that (A.15) holds for $\gamma \leq \bar{\gamma}_0$ and $V_{1|1}(\gamma) \geq 0$ for $\gamma \leq \bar{\gamma}_1$ respectively.

We first show $\bar{\gamma}_1 < \bar{\gamma}_0$. Assume $\bar{\gamma}_1 \geq \bar{\gamma}_0$. Then, whereas Tier 1's optimal profit is zero at $\bar{\gamma}_1$, Tier 0's profit should be negative if Tier 0 invests any. Let $\bar{\Theta}_1$ denote Tier 1's optimal quality decision at $\bar{\gamma}_1$. Assume that Tier 0 also mimics this decision. According to Lemma 1.1, if $K_0 \geq K_1 \bar{\Theta}_1^{\delta_\theta} - \bar{\Theta}_1^\beta / N$, Tier 0's profit is greater than or equal to Tier 1's although Tier 0's decision is suboptimal. Notice that if K_0 is relatively larger than K_1 , the equation holds implying that Tier 0's profit is positive, showing that $\bar{\gamma}_1 < \bar{\gamma}_0$. For $\gamma \in (\bar{\gamma}_1, \bar{\gamma}_0)$, both (A.15) and (A.16) hold as $V_{1|0}(\gamma) \geq 0$ despite its suboptimal decision $\bar{\Theta}_1$. If Tier 0 adopts the optimal decision, (A.16) holds even for some $\gamma < \bar{\gamma}_1$.

Next, consider γ goes to 0. Again, according to Lemma 1.1, if $\delta_\theta \leq 2\beta$, then optimal qualities under different leadership increases arbitrarily large. Even if Tier 1 mimics Tier 0's optimal quality decision Θ_0 , $\lim_{\Theta_0 \rightarrow \infty} \frac{\Pi_{1|1}(\Theta_0)}{V_{1|0}} = \lim_{\Theta_0 \rightarrow \infty} \frac{(K_0 N + \Theta_0^\beta + 2K_1 N \Theta_0^{\delta_\theta})^2}{K_1 N \Theta_0^{\delta_\theta} (2K_0 N + 2\Theta_0^\beta + K_1 N \Theta_0^{\delta_\theta})} > 1$. This implies that there exists γ^1 such that $V_{1|1}(\gamma) > V_{1|0}(\gamma)$ for $\gamma < \gamma^1$ and (A.15) and (A.16) hold for $\gamma \in [\gamma^1, \bar{\gamma}_0]$. Thus, if

$\gamma < \gamma^1$, Tier 1 is the investment anchor in equilibrium. When $\gamma^1 \leq \gamma < \bar{\gamma}_0$, Tier 0 is the anchor. \square

Proof of Lemma 1.2. In general, Tier l investment anchor should solve the following problem to determine how much to invest in cost reduction R&D:

$$\max_x \quad \Pi_{l|l}(x|\theta) = \frac{\theta^\beta}{2} Q_l(x) - \frac{\eta x}{K_1 - x},$$

where $Q_l(x)$ is the optimal quantity for a cost reduction x obtained from Lemma 1.1 by replacing K_1 with $K_1 - x$. By solving the first order condition, one can get the optimal cost reduction x_l . For example,

$$x_1(\theta) = \frac{4\sqrt{\eta K_1} \theta^{\beta - \frac{\delta\theta}{2}} (\theta^\beta + K_0 N) + K_1 (8\eta \theta^\beta + 8\eta K_0 N + 4\eta K_1 N \theta^{\delta\theta} - N \theta^{2\beta})}{n(4\eta K_1 \theta^{\delta\theta} - \theta^{2\beta})},$$

which decreases in η since $\partial x_1 / \partial \eta < 0$. Thus, we obtain

$$\eta_1(\theta) = \frac{K_1 N^2 \theta^{2\beta + \delta\theta}}{4(2\theta^\beta + 2K_0 N + K_1 N \theta^{\delta\theta})^2}.$$

$x_0(\cdot)$ and $\eta_0(\cdot)$ can be derived similarly. Now, we establish the relationship between η_0 and η_1 with respect to θ . Define $h(\theta)$ as follows for convenience.

$$h(\theta) \triangleq \frac{\eta_0(\theta)}{\eta_1(\theta)} = \frac{2(2K_0 N + 2\theta^\beta + K_1 N \theta^{\delta\theta})^2}{(K_0 N + \theta^\beta + 2K_1 N \theta^{\delta\theta})^2}.$$

Note that $h(0) = 8$, $\lim_{\theta \rightarrow \infty} h(\theta) = 1/2$, and $h'(\theta) < 0$. Thus, there exists a threshold $\bar{\theta}$ such that $\eta_0 > \eta_1$ for $\theta < \bar{\theta}$. By equating $h(\theta) = 1$, we characterize $\bar{\theta}$ as $\bar{\theta}^\beta = \frac{N}{7}(3\sqrt{2}K_1 \theta^{\delta\theta} - 7K_0 - 2K_1 \theta^{\delta\theta})$, which leads $\eta_0(\bar{\theta}) = \eta_1(\bar{\theta}) = \frac{9-4\sqrt{2}}{36K_1} \theta^{2\beta - \delta\theta} \triangleq \bar{\eta}$. Since $\eta_i(\theta)$ is increasing in θ , $\eta_1(\theta) \leq \eta_0(\theta) \leq \bar{\eta}$ for $\theta \leq \bar{\theta}$ and $\bar{\eta} < \eta_0 < \eta_1$ for $\theta > \bar{\theta}$. \square

Proof of Proposition 1.4. For part **(a)**, $x_i \geq 0$ for $\eta \leq \bar{\eta}$. Then,

$$\begin{aligned} x_0(\theta) - x_1(\theta) &\equiv \frac{2}{\sqrt{\eta\theta^{2\beta+\delta_\theta} - 2\eta\theta^{\delta_\theta}}} - \frac{1}{\sqrt{2\eta\theta^{2\beta+\delta_\theta} - 4\eta\theta^{\delta_\theta}}} \\ &\equiv \frac{9 - 4\sqrt{2}}{36K_1}\theta^{2\beta-\delta_\theta} - \eta \\ &= \bar{\eta} - \eta \geq 0. \end{aligned}$$

Therefore, $x_0(\theta) \geq x_1(\theta)$.

For part **(b)**, with the results from Lemma 1.2, market coverages for $\eta \leq \bar{\eta}$ are

$$\begin{aligned} Q_0(x_0(\theta)) &= \frac{\theta^\beta - 2\sqrt{2K_1\eta\theta^{\delta_\theta}}}{2(K_0 + \theta^\beta/N)}, \\ Q_1(x_1(\theta)) &= \frac{\theta^\beta - 2\sqrt{K_1\eta\theta^{\delta_\theta}}}{4(K_0 + \theta^\beta/N)}. \end{aligned}$$

It is easy to see that Q_0/Q_1 is decreasing from 2 to $-\infty$ as η increases 0 to $\theta^{2\beta-\delta_\theta}/4$. By equating $Q_0/Q_1 = 1$, we obtain $\eta^\rho \triangleq \frac{9+4\sqrt{2}}{196K_1}\theta^{2\beta-\delta_\theta} < \bar{\eta}$ such that $Q_0 \geq Q_1$ for $\eta \leq \eta^\rho$.

For part **(c)**, Tier 1's profits under each leadership for $\eta \leq \bar{\eta}$ can be expressed as

$$\begin{aligned} \Pi_{1|1} &= \frac{8K_0N\eta + 8\eta\theta^\beta + N\theta^{2\beta} - 4N\sqrt{K_1\eta}\theta^{\beta+\delta_\theta/2} + 4K_1N\eta\theta^{\delta_\theta}}{8K_0N + 8\theta^\beta}, \\ \Pi_{1|0} &= \frac{\sqrt{2K_1\eta}N\theta^{\beta+\delta_\theta/2} - 4K_1N\eta\theta^{\delta_\theta}}{4K_0N + 4\theta^\beta}. \end{aligned}$$

For the supplier to be better off by being the follower, $\Pi_{1|1} - \Pi_{1|0} \leq 0$. However,

$$\begin{aligned}\Pi_{1|1} - \Pi_{1|0} &\equiv 8K_0N\eta - 2(2 + \sqrt{2})\sqrt{K_1\eta}N\theta^{\beta+\delta_\theta/2} + 12K_1N\eta\theta^{\delta_\theta} + \theta^\beta(8\eta + N\theta^\beta) \\ &= (8K_0N + 8\theta^\beta + 12K_1n\theta^{\delta_\theta})y^2 - 2(2 + \sqrt{2})\sqrt{K_1}N\theta^{\beta+\delta_\theta/2}y + n\theta^{2\beta},\end{aligned}$$

where $y = \sqrt{\eta}$. Tier 1's profit difference is the quadratic equation with respect to y . Since its discriminant $-8N\theta^{2\beta}(4K_0N + 4\theta^\beta + (3 - 2\sqrt{2})K_1N\theta^{\delta_\theta}) < 0$, the difference is positive for $\eta \leq \bar{\eta}$. \square

Lemma A.3. *Consider a supply chain under revenue sharing. Tier 1 leader's optimal production quantity and profit are*

$$\begin{aligned}Q_0(\Theta) &= N\Theta^\beta / (4K_0N + 2(2 - \lambda)\Theta^\beta + K_1N\Theta^{\delta_\theta}), \\ \Pi_{1|1}(\Theta) &= \frac{N\Theta^{2\beta}}{8K_0N + 4(2 - \lambda)\Theta^\beta + 4K_1N\Theta^{\delta_\theta}} - \gamma\Theta^{\delta_D}.\end{aligned}$$

Proof of Lemma A.3. Tier 1 leader's profit function without development cost is

$$\begin{aligned}\Pi_{1|1}(q) &= \lambda p(q)q + w(q)q - K_1\Theta^{\delta_\theta}q^2 \\ &= p(q)q - (1 - \lambda)\frac{\Theta^\beta}{N}q^2 - (2K_0 + K_1\Theta^{\delta_\theta})q^2,\end{aligned}\tag{A.17}$$

where $w(q) = (1 - \lambda)(N - 2q)\Theta^\beta/N - 2K_0q$ under optimality. Notice that the revenue sharing is equivalent to the wholesale price only contract when $\lambda = 0$, i.e., (A.17) = (1.3). Moreover, if $\lambda = 1$, the second term in (A.17), the loss due to double marginalization, is zero. The first order condition with respect to q gives Q_0 . Replacing q with Q_0 in $\Pi_{1|1}(q)$, we obtain its profit in terms of Θ with development cost. \square

Proof of Proposition 1.5. Let $\pi_{i|j}$ denote Tier i 's profit under Tier j 's anchoring.

For Tier 1 to be better off under Tier 0's anchoring,

$$\pi_{1|1}(\theta_1) \leq \pi_{1|0}(\theta_0), \quad (\text{A.18})$$

$$0 \leq \pi_{0|0}(\theta_0). \quad (\text{A.19})$$

We define θ_j as the optimal quality improvement decision under Tier j 's anchoring. Tier 1's profit function when it is the leader is

$$\pi_{1|1}(\theta) = \frac{N\theta^{2\beta}}{8K_0N + 4(2 - \lambda)\theta^\beta + 4K_1N\theta^{\delta_\theta}} - \gamma\theta^{\delta_D}.$$

We have shown that there exists γ^1 under (over) which the equilibrium is Tier 1 (0) in Proposition 1.3 under the wholesale price contract, i.e., $\lambda = 0$. As λ increases, $\pi_{1|1}$ increases and the supplier is more likely to be the anchor in equilibrium, implying that γ^1 increases in λ . We will show that there exists a corresponding finite threshold γ for $\lambda = 1$, i.e. the manufacturer (Tier 0) can still be the anchor.

We know that $\pi_{i|i}$ decreases in γ for $\delta_\theta \in (1, 2\beta]$ from Proposition 1.3. Thus, there exists $\bar{\gamma}_i$ over which Tier i anchor's IR constraint does not hold. If $K_0 > K_1\theta^{\delta_\theta}$, then $\pi_{0|0}(\theta_1) \geq \pi_{1|1}(\theta_1)$. That is, the Tier 0 anchor earns more than the Tier 1 anchor in spite of Tier 0's suboptimal decision that mimics Tier 1's decision. Thus, for large enough K_0/K_1 , $\bar{\gamma}_1 < \bar{\gamma}_0$. Therefore, for $\gamma \in (\bar{\gamma}_1, \bar{\gamma}_0)$, both (A.19) and (A.18) hold. Being similar to the proof in Proposition 1.3, one can show that $\pi_{1|1}(\theta_0)/\pi_{1|0}(\theta_0)$ converge to a constant which is greater than 1 as γ decreases and θ_0 increases, implying that Tier 1 is the investment anchor. Thus, there exists a threshold $\gamma_R^1 < \bar{\gamma}_0$ under (over) which Tier 1 (0) is the investment anchor in equilibrium. \square

Proof of Lemma 1.3. Let π_s (Π_s) and π_1 (Π_1) denote the supplier's (supply chain's)

profits with respect to a quality level θ under the simultaneous and the sequential procurement with Tier 1 initiator contracts, respectively. If the same quality level is given for both cases, it is evident that the supplier becomes worse off under the simultaneous case since the firm does not have the first mover advantage but the supply chain is better off, i.e. $\pi_1(\theta) > \pi_s(\theta)$ and $\Pi_1(\theta) < \Pi_s(\theta)$.

First, we show that for a small γ , $\Pi_1 < \Pi_s$. The first order conditions for π_s and π_1 are as follows.

$$\frac{\partial \pi_s}{\partial \theta} = -\delta_D \gamma \theta^{\delta_D - 1} + \frac{K_1 N^2 \theta^{2\beta + \delta\theta - 1} (\delta\theta \theta^\beta + K_0 N (2\beta + \delta\theta) + K_1 N (2\beta - \delta\theta) \theta^{\delta\theta})}{4(\theta^\beta + K_0 N + K_1 n \theta^{\delta\theta})^3} = 0, \quad (\text{A.20})$$

$$\frac{\partial \pi_1}{\partial \theta} = -\delta_D \gamma \theta^{\delta_D - 1} + \frac{N \theta^{2\beta - 1} (2\beta \theta^\beta + 4\beta K_0 n + K_1 n (2\beta - \delta\theta) \theta^{\delta\theta})}{4(2\theta^\beta + 2K_0 N + K_1 N \theta^{\delta\theta})^2} = 0. \quad (\text{A.21})$$

Notice that if $\delta\theta \leq 2\beta$, both fraction terms in (A.20) and (A.21) are always positive and there exist solutions solving both first order conditions. The highest degree of θ in each fraction term is $2\beta - \delta\theta - 1 < 0$ because $1 < \delta\theta \leq 2\beta$ and $0 < \beta \leq 1$. It implies that each fraction term decreases to zero as θ goes to infinity. Thus, as γ decreases, θ should increase to satisfy the first order conditions. Next, suppose the supplier under the simultaneous contract mimics the supplier under the sequential contract. For θ solving (A.21), we obtain the following by rearranging (A.21).

$$\gamma = \frac{N \theta^{2\beta - 1} (2\beta \theta^\beta + 4\beta K_0 N + K_1 N (2\beta - \delta\theta) \theta^{\delta\theta})}{4\delta_D \theta^{\delta_D - 1} (2\theta^\beta + 2K_0 N + K_1 N \theta^{\delta\theta})^2}.$$

However, substituting the same θ in (A.20) results in

$$\gamma' = \frac{K_1 N^2 \theta^{2\beta + \delta\theta - 1} (\delta\theta \theta^\beta + K_0 N (2\beta + \delta\theta) + K_1 N (2\beta - \delta\theta) \theta^{\delta\theta})}{4\delta_D \theta^{\delta_D - 1} (\theta^\beta + K_0 N + K_1 N \theta^{\delta\theta})^3},$$

where γ' may be different from γ . However,

$$\begin{aligned} \lim_{\theta \rightarrow \infty} \frac{\gamma}{\gamma'} &= \lim_{\theta \rightarrow \infty} \frac{K_1 N \theta^{\delta_\theta} (2\theta^\beta + 2K_0 N + K_1 N \theta^{\delta_\theta})^2}{(\theta^\beta + K_0 N + K_1 N \theta^{\delta_\theta})^3} \\ &\quad \cdot \frac{\delta_\theta \theta^\beta + K_0 N (2\beta + \delta_\theta) + K_1 N (2\beta - \delta_\theta) \theta^{\delta_\theta}}{2\beta \theta^\beta + 4\beta K_0 N + K_1 N (2\beta - \delta_\theta) \theta^{\delta_\theta}} \\ &= 1. \end{aligned}$$

This implies that for a small γ , the optimal quality levels under different contracts are negligible and $\Pi_s > \Pi_1$.

Second, we prove for a large γ , $\Pi_s \geq \Pi_1$. Define $\theta_s(\gamma) = \arg \max_{\theta \geq 0} \pi_s(\theta|\gamma)$. Since π_s is continuous and differentiable for $\theta > 0$, there exists some $\theta_s(\bar{\gamma})$ such that $\pi_s(\theta_s(\bar{\gamma})) = 0$ and $\pi'_s(\theta)|_{\theta=\theta_s(\bar{\gamma})} = 0$. By solving each condition with respect to γ , we have the following equation at $\gamma = \bar{\gamma}$.

$$\begin{aligned} \frac{K_1 N^2 \theta^{2\beta - \delta_D + \delta_\theta}}{4(K_0 N + \theta^\beta + K_1 N \theta^{\delta_\theta})^2} &= \frac{K_0 N (2\beta + \delta_\theta) + \delta_\theta \theta^\beta + K_1 N (2\beta - \delta_\theta) \theta^{\delta_\theta}}{(K_0 N + \theta^\beta + K_1 N \theta^{\delta_\theta})^3} \\ &\quad \cdot \frac{K_1 N^2 \theta^{2\beta - \delta_D + \delta_\theta}}{4\delta_D} \end{aligned} \quad (\text{A.22})$$

Since $\theta_s(\bar{\gamma})$ solves (A.22) and is greater than 0, after rearranging terms we have $K_0 N (-2\beta + \delta_D - \delta_\theta) + (\delta_D - \delta_\theta) \theta_s(\bar{\gamma})^\beta + K_1 N (-2\beta + \delta_D + \delta_\theta) \theta_s(\bar{\gamma})^{\delta_\theta} = 0$. We remind that $\beta < \delta_\theta$ and $\beta < \delta_D$, resulting in $-2\beta + \delta_D + \delta_\theta > 0$. Thus, for this equation to have the solution regardless of K_0 and K_1 , $-2\beta + \delta_D - \delta_\theta < 0$ or $\delta_D - \delta_\theta \leq 0$. As the latter implies the former, the former is a weaker condition for the existence of $\bar{\gamma}$. Therefore, for $-2\beta + \delta_D - \delta_\theta < 0$, there exists $\gamma = \bar{\gamma}$ such that $\theta_s(\bar{\gamma}) > 0$ and $\pi_1(\theta_s(\bar{\gamma})) > \pi_s(\theta_s(\bar{\gamma})) = 0$. Since $\theta_s(\bar{\gamma})$ is suboptimal for π_1 , $\pi_1^* > 0$. Hence, there exists some $\gamma > \bar{\gamma}$ such that $\pi_s = 0$ but $\pi_1^* > 0$, resulting in $\Pi_1 > \Pi_s$ or equivalently the supply chain is better off under the sequential contracting. \square

Appendix B

Proofs for Chapter 2

Proof of Proposition 2.1. For the part (i), suppose the technology is licensed under SSB and $v_l \geq \alpha v_h$. Consider M 's product line decision. It is clear that if *Extension* is feasible, *Standard* is not optimal since M can mimic *Standard* by setting two products quality equal in *Extension*. Thus, M compares *Extension* and *Niche* for given w and t . According to Moorthy and Png 1992 where $\delta_m = 2$, there is quality distortion for the lower quality product when M offers two different productions, which results in M 's profit as expressed in LHS of the following equation (B.1). For *Niche*, M sells one product at the most expensive price to h segment and earns RHS of (B.1).

$$\frac{v_l^2 - 2\alpha v_l v_h + \alpha v_h^2}{4c_f(1-\alpha)} t^2 - w \geq \alpha \left(\frac{(v_h t \alpha^\gamma)^2}{4c_f} - w \right) \quad (\text{B.1})$$

Let w_{IR} be w such that M 's profit from *Extension* is zero. If $\frac{v_l^2 - 2\alpha v_l v_h + \alpha v_h^2}{4c_f(1-\alpha)} \geq \frac{(v_h t \alpha^\gamma)^2}{4c_f}$, *Extension* is optimal even at $w = w_{IR}$ regardless of t . After solving this condition with respect to γ , we obtain $\underline{\gamma} \triangleq \ln \left(\left(\frac{v_l}{v_h} - \alpha \right)^2 \frac{1}{1-\alpha} + \alpha \right) / 2 \ln \alpha$.

Next, consider S of which profit is $\pi_s(w) = (w(1-r) - c_s)D$ for $D \in \{1, \alpha\}$.

If $\gamma \geq \underline{\gamma}$, w_{IR} is the optimal price for *Extension*. S compare this profit to *Niche* by setting $w = w_{IR}^h$ where RHS of (B.1) is zero. Since we already show that $w_{IR} \geq w_{IR}^h$ for $\gamma \geq \underline{\gamma}$, $w = w_{IR}$ is also optimal, if S 's IR condition is satisfied, i.e. $r \leq 1 - c_s/w_{IR}$.

Finally, TP 's problem is also to choose between *Extension* and *Niche* to maximize its profit

$$\max_{t,r} \pi_I(t,r) = \begin{cases} -c_t t^{\delta_i} + w_{IR} r & \text{Extension,} \\ -c_t t^{\delta_i} + w_{IR}^h r \alpha & \text{Niche.} \end{cases}$$

It is clear that *Extension* is optimal by setting $r = 1 - c_s/w_{IR}$. Therefore, M 's profit is sequentially extracted by S and then by TP . In short, TP integrates the supply chain. The same thing holds for general $\delta_m > 1$, where $\underline{\gamma} \triangleq \frac{\delta_m - 1}{\delta_m} \log \left(\alpha + \left(\frac{1}{1-\alpha} \right)^{\frac{1}{\delta_m - 1}} \left(\frac{v_l}{v_h} - \alpha \right)^{\frac{\delta_m}{\delta_m - 1}} \right) / \log(\alpha)$.

For the part (ii), consider $\gamma > 1/2$ so that $1/\alpha < 1/\alpha^{\gamma+1/2}$. For $1/\alpha < v_h/v_l$, *Extension* is infeasible. The manufacturer should choose between *Standard* or *Niche*. Its profit under *Standard* is $(v_l t)^2 / 4c_f - w$. By comparing this to *Niche* profit, we derive a threshold wholesale price $\frac{v_l^2 - v_h^2 \alpha^{1+2\gamma}}{4c_f(1-\alpha)} t^2$ over which *Niche* is chosen. Notice that $v_l^2 - v_h^2 \alpha^{1+2\gamma} < 0$ is equivalent to $\frac{1}{\alpha^{\gamma+1/2}} < \frac{v_h}{v_l}$, which implies that *Niche* is chosen for any $w > 0$. That is, the manufacturer does not deviate from *Niche*. So does the supplier. Hence, TP adopting SSB can extract all the profits from downstream without incurring any negative impacts on downstream quality investment. □

Lemma B.1. Let D_1 and D_2 be the demand for each manufacturer. Define

$w_l = \frac{1}{y} \frac{(v_l t)^y}{(\delta_m c_f)^x}$ and $w_h = \frac{1}{y} \frac{(v_h t)^y}{(\delta_m c_f)^x}$, where $x = \frac{1}{\delta_m - 1}$ and $y = \frac{\delta_m}{\delta_m - 1}$. For some t and

$w = \min\{w_1, w_2\}$, there are three equilibria in market coverage.

1. No coverage. If $w > \max\{w_l, w_h\}$, the market is not covered.

2. Partial coverage. If $w_l < w \leq w_h$ and $\alpha v_h/v_l \geq 1$, the optimal strategies and outcomes are

$$\begin{aligned}(\theta_1^p, \theta_2^p) &= \left(\left(\frac{v_h \alpha^\gamma t}{\delta_m c_f} \right)^x, \left(\frac{v_h \alpha^\gamma t}{\delta_m c_f} \right)^x \right), \\(p_1^p(\theta_1, \theta_2), p_2^p(\theta_1, \theta_2)) &= (w + c_f \theta_1^{\delta_m}, w + c_f \theta_2^{\delta_m}), \\(D_1, D_2) &= (\alpha/2, \alpha/2), \\ \pi_1^p &= \pi_2^p = 0.\end{aligned}$$

3. Full coverage (l, h). If $w \leq \min\{w_l, w_h\}$ or $\alpha^\gamma v_h/v_l < 1$, the optimal strategies and outcomes are

$$\begin{aligned}(\theta_1^f, \theta_2^f) &= \left(\left(\frac{v_l t}{\delta_m c_f} \right)^x, \left(\frac{v_h t}{\delta_m c_f} \right)^x \right), \\(p_1^f(\theta_1, \theta_2), p_2^f(\theta_1, \theta_2)) &= (v_l \theta_1 t, v_h t(\theta_2 - \theta_1) + v_l \theta_1 t), \\(D_1, D_2) &= (1 - \alpha, \alpha), \\ \pi_1^f &= \left(\frac{\delta_m - 1}{\delta_m} \frac{t^y}{c_f^x} v_l^y - w \right) (1 - \alpha), \\ \pi_2^f &= \left(\frac{1}{\delta_m} \frac{t^y}{c_f^x} (\delta_m v_l^y - \delta_m v_h v_l^x + (\delta_m - 1) v_h^y) - w \right) \alpha.\end{aligned}$$

Proof of Lemma B.1. Lemma B.1 is analogous to Lemma B.2. We prove a more complicated Lemma B.2 in detail. The same proof can be easily modified for Lemma B.1 by replacing $T(1 - R)$ with t . \square

Proof of Lemma 2.1. Let $k = \delta_i \delta_m - \delta_i - \delta_m > 0$. It implies that the technology

improvement harder than system quality improvement and is a mild regularity condition ensuring the existence of solutions. Because of the price competition in Tier 1, TP can choose either the full or the partial coverages without concerning a supplier's deviation. For the full coverage, M_1 's IR constraint is $w \leq \frac{\delta_m - 1}{c_f^x} \left(\frac{v_l t}{\delta_m} \right)^y$ where $x = 1/(\delta_m - 1)$ and $y = \delta_m/(\delta_m - 1)$. Since TP 's profit is increasing in r , TP makes this constraint binding by setting $r(t) = 1 - \frac{c_s}{w} = 1 - \frac{c_s c_f^x}{\delta_m - 1} \left(\frac{\delta_m}{v_l t} \right)^y$ and $t^* = \left(\frac{v_l^y}{\delta_i c_t (c_f \delta_m)^x} \right)^{\frac{\delta_m - 1}{k}}$. We note that t^* is independent of c_s . The optimal profit function is

$$\pi_I^f = \frac{v_l^{1+z_m+z_i}}{\delta_i^{z_m+1} \delta_m^{z_i+1} c_t^{z_m} c_f^{z_i}} k - c_s,$$

where $z_m = \frac{\delta_m}{\delta_i \delta_m - \delta_i - \delta_m}$ and $z_i = \frac{\delta_i}{\delta_i \delta_m - \delta_i - \delta_m}$.

Under the partial coverage, M_1 and M_2 are competing for the same h segment and their profit functions are identical. So are IR constraints, $w \leq \frac{\delta_m - 1}{c_f^x} \left(\frac{v_h \alpha^\gamma t}{\delta_m} \right)^y$. TP makes the IR constraint binding by setting $r(t) = 1 - \frac{c_s c_f^x}{\delta_m - 1} \left(\frac{\delta_m}{v_h \alpha^\gamma t} \right)^y$ and $t^* = \left(\frac{(v_h \alpha^\gamma)^y}{\delta_i c_t (c_f \delta_m)^x} \alpha \right)^{\frac{\delta_m - 1}{k}}$. The resulting profit is

$$\pi_I^p = \frac{(v_h \alpha^\gamma)^{1+z_m+z_i}}{\delta_i^{z_m+1} \delta_m^{z_i+1} c_t^{z_m} c_f^{z_i}} \alpha^{1+z_m} k - \alpha c_s.$$

It is clear that π_I^p is increasing in v_h but π_I^f is not. Hence, there exists a market inequality threshold of \tilde{v}_h/v_l under which the full coverage is optimal and over which the partial coverage is optimal. The threshold is expressed as $\frac{\tilde{v}_h}{v_l} = \frac{1}{\alpha^{1+\gamma-1/\delta_m}} \left(1 - \frac{\delta_i^{1+z_m} \delta_m^{1+z_i} C}{v_l^{1+z_m+z_i} k} (1 - \alpha) \right)^{\frac{k}{\delta_m \delta_i}}$.

□

Lemma B.2. *Let D_1 and D_2 be the demand for each manufacturer. Define*

$w_{lF}(T, R) = \frac{1}{y} \frac{(v_l T(1-R))^y}{(\delta_m c_f)^x}$ and $w_{hF}(T, R) = \frac{1}{y} \frac{(v_h \alpha^\gamma T(1-R))^y}{(\delta_m c_f)^x}$, where $x = \frac{1}{\delta_m - 1}$ and $y = \frac{\delta_m}{\delta_m - 1}$. For some T, R , and $w = \min\{w_1, w_2\}$, there are three equilibria in market coverage.

1. No coverage. If $w > \max\{w_{lF}, w_{hF}\}$, the market is not covered.
2. Partial coverage. If $w_{lF} < w \leq w_{hF}$ and $\alpha v_h / v_l \geq 1$, the optimal strategies and outcomes are

$$\begin{aligned} (\theta_{1F}^p, \theta_{2F}^p) &= \left(\left(\frac{v_h \alpha^\gamma T(1-R)}{\delta_m c_f} \right)^x, \left(\frac{v_h \alpha^\gamma T(1-R)}{\delta_m c_f} \right)^x \right), \\ (p_{1F}^p(\theta_1, \theta_2), p_{2F}^p(\theta_1, \theta_2)) &= \left(\frac{w + c_f \theta_1^{\delta_m}}{1-R}, \frac{w + c_f \theta_2^{\delta_m}}{1-R} \right), \\ (D_1, D_2) &= (\alpha/2, \alpha/2), \\ \Pi_{1F}^p &= \Pi_{2F}^p = 0. \end{aligned}$$

3. Full coverage. If $w \leq \min(w_{lF}, w_{hF})$ or $v_l > \alpha v_h$, the optimal strategies and outcomes are

$$\begin{aligned} (\theta_{1F}^f, \theta_{2F}^f) &= \left(\left(\frac{v_l T(1-R)}{\delta_m c_f} \right)^x, \left(\frac{v_h T(1-R)}{\delta_m c_f} \right)^x \right), \\ (p_{1F}^f(\theta_1, \theta_2), p_{2F}^f(\theta_1, \theta_2)) &= (v_l T \theta_1, v_h T(\theta_2 - \theta_1) + v_l T \theta_1), \\ (D_1, D_2) &= (1 - \alpha, \alpha), \\ \Pi_{1F}^f &= \left(\frac{\delta_m - 1}{\delta_m^y} \frac{T^y (1-R)^y}{c_f^x} v_l^y - w \right) (1 - \alpha), \\ \Pi_{2F}^f &= \left(\frac{1}{\delta_m^y} \frac{T^y (1-R)^y}{c_f^x} (\delta_m v_l^y - \delta_m v_h v_l^x + (\delta_m - 1) v_h^y) \right. \\ &\quad \left. - w \right) \alpha. \end{aligned}$$

Proof of Lemma B.2. There are four cases of market coverage; no, partial low,

partial high and full coverages. Among them, no coverage is straight forward and partial low cannot be achieved since $v_l < v_h$. We focus on partial high and full coverages assuming $\theta_1 < \theta_2$ if $\theta_1 \neq \theta_2$ without loss of generality.

First, we analyze equilibrium under full coverage. There exists $w_{lF} > 0$ such that both firms are willing to participate if $w \leq w_{lF}$, which is identified as the result of the analysis. According to one product per firm assumption, M_1 has l segment and M_2 has h segment. Consumers' IC constraints (Moorthy and Png 1992) imply that

$$p_{1F}^f(\theta_1) = v_l T \theta_1,$$

$$p_{2F}^f(\theta_2, \theta_1) = v_h T (\theta_2 - \theta_1) + p_{1F}^f(\theta_1).$$

However, the optimal quality for segment l is not distorted thanks to the competition.

To see this, M_1 solves

$$\begin{aligned} \max_{\theta_1} \pi_1(\theta_1) &= (p_{1F}^f(\theta_1)(1-R) - w - c_f \theta_1^{\delta_m})(1-\alpha) \\ &= (v_l T \theta_1 (1-R) - w - c_f \theta_1^{\delta_m})(1-\alpha), \\ \theta_{1F}^f &= \left(\frac{v_l T (1-R)}{\delta_m c_f} \right)^{\frac{1}{\delta_m - 1}}. \end{aligned}$$

Similarly, $\theta_{2F}^f = \left(\frac{v_h T (1-R)}{\delta_m c_f} \right)^{\frac{1}{\delta_m - 1}}$. The full coverage equilibrium strategy and profits

are

$$\begin{aligned}
(\theta_{1F}^f, \theta_{2F}^f) &= \left(\left(\frac{v_l T(1-R)}{\delta_m c_f} \right)^x, \left(\frac{v_h T(1-R)}{\delta_m c_f} \right)^x \right), \\
(p_{1F}^f(\theta_1, \theta_2), p_{2F}^f(\theta_1, \theta_2)) &= (v_l T \theta_1, v_h T(\theta_2 - \theta_1) + v_l T \theta_1), \\
\Pi_{1F}^f &= \left(\frac{\delta_m - 1}{\delta_m^y} \frac{T^y (1-R)^y}{c_f^x} v_l^y - w \right) (1 - \alpha), \\
\Pi_{2F}^f &= \left(\frac{1}{\delta_m^y} \frac{T^y (1-R)^y}{c_f^x} (\delta_m v_l^y - \delta_m v_h v_l^x + (\delta_m - 1) v_h^y) - w \right) \alpha,
\end{aligned}$$

where $x = \frac{1}{\delta_m - 1}$ and $y = \frac{\delta_m}{\delta_m - 1}$. According to π_{1F}^f , the IR constraint is $w \leq \frac{1}{y} \frac{(v_l T(1-R))^y}{(\delta_m c_f)^x} \triangleq w_{lF}(T, R)$.

Next, the partial coverage can be achieved by either or both of manufacturers. Since two manufacturers are identical, if one can only enter h segment because of IR constraint, then both are competing for h segment and have equal demand. Hence, the latter is equilibrium. They set the optimal quality at the lowest price. The partial coverage equilibrium strategy and profit are

$$\begin{aligned}
\theta_F^p &= \left(\frac{v_h T \alpha^\gamma (1-R)}{\delta_m c_f} \right)^x, \\
p_F^p(\theta) &= \frac{w + c_f \theta^{\delta_m}}{1-R}, \\
\Pi_F^p(\theta_F^p, p_F^p(\theta_F^p)) &= 0.
\end{aligned}$$

For this to be indeed optimal, the product should satisfy consumer's IR, $v_h \theta_F^p T \alpha^\gamma - p_F^p \geq 0$.

$$w \leq \frac{1}{y} \frac{(v_h \alpha^\gamma T(1-R))^y}{(\delta_m c_f)^x} \triangleq w_{hF}(T, R).$$

□

Lemma B.3. Suppose there are identical suppliers and manufacturers in TISC. Assume TP's participation condition holds, i.e. $\delta_i \left(\frac{\delta_i \delta_m}{\delta_i - 1} \right)^{\delta_i - 1} \left(\frac{C}{\delta_m - 1} \right)^{\frac{k}{\delta_m}} \leq A(v_h) v_l^{\frac{k}{\delta_m - 1}}$, where $A(v_h) = v_l^{\frac{\delta_m}{\delta_m - 1}} - \alpha v_h v_l^{\frac{1}{\delta_m - 1}} + \alpha v_h^{\frac{\delta_m}{\delta_m - 1}}$ and $C = c_s c_t^{\delta_m/k} c_f^{\delta_i/k}$. Under FSB full coverage case, the optimal decision $(T, R(T))$ is

$$\left\{ \begin{array}{l} \left(\left(\frac{\left(\frac{c_s}{c_f} \frac{1}{\delta_m - 1} \right)^{1/\delta_m} A(v_h)}{\delta_i c_t v_l^{\frac{1}{\delta_m - 1}}} \right)^{\frac{1}{\delta_i - 1}}, 1 - \frac{\delta_m}{(\delta_m - 1)^{\frac{\delta_m - 1}{\delta_m}}} \frac{(c_f c_s^{\delta_m - 1})^{1/\delta_m}}{v_l T} \right) \quad \text{if} \\ A(v_h) v_l^{\frac{k}{\delta_m - 1}} < \delta_i \delta_m^{2\delta_i - 2} \left(\frac{C}{\delta_m - 1} \right)^{\frac{k}{\delta_m}}, \\ \left(\left(\frac{A(v_h)}{\delta_i c_t} \right)^{\frac{\delta_m - 1}{k}} \delta_m^{-2/k} c_f^{-1/k}, \frac{\delta_m - 1}{\delta_m} \right) \quad \text{otherwise.} \end{array} \right.$$

Proof of Lemma B.3. Notice the following.

$$\begin{aligned} \theta_1(T, R) &= \left(\frac{v_l T (1 - R)}{\delta_m c_f} \right)^{\frac{1}{\delta_m - 1}}, \\ p_1(T, R) &= (v_l T)^{\frac{\delta_m}{\delta_m - 1}} \left(\frac{1 - R}{\delta_m c_f} \right)^{\frac{1}{\delta_m - 1}} \\ &\triangleq A_1(T) (1 - R)^{\frac{1}{\delta_m - 1}}, \\ p_2(T, R|v_h) &= \left((v_l T)^{\frac{\delta_m}{\delta_m - 1}} - (v_l T)^{\frac{1}{\delta_m - 1}} v_h T + (v_h T)^{\frac{\delta_m}{\delta_m - 1}} \right) \left(\frac{1 - R}{\delta_m c_f} \right)^{\frac{1}{\delta_m - 1}} \\ &\triangleq A_2(T|v_h) (1 - R)^{\frac{1}{\delta_m - 1}}. \end{aligned}$$

The technology provider's problem is

$$\begin{aligned}
\max_{T,R} \quad & \Pi_I(T, R) = -c_t T^{\delta_i} + R(p_1(T, R)(1 - \alpha) + p_2(T, R|v_h)\alpha) \\
& = -c_t T^{\delta_i} + R \left(A_1(T)(1 - R)^{\frac{1}{\delta_m - 1}}(1 - \alpha) + A_2(T|v_h)(1 - R)^{\frac{1}{\delta_m - 1}}\alpha \right) \\
& = -c_t T^{\delta_i} + R(1 - R)^{\frac{1}{\delta_m - 1}} (A_1(T)(1 - \alpha) + A_2(T|v_h)\alpha) \\
\text{subject to} \quad & c_s \leq p_1(T, R)(1 - R) - c_f \theta_1^{\delta_m}(R), \\
& R \in (0, 1).
\end{aligned}$$

Let $R_b(T)$ and $R_u(T|v_h)$ denote optimal royalty rates for when the IR constraint is binding and not binding respectively. We note that while $R_u = (\delta_m - 1)/\delta_m$ is independent of T and v_h , R_b is depending explicitly on T and implicitly on v_h via T . $R_u(T)$ can be easily obtained from the first order condition. Then, the optimal royalty rate for some T is $R(T) = \min(R_b(T), R_u(T))$. When $R(T) = R_u(T)$, $\pi_I(T)$ is a polynomial with respect to T with a constant term increasing in v_h . Thus, the optimal technology level T_u is increasing in v_h . This applies to the case when $R(T) = R_b(T)$ and T_b is also increasing in v_h .

$$\begin{aligned}
T_u &= \left(\frac{A(v_h)}{\delta_i c_t} \right)^{\frac{\delta_m - 1}{K}} \delta_m^{-2/K} c_f^{-1/K}, \\
T_b &= \left(\frac{\left(\frac{c_s}{c_f} \frac{1}{\delta_m - 1} \right)^{1/\delta_m} A(v_h)}{\delta_i c_t v_l^{\frac{1}{\delta_m - 1}}} \right)^{\frac{1}{\delta_i - 1}},
\end{aligned}$$

where $A(v_h) = v_l^{\frac{\delta_m}{\delta_m - 1}} - \alpha v_h v_l^{\frac{1}{\delta_m - 1}} + \alpha v_h^{\frac{\delta_m}{\delta_m - 1}}$ and $K = \delta_i \delta_m - \delta_i - \delta_m$. After plugging T_b in $R_b(T_b)$ and comparing with R_u , $(T_u, R_u(T))$ is the solution if and only if

$$\delta_i (\delta_m^2)^{\delta_i - 1} \left(\frac{C}{\delta_m - 1} \right)^{\frac{K}{\delta_m}} < A(v_h) v_l^{\frac{K}{\delta_m - 1}},$$

where $C = c_s c_t^{\frac{\delta_m}{k}} c_f^{\frac{\delta_i}{k}}$. With T_b and $R_b(T)$, we obtain TP 's IR

$$\delta_i \left(\frac{\delta_i \delta_m}{\delta_i - 1} \right)^{\delta_i - 1} \left(\frac{C}{\delta_m - 1} \right)^{\frac{K}{\delta_m}} \leq A(v_h) v_l^{\frac{K}{\delta_m - 1}}.$$

Therefore, the optimal solution is

$$(T, R(T)) = \begin{cases} (0, 1) & \text{if } A(v_h) v_l^{\frac{K}{\delta_m - 1}} < \delta_i \left(\frac{\delta_i \delta_m}{\delta_i - 1} \right)^{\delta_i - 1} \left(\frac{C}{\delta_m - 1} \right)^{\frac{K}{\delta_m}}, \\ (T_b, R_b(T)) & \text{if } \delta_i \left(\frac{\delta_i \delta_m}{\delta_i - 1} \right)^{\delta_i - 1} \left(\frac{C}{\delta_m - 1} \right)^{\frac{K}{\delta_m}} \leq A(v_h) v_l^{\frac{K}{\delta_m - 1}} \\ & < \delta_i (\delta_m^2)^{\delta_i - 1} \left(\frac{C}{\delta_m - 1} \right)^{\frac{K}{\delta_m}}, \\ (T_u, R_u(T)) & \text{otherwise.} \end{cases}$$

The corresponding profit is

$$\Pi_I = \begin{cases} 0, \\ c_s \left(\frac{\delta_i - 1}{C^{\frac{k}{\delta_m(\delta_i - 1)}}} \left(\frac{1}{\delta_i (\delta_m - 1)^{1/\delta_m}} \right)^{\frac{\delta_i}{\delta_i - 1}} \left(\frac{A}{v_l^{1/(\delta_m - 1)}} \right)^{\frac{\delta_i}{\delta_i - 1}} - \frac{A}{v_l^{\frac{\delta_m}{\delta_m - 1}}} \frac{\delta_m}{\delta_m - 1} \right), \\ \frac{A^{1+z_m}}{\delta_m^{1+2z_i} \delta_i^{1+z_m} c_t^{z_m} c_f^{z_i}} K. \end{cases}$$

□

Lemma B.4. *Suppose there are identical suppliers and manufacturers in TISC. For partial coverage under FSB, the optimal royalty rate decreases from R_h to R_l as market inequality increases.*

Proof of Lemma B.4. The full system price (p^p) is affected by two factors w and R . Since w is determined at c_s due to the competition in Tier 1, p^P is solely

determined by R . Therefore, the technology provider solves the following problem.

$$\begin{aligned} & \underset{T,R}{\text{maximize}} \quad \Pi_I^p(T, R) = -c_t T^3 + R \frac{c_f (\theta_2^p)^{\delta_m} + c_s}{1-R} \alpha \\ & \text{subject to} \quad c_s > v_l \theta_1(T, R) T (1-R) - c_f \theta_1(T, R)^{\delta_m}, \end{aligned} \quad (\text{B.2})$$

$$c_s \leq v_h \alpha^\gamma \theta_2^p T (1-R) - c_f (\theta_2^p)^{\delta_m}. \quad (\text{B.3})$$

(B.2) assures the manufacturers in Tier 0 that the deviation to l segment is not profitable and (B.3) guarantees that the concentration on h segment is profitable. There are three candidates for the partial coverage optimal royalty rate R^p . Let R_l and R_h be the boundary solutions for two constraints, respectively, and $R_i \in (R_l, R_h)$ denotes the feasible interior solution of the first order condition of Π_I^p with respect to R .

First, we shows that as v_h increases the boundary royalty rates increase. Let R_l and R_h be the each boundary solution for (B.2) and (B.3) respectively.

$$\begin{aligned} R_l &= 1 - \frac{c_f \left(\frac{c_s}{c_f (\delta_m - 1)} \right)^{\frac{\delta_m - 1}{\delta_m}} \delta_m}{v_l T}, \\ R_h &= 1 - \frac{c_f \left(\frac{c_s}{c_f (\delta_m - 1)} \right)^{\frac{\delta_m - 1}{\delta_m}} \delta_m}{v_h \alpha^\gamma T}. \end{aligned}$$

Both are clearly increasing in T . Let T_l and T_h be the corresponding optimal technologies to R_l and R_h respectively. When R is replaced with R_l ,

$$\Pi_I^p(T) = -c_t T^{\delta_i} + \left(R_l v_l \theta_1 T + \frac{R_l}{1-R_l} c_f (\theta_2^{\delta_m} - \theta_1^{\delta_m}) \right) \alpha.$$

As v_h increases, θ_2 increases. So do the parenthesis term and T_l . This applies to

T_h as well. Explicitly,

$$T_l = \left(\frac{\alpha v_l \left(\frac{c_s}{c_f(\delta_m-1)} \right)^{\frac{1}{\delta_m}} \left(-1 + \left(\frac{v_h}{v_l} \right)^{\frac{\delta_m}{\delta_m-1}} \alpha^\gamma \frac{\delta_m}{\delta_m-1} + \delta_m \right)}{c_t \delta_i \delta_m} \right)^{\frac{1}{\delta_i-1}},$$

$$T_h = \left(\frac{v_h \alpha^\gamma \left(\frac{c_s}{c_f(\delta_m-1)} \right)^{\frac{1}{\delta_m}}}{c_t \delta_i} \alpha \right)^{\frac{1}{\delta_i-1}}.$$

Next, we prove there is a threshold of $v_h \alpha^\gamma$ under (over) which R_h is more (less) profitable than R_l . With all these solutions of R and T , one can compare the profit functions which are convexly increasing in $v_h \alpha^\gamma \geq v_l$. We note that the highest degree of $v_h \alpha^\gamma$ in $\Pi_I^p(T_l, R_l(T_l))$ is $\frac{\delta_m}{\delta_m-1} \frac{\delta_i}{\delta_i-1}$. The highest degree of v_h in $\Pi_{IF}^p(T_h, R_h(T_h))$ is $\frac{\delta_i}{\delta_i-1}$, which implies that $\Pi_{IF}^p(T_l, R_l(T_l))$ is increasing faster. Moreover, when $v_h \alpha^\gamma = v_l$, $R_h = R_l$ and $T_h = T_l$. So are the profit functions. Therefore, there exists a threshold of $v_h \alpha^\gamma$ under which $(T_h, R_h(T))$ is optimal and over which $(T_l, R_l(T))$ is.

Lastly, consider the interior solution for the royalty rate, R_i . FOC is written as

$$(1 - (1 - R_i)\delta_m) \left(\frac{v_h \alpha^\gamma T (1 - R_i)}{c_f \delta_m} \right)^{\frac{\delta_m}{\delta_m-1}} = (\delta_m - 1) \frac{c_s}{c_f}.$$

Since RHS is positive, it is necessary that $R_i > 1 - 1/\delta_m$. We note that LHS is increasing and then decreasing in $R_i \in [1 - 1/\delta_m, 1]$. As $v_h \alpha^\gamma$ increases, R_i decreases to satisfy the equation. We remind two feasibility conditions for R_i and for the partial coverage, $R_l < R_i < R_h$ and $v_h \alpha^\gamma \geq v_l$ respectively. When $v_h \alpha^\gamma = v_l$, $R_l = R_h$ and R_i is not feasible. Since R_i decreases but R_l increases in $v_h \alpha^\gamma$, R_i is not feasible for large enough $v_h \alpha^\gamma$. Therefore, R^p changes from R_h to R_l as $v_h \alpha^\gamma$ increases. □

Proof of Lemma 2.2. We show that the partial coverage can be optimal for large α and intermediate v_h . First, we prove that R^p must be either R_h or R_i for the partial coverage to be optimal. Assume $R^p = R_l$. For some $T > 0$, the market is either fully or partially covered. Because the technology investment is same, the royalty profit under the partial coverage should be greater than that under the full coverage. For the same T and R , θ_2 is the same under both coverages. However, the competition in the partial coverage drives p_2 down. The royalty profit from h segment under the partial coverage is less than that under the full coverage. Hence, the partial coverage with R_l cannot earn more profit than the full coverage.

Second, assume $A(v_h)v_l^{\frac{K}{\delta_m-1}} = \delta_i\delta_m^{2\delta_i-2}\left(\frac{C}{\delta_m-1}\right)^{\frac{K}{\delta_m}}$ and let Π_{Iu} be the unconstrained profit of FSB TP . We compare this to $\Pi_I^p(T_h, R_h)$, which may be suboptimal for the partial coverage. Let $v_h = \frac{v_l}{\alpha^\gamma}q$ for some $q > 1$. The difference is

$$\begin{aligned} \Pi_I^p - \Pi_{Iu} = & c_t(\delta_i - 1) \left(\frac{v_h \alpha^{\gamma+1} \left(\frac{c_s}{c_f(\delta_m-1)} \right)^{1/\delta_m}}{c_t \delta_i} \right)^{\frac{\delta_i}{\delta_i-1}} - \frac{\delta_m}{\delta_m-1} c_s \alpha \\ & - \frac{A(v_h)^{1+z_m}}{c_t^{z_m} c_f^{z_i}} \frac{k}{\delta_i^{1+z_m} \delta_m^{1+2z_i}}. \end{aligned}$$

After some algebra, it can be reduced to

$$h(q, \alpha) \triangleq \alpha \left(\delta_m(\delta_i - 1) \frac{q^{\frac{\delta_i}{\delta_i-1}}}{\sqrt{A'}} \alpha^{\frac{1}{\delta_i-1}} - \delta_i \right) - A'k,$$

where $A' = 1 - \frac{q}{\alpha^{\gamma-1}} + \left(\frac{q}{\alpha^\gamma}\right)^{\frac{\delta_m}{\delta_m-1}} \alpha$. We note that $h(1,1) = 0$. h 's local behaviors around $k = 1$ and $\alpha = 1$ are $\frac{\partial h(1,\alpha)}{\partial \alpha} \Big|_{\alpha=1} = \frac{\gamma(3\delta_i\delta_m - 3\delta_m - 2\delta_i) + \delta_i 2(\delta_m-1)^2}{2(\delta_m-1)} > 0$ and $\frac{\partial h(q,1)}{\partial q} \Big|_{q=1} = \frac{3\delta_m + \delta_i(\delta_m-2)(2\delta_m-1)}{2(\delta_m-1)}$, which is positive if $\delta_m \geq 2$ or if $\delta_m \in (1,2)$ and $\delta_i < -\frac{3\delta_m}{2\delta_m^2 - 5\delta_m + 2}$. Thus, when α is close to 1 and $\frac{\partial h(q,1)}{\partial q} \Big|_{q=1} > 0$, the difference

increases from negative to positive as q increases. However, as the highest degree of q has negative coefficient, h becomes negative for large enough q . Apparently, when α is small or $\frac{\partial h(q,1)}{\partial q}|_{q=1} < 0$, h is negative. In short, FSB TP 's optimal coverage policy is an interval for large enough α and intermediate market inequality under limited convexity condition. □

Lemma B.5. *There exists $\bar{\alpha} \in [0, 1]$ such that for $\alpha \leq \bar{\alpha}$ and $\forall v_h > v_l$, the market is fully covered regardless of the royalty bases.*

Proof of Lemma B.5. We seek for the lower bound of α under which the market is fully covered by both SSB and FSB for all $v_h > v_l$. In Lemma 2.1, we obtain two profit functions π_I^f and π_I^p for Full and Partial coverages with the threshold market inequality $\frac{\tilde{v}_h}{v_l}$, which is an 1-1 function of α . Let $\alpha_1(v_h/v_l)$ be the inverse function of $\frac{\tilde{v}_h}{v_l}$. Using Lemma B.3, let us define $\alpha_2(v_h/v_l)$ which solves $\Pi_I = \pi_I^p$. Note that α_2 may not exist if $\Pi_I < \pi_I^f$. Then, let $\bar{\alpha}(v_h/v_l) = \min(\alpha_1(v_h/v_l), \alpha_2(v_h/v_l))$, which always exists. Finally, we can define $\bar{\alpha} = \arg \inf_{v_h > v_l} \{\bar{\alpha}(v_h/v_l)\}$. For moderate parameter values, $\bar{\alpha} \approx 0.647$ as illustrated in Figure B.1. □

Proof of Proposition 2.2. Assume the following TP 's participation constraints under SSB and FSB, respectively, to ensure a meaningful comparison.

$$v_l^{\delta_m \delta_i / k} \geq \delta_i^{z_m + 1} \delta_m^{z_i + 1} C / k,$$

$$\delta_i \left(\frac{\delta_i \delta_m}{\delta_i - 1} \right)^{\delta_i - 1} \left(\frac{C}{\delta_m - 1} \right)^{\frac{k}{\delta_m}} \leq A(v_h) v_l^{\frac{k}{\delta_m - 1}}.$$

¹Parameter values are $\delta_m = 2, \delta_i = 3, c_s = 0.35, c_t = 0.5, c_f = 0.25, \gamma = 1$, and $v_l = 1$.

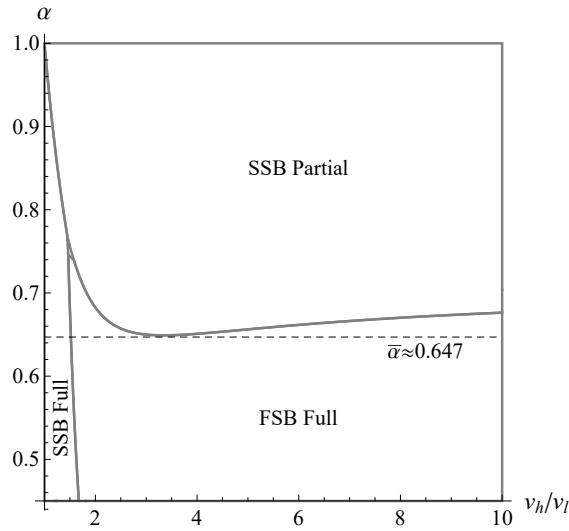


Figure B.1: Technology Provider's Optimal Business Model in v_h/v_l and α ¹

Suppose $\alpha < \bar{\alpha}$ where SSB partial is not optimal. Consider FSB partial coverage. It is clear that SSB partial dominates FSB partial since SSB TP does not impose negative impacts on full system quality. Therefore, if $\alpha < \bar{\alpha}$, the optimal policy is either SSB full for FSB full. While π_I^f is constant in v_h , Π_I^f is increasing in v_h . It is clear that there exists a some threshold v_h for TP under which SSB is optimal but over which FSB is optimal. We define such a threshold as ν_I . We will show such thresholds for each entity, namely consumer (ν_C), manufacturer (ν_M) and social welfare (ν_{SW}). Define $x = \frac{1}{\delta_m - 1}$ and $y = \frac{\delta_m}{\delta_m - 1}$.

- M_1 : It weakly prefers FSB regardless of v_h since the profit is zero under SSB full but can be positive under FSB full.
- M_2 : Let π_2 and Π_2 be the profits under SSB and FSB. The functional forms clearly show that both are convex increasing. If

$$\pi_2 = \frac{t^y}{(\delta_m c_f)^x} \left(\frac{v_h^y}{y} - (v_h - v_l)v_l^x \right) - w,$$

$$\Pi_2 = \frac{(T(1-R))^y}{(\delta_m c_f)^x} \left(\frac{v_h^y}{y} - (v_h - v_l)(v_l)^x \right) - c_s.$$

$\Pi_2 = \pi_2$ is equivalent to $\left(\frac{v_h^y}{y} - (v_h - v_l)(v_l)^x\right)((T(1-R))^y - t^y) = w - c_s$.

Notice that RHS is positive for $w > c_s$. For this to hold, $T(1-R) > t$ at ν_M .

- l consumer: His surplus is always zero regardless of business models.
- h consumer: Let u_h and U_h be h consumer's utilities under SSB and FSB.

$$\begin{aligned} u_h(t) &= v_h \theta_2 t - p_2 \\ &= v_h \theta_2 t - (v_h t (\theta_2 - \theta_1) - v_l \theta_1 t) \\ &= \theta_1 t (v_h - v_l) \\ &= \left(\frac{v_l}{\delta_m c_f}\right)^x (v_h - v_l) t^y. \end{aligned}$$

Similarly,

$$U_h(T, R) = \left(\frac{v_l}{\delta_m c_f}\right)^x (v_h - v_l) T^y (1-R)^x.$$

It is clear that if $T^y (1-R)^x \geq t^y$ the consumer is better off under FSB.

Since $y = x + 1$, $T^y (1-R)^x > T^y (1-R)^y \geq t^y$. That is if M_2 prefers FSB, h consumer is already better off under FSB. Thus, $\nu_C < \nu_M$.

- Innovator: We prove $T < t$ at ν_I .

ν_I is from either the unconstrained FSB profit or the constrained FSB profit with SSB profit. Assume that it is from the unconstrained profit function.

At ν_I ,

$$\begin{aligned} \Pi_I^u - \pi_I &= 0, \\ \left(v_l^{\frac{\delta_i \delta_m}{k}} - \frac{A \frac{\delta_i (\delta_m - 1)}{k}}{\delta_m^{\delta_i/k}}\right) &= c_s c_t^{z_m} c_f^{z_i} \delta_m^{1+z_i} \delta_i^{1+z_m} \frac{1}{k}. \end{aligned}$$

For LHS to be positive, $v_l^{\delta_m} > A^{\delta_m-1}/\delta_m$. Let $A = v_l^{\delta_m/(\delta_m-1)}\tau$ where $\tau > 1$.

$$v_l^{\delta_m} - A^{\delta_m-1}/\delta_m = v_l^{\delta_m} \frac{\delta_m - \tau^{\delta_m-1}}{\delta_m} > 0,$$

$$\delta_m > \tau^{\delta_m-1}.$$

The following shows that $\delta_m > \tau^{\delta_m-1}$ implies $T < t$.

$$T = \left(\frac{A}{\delta_i c_t} \right)^{\frac{\delta_m-1}{k}} \frac{1}{\delta_m^{2/k} c_f^{1/k}} < \left(\frac{v_l^{\delta_m}}{c_f \delta_m (c_t \delta_i)^{\delta_m-1}} \right)^{1/k} = t,$$

$$\left(\frac{A}{\delta_i c_t} \right)^{\delta_m-1} \frac{1}{\delta_m^2 c_f} < \frac{v_l^{\delta_m}}{c_f \delta_m (c_t \delta_i)^{\delta_m-1}},$$

$$\tau^{\delta_m-1} < \delta_m.$$

Next, consider ν_I is from the constrained FSB. We show that $\Pi_I^c > \pi_I$ for $t = T$ at $v_h/v_l = \nu_{tech}$. Define $B = \frac{A}{v_l^{1/(\delta_m-1)}}$. By solving $t = T$ with respect to B , we obtain

$$B = c_f^{\frac{1-\delta_i}{k} + \frac{1}{\delta_m}} c_s^{-1/\delta_m} c_t^{-1/k} \delta_i^{-1/k} (\delta_m - 1)^{\frac{1}{\delta_m}} \delta_m^{\frac{1-\delta_i}{k}} v_l^{\frac{(\delta_i-1)\delta_m}{k}}.$$

Since π_I is constant under the full coverage, we normalize $\pi_{I,SSB} = 0$ without loss of generality by setting $v_l^{\delta_i \delta_m/k} = XC$ where $X = \frac{\delta_i^{1+z_m} \delta_m^{1+z_i}}{k}$ and $C = c_s c_t^{z_m} c_f^{z_i}$. After plugging B into Π_I^c and rearranging it, $\Pi_I^c \geq 0$ is equivalent to

$$v_l^{\frac{\delta_i \delta_m - \delta_i}{k}} \geq \frac{c_s (\delta_m - 1)^{1/\delta_m} \delta_m^{\frac{1}{k} + 1} c_f^{\frac{1}{\delta_m} + \frac{1}{k}} c_t^{\frac{\delta_m-1}{k}} \delta_i^{\frac{\delta_m+k}{k}}}{(\delta_i - 1) (\delta_m - 1) c_s^{1/\delta_m} \delta_i^{1/k}}$$

$$(\delta_i - 1) \left(\frac{\delta_m - 1}{k} \right)^{1 - \frac{1}{\delta_m}} \delta_i^{-1/\delta_m} \geq 1$$

$$\frac{k}{k + \delta_m} \geq \left(\frac{k}{k + 1} \right)^{\delta_m}.$$

The second inequality is derived using $v_l^{\delta_i \delta_m / k} = XC$. The third is obtained after multiplying each side with $(\delta_m - 1)/k$, which holds since $k(k+1)^{\delta_m} \geq (k + \delta_m)k^{\delta_m} = k^{\delta_m+1} + \delta_m k^{\delta_m}$. Therefore, $T < t$ at ν_I or equivalently $\nu_I < \nu_{tech}$. Moreover, when consumers and M_2 are indifferent between business models, they require much higher technology quality, $T^y(1-R)^y \geq t^y$ and $T(1-R) > t$ as shown above respectively. Thus, $\nu_I < \nu_{tech} < \nu_C < \nu_{M_2}$.

- Social Welfare: Let π_{SW} and Π_{SW} be the social welfare under SSB and FSB.

$$\begin{aligned}\pi_{SW} &= \pi_I + \pi_S + \pi_1 + \pi_2 + u_l + u_h \\ &= -c_t t^{\delta_i} + \frac{\alpha v_h^y + (1-\alpha)v_l^y t^y}{(\delta_m c_f)^x} - c_s, \\ \Pi_{SW} &= -c_t T^{\delta_i} + \frac{\alpha v_h^y + (1-\alpha)v_l^y T^y (1-R)^x}{(\delta_m c_f)^x} \left(\frac{1}{y} + \frac{R}{\delta_m} \right) - c_s,\end{aligned}$$

where π_S is the suppliers profits equal to zero due to price competition. Assume $t = T$. If $1/y > (1-R)^x(1/y + R/\delta_m)$, then SSB is preferred.

$$\begin{aligned}\frac{1}{y} &> (1-R)^x \left(\frac{1}{y} + \frac{R}{\delta_m} \right), \\ \frac{\delta_m - 1}{\delta_m} &> (1-R)^x \frac{\delta_m - (1-R)}{\delta_m}, \\ \delta_m - \delta_m(1-R)^x &> 1 - (1-R)^y, \\ \delta_m(1 - (1-R)^x) &> 1 - (1-R)^y.\end{aligned}$$

The third inequality uses $y = x + 1$. The last inequality holds since $\delta_m > 1$ and $y > x$. This proves $\pi_{SW} > \Pi_{SW}$ at $t = T$ implying $\nu_I < \nu_{SW}$. Next, we show that $\Pi_{SW} > \pi_{SW}$ at ν_C or $T^y(1-R)^x = t^y$. Gathering revenue or surplus in

LHS and technology investment in RHS, we have the following inequality.

$$\frac{\alpha v_h^y + (1 - \alpha)v_l^y}{(\delta_m c_f)^x} \left(T^y (1 - R)^x \left(\frac{1}{y} + \frac{R}{\delta_m} \right) - \frac{t^y}{y} \right) > c_t (T^{\delta_i} - t^{\delta_i}),$$

$$\frac{\alpha v_h^y + (1 - \alpha)v_l^y}{(\delta_m c_f)^x} t^y \frac{R}{\delta_m} > 0 > c_t (T^{\delta_i} - t^{\delta_i}).$$

Therefore, the thresholds of all entities satisfy $\nu_I < \nu_{SW} < \nu_C < \nu_M$.

□

Proof of Proposition 2.3. In Proposition 2.2, for a given v_l , small enough supply chain cost parameters, and $\alpha < \bar{\alpha}$, we show $\Pi_I - \pi_I$ and $\Pi_2 - \pi_2$ are monotonically increasing in v_h from negative to positive where $\Pi_I - \pi_I$ becomes positive at a smaller value of v_h . Define v_{h1} such that $\Pi_I - \pi_I = 0$ and $\Pi_2 - \pi_2 < 0$. Similarly, one can consider v_{h2} such that $\Pi_I - \pi_I > 0$ and $\Pi_2 - \pi_2 = 0$. Both profit difference functions are monotone. So is their sum, $\Delta \triangleq (\Pi_I - \pi_I) - (\pi_2 - \Pi_2)$. It is clear that Δ is increasing between v_{h1} and v_{h2} from negative to positive. Let us define \hat{v}_h such that $\Delta = 0$. Then, for $v_h \in (v_{h1}, \hat{v}_h)$, M_2 can have TP to adopt SSB by giving $|\Pi_I - \pi_I|$. For $v_h \in [\hat{v}_h, v_{h2})$, TP can implement FSB without incurring the conflict of interests with M_2 by subsidizing $|\Pi_2 - \pi_2|$.

Although characterizations of v_{h1} and v_{h2} generally intractable, we can obtain them for a special case. Consider $\delta_m = 2$, $\delta_i = 3$, $\gamma = 1$, and $\alpha < \bar{\alpha}$. Define $A(v_h) = v_l^2 - \alpha v_l v_h + \alpha v_h^2$. For some supply chain costs (c_t, c_s, c_f) , one can define v'_h such that $A(v'_h)v_l = 48\sqrt{c_s c_t^2 c_f^3}$. and TP 's optimal decisions are the unconstrained one for $v_h \geq v'_h$ or $A(v_h)v_l \geq 48\sqrt{c_s c_t^2 c_f^3}$. Consider TP 's additional profit from SSB

to FSB.

$$\begin{aligned}
\Pi_I(v'_h) - \pi_I(v'_h) &= \frac{A(v'_h)^3}{3456c_t^2c_f^3} - \left(\frac{v_l^6}{432c_t^2c_f^3} - c_s \right) \\
&= \frac{1}{3456c_t^2c_f^3} \left(A(v'_h)^3 + 3456c_sc_t^2c_f^3 - 8v_l^6 \right) \\
&= \frac{1}{3456c_t^2c_f^3} \left(A(v'_h)^3 - 8v_l^6 + \frac{3}{2}A(v'_h)^2v_l^2 \right).
\end{aligned}$$

Note that $\Pi_I(v'_h) - \pi_I(v'_h) \geq 0$ if $A(v'_h) \geq 2v_l^2$, which is equivalent to

$$v'_h \geq \frac{\alpha + \sqrt{\alpha(4+\alpha)}}{2\alpha} v_l \triangleq v'_{h1}.$$

One can verify that $\Delta(v'_{h1}) = -6v_l^6(4+9\alpha-3\sqrt{\alpha(4+\alpha)}) < 0$ for $\alpha \in (0,1)$ and $A(v'_{h1})v_l \geq \sqrt{c_sc_t^2c_f^3} \equiv v_l^3 \geq 24\sqrt{c_sc_t^2c_f^3}$. $v_{h2} \triangleq v_l \frac{\alpha + \sqrt{\alpha(12+\alpha)}}{2\alpha}$ can be obtained by equating Π_2 and π_2 and $\Delta(v_{h2}) > 0$ can be easily verified. Therefore, if $v_l^3 \geq 24\sqrt{c_sc_t^2c_f^3}$, Δ is increasing from negative to positive between v'_{h1} and v_{h2} .

□

Lemma B.6. *For some T , the optimal royalty rate for each case is*

$$\begin{aligned}
R_b(T) &= 1 - \frac{2\sqrt{c_fc_s}}{v_l T}, \\
R_{u1} &= \max\left(0, \frac{(2\alpha-1)v_l^2 - \alpha v_l v_h + \alpha v_h^2}{2\alpha(v_l^2 - v_l v_h + v_h^2)}\right), \\
R_{u2} &= \max\left(0, \frac{-\alpha v_h^2 + v_l(v_l - 4\alpha v_l + 3\alpha v_h)}{2v_l(v_l - 2\alpha v_l + \alpha v_h)}\right), \\
\hat{R}(T) &= \begin{cases} 1 - \frac{2\sqrt{c_fc_s}}{T} \sqrt{\frac{1-2\alpha}{-\alpha v_h^2 + 2\alpha v_l v_h + (1-3\alpha)v_l^2}} & \text{if } v_h/v_l \leq 1 + \sqrt{(1-2\alpha)/\alpha} \\ & \text{and } \alpha < 1/2, \\ 0 & \text{otherwise,} \end{cases}
\end{aligned}$$

Let $R^*(T)$ denote the optimal royalty rate for Full coverage under FSB, namely $R^*(T) = \arg \max\{\Pi_I(T, R_b(T)), \Pi_I(T, R_{u1}(T)), \Pi_I(T, R_{u2}(T)), \Pi_I(T, \hat{R}(T))\}$. Assume $\Pi_I(T, R^*(T)) \geq 0$. Then,

$$R^*(T) = \begin{cases} R_{u2} & \text{if } R_{u2} < R_b(T), R_{u1} < \hat{R}(T), \text{ and } R_{u2} < \hat{R}(T), \\ R_{u1} & \text{if } R_{u1} < R_b(T), R_{u1} > \hat{R}(T), \text{ and } R_{u2} > \hat{R}(T), \\ \hat{R}(T) & \text{if } R_{u1} \leq \hat{R}(T) \text{ and } R_{u2} \geq \hat{R}(T), \\ R_b(T) & \text{otherwise.} \end{cases}$$

Proof of Lemma B.6. Each royalty rate can be obtained by the first order condition or the boundary condition after replacing M with each case. The four cases follow their definitions. Specifically,

1. $0 < B_1 < B_2$ and $M = B_1$

For some T , $B_1 < B_2$ is equivalent to

$$\left(\frac{v_l^2}{4c_f}(1-R)^2T^2 - c_s\right)(1-\alpha) < \left(\frac{2v_l^2 - 2v_hv_l + v_h^2}{4c_f}(1-R)^2T^2 - c_s\right)\alpha.$$

When $\hat{R}(T) > 0$, it equates the both sides. If $R_{u1} > \hat{R}(T)$ and $R_{u2} > \hat{R}(T)$, then $B_1 < B_2$ holds. Additionally, if R_{u1} satisfies IR condition or $R_{u1} < R_b(T)$, it is optimal.

2. $0 < B_2 < B_1$ and $M = B_2$

Similarly, for $B_2 < B_1$ to hold, $R_{u1} < \hat{R}(T)$ and $R_{u2} < \hat{R}(T)$ are necessary. If R_{u2} meets this and IR condition, it is optimal.

3. $0 < B_1 = B_2$ and $M = B_1$

When both $R_{u1} > \hat{R}(T)$ and $R_{u2} < \hat{R}(T)$ do not hold, neither $B_1 < B_2$ nor $B_2 < B_1$ do. Hence, $B_1 = B_2$.

□

Proof of Proposition 2.4. Consider $\alpha > 1/2$. $B_2 > B_1$ since M_2 's margin is higher than M_1 , resulting in $M = B_1$. Assume that M_1 's IR is not binding. Then,

$$T^* = \frac{(\alpha v_h^2 - \alpha v_h v_l + v_l^2)^2}{12\alpha c_f c_t (v_h^2 - v_h v_l + v_l^2)},$$

$$R^* = \frac{(v_h^2 \alpha - v_h v_l \alpha + v_l^2 (-1 + 2\alpha))}{2(v_h^2 - v_h v_l + v_l^2) \alpha}.$$

For $R^* > 0$, $\alpha > \frac{v_l^2}{2v_l^2 - v_l v_h + v_h^2}$ which is implied by $\alpha > 1/2$. To satisfy M_1 's IR,

$$\sqrt{C} \leq \frac{v_l(v_l^2 - \alpha v_l v_h + \alpha v_h^2)^3}{48(v_l^2 - v_l v_h + v_h^2)^2 \alpha^2},$$

which gives α 's upper bound $\bar{\alpha}(v_h/v_l)$. Suppose $B_2 \leq B_1$. Since the margin of M_2 is higher than that of M_1 , if B_2 to be zero due to a high R , the margin of M_1 is negative or IR does not hold. Thus, $0 = B_2 < B_1$ cannot be the case. If $0 < B_2 < B_1$, then $M > 0$. Therefore, $M = 0$ or $R^*(T) = R_b(T)$ only if $\bar{\alpha}(v_h/v_l) < \alpha < 1$.

1. R^* may not be increasing in v_h/v_l .

Suppose $R^* = R_{u2}$. $R_{u2} > 0$ if $v_h/v_l \in (1, \frac{3\alpha + \sqrt{4\alpha - 7\alpha^2}}{2\alpha})$. Its derivative with respect to v_h shows that it is negative if $v_h/v_l > \frac{2\alpha - 1 + \sqrt{(1-\alpha)^2 + \alpha^2}}{\alpha}$. By comparing two bounds, we have

$$\frac{2\alpha - 1 + \sqrt{(1-\alpha)^2 + \alpha^2}}{\alpha} < \frac{3\alpha + \sqrt{4\alpha - 7\alpha^2}}{2\alpha}$$

$$2\sqrt{(1-\alpha)^2 + \alpha^2} < 2 - \alpha + \sqrt{4\alpha - 7\alpha^2},$$

since $2\sqrt{(1-\alpha)^2 + \alpha^2} \leq 2$ and $-\alpha + \sqrt{4\alpha - 7\alpha^2} > 0$ for $\alpha < 1/2$, which is necessary for $R^* = R_{u2}$. Thus, R_{u2} is decreasing in v_h/v_l . So is R^* .

2. $\alpha \neq 1/2$, SSB is better for low v_h/v_l .

Let us normalize SSB TP 's profit at $v_h = v_l$ to zero by setting $v_l^6 = 432C$, where $C = c_s c_t^2 c_f^3$. $M \in \{0, B_1, B_2\}$. We know that FSB cannot outperform $M = 0$ from the base case analysis. The other two cases are very similar. We present the proof for $M = B_1$.

(a) $\alpha > 1/2$

$B_1 < B_2$ holds. At $v_h = v_l$, $R_{u1} = 1 - \frac{1}{2\alpha}$. For this to be the solution, it should satisfy manufacturer's IR, $R_{u1} \leq R_b(T_{u1})$.

$$1 - \frac{1}{2\alpha} \leq 1 - \frac{24\alpha\sqrt{C}}{v_l^3}$$

$$48\alpha^2\sqrt{C} \leq v_l^3$$

$$\alpha \leq \left(\frac{\sqrt{3}}{4}\right)^{1/2}$$

For $\frac{1}{2} < \alpha < \left(\frac{\sqrt{3}}{4}\right)^{1/2}$, FSB TP 's IR is

$$\left(\frac{v_l^6}{3456C} \frac{1}{\alpha^3} - 2(1-\alpha)\right) c_s > 0$$

$$\frac{1}{8\alpha^3} > 2(1-\alpha).$$

Notice that both sides have the same value at $\alpha = 1/2$. While LHS convexly decreases, RHS does linearly, which means they cross once for $\alpha > 1/2$. The inequality does not hold at $\alpha = \left(\frac{\sqrt{3}}{4}\right)^{1/2}$. Therefore, when $M = B_1$, FSB TP cannot weakly dominate SSB for all v_h/v_l .

(b) $\alpha < 1/2$ and $B_2 < B_1$

One can prove this case similarly.

(c) $\alpha < 1/2$ and $B_1 < B_2$

For $B_1 < B_2$ to be true,

$$\left(\frac{v_l^2}{4c_f}T^2(1-R)^2 - c_s\right)(1-\alpha) < \left(\frac{v_h^2 - 2v_hv_l + 2v_l^2}{4c_f}T^2(1-R)^2 - c_s\right)\alpha.$$

Since $\alpha < 1/2$, the inequality does not hold for small v_h/v_l . Thus, FSB with $M = B_1$ cannot weakly dominate SSB for all v_h/v_l .

□

Lemma B.7 (SSB TP's Optimal Decisions For Each Strategy). *Let $C_1 = c_1c_t^2c_f^3$ and $C_2 = c_2c_t^2c_f^3$. Assume $432C_2 \leq v_l^6$ and $432C_2 \leq v_h^6\alpha^8$.*

1. (Monopoly/Deter) *If TP is the monopoly or wants to deter, her optimal decision and profit are*

$$(t^d(\beta), r^d(t, \beta), w^d(t, \beta)) = \left(\frac{v_l^2}{6c_fc_t}, 1, \frac{(v_lt)^2}{4c_f}\right),$$

$$\pi_I^d = \frac{v_l^6}{432c_t^2c_f^3} - c_2.$$

2. (Share) *If $144C_1 > \beta^2v_l^2(\beta^2v_l^2 + \alpha(1-\beta^2)v_h^2)^2$, sharing is not feasible. Otherwise,*

$$(t^s(\beta), r^s(t, \beta)) = \left(\frac{\beta^2v_l^2 + \alpha(1-\beta^2)v_h^2}{6c_fc_t}, 1 - \frac{4c_fc_1}{(v_lt\beta)^2}\right),$$

$$w_I^s(t, \beta) = (v_h^2(1-\beta^2) + v_l^2\beta^2)\frac{t^2}{4c_f},$$

$$\pi_I^s(\beta) = \frac{(\beta^2v_l^2 + \alpha(1-\beta^2)v_h^2)^3}{432c_t^2c_f^3} - (1-\alpha)c_1 - \alpha c_2.$$

If $v_h \leq v_l/\sqrt{\alpha} \triangleq v_h^{s2}$, π_I^s is increasing in β . Otherwise, it decreasing in β .

3. (Forego) If $432C_1 > (v_l\beta)^6$, feasible. Otherwise, the optimal foregoing decision and profit are

$$(t^f(\beta), r^f(t, \beta)) = \left(\frac{(v_l\beta)^2}{6c_f c_t}, 1 - \frac{4c_f c_1}{(v_l t \beta)^2} \right),$$

$$\pi_I^f(\beta) = \frac{(v_l\beta)^6}{432c_t^2 c_f^3} - c_1.$$

Proof of Lemma B.7. 1. (Monopoly/Deter) If $r = 1$, no supplier can enter. The market has one subsystem of quality 1. The optimal decision is the same to that in Lemma 2.1.

2. (Share) Consider Tier 1 problem about subsystem price. Under *Share* equilibrium, TP and S_1 sell their subsystems to M_2 and M_1 respectively. They set subsystem prices such that both manufacturers would not deviate. This gives

$$w_S(t, \beta) + \frac{(v_l t)^2}{4c_f}(1 - \beta^2) \leq w_I(t, \beta) \leq w_S(t, \beta) + \frac{(v_h t)^2}{4c_f}(1 - \beta^2),$$

where w_I and w_S are the subsystem prices for TP and S_1 , respectively. When these inequalities hold, the demands for TP and S_1 do not change. Thus, $w_S(t, \beta) = \frac{(v_l t \beta)^2}{4c_f}$ and $w_I(t, \beta) = w_S(t, \beta) + \frac{(v_h t)^2}{4c_f}(1 - \beta^2) = (v_h^2(1 - \beta^2) + v_l^2\beta^2)\frac{t^2}{4c_f}$. If S_1 were to deviate, it lowers the price to take both segments by

setting $w_S^{lh} = c_2 - \frac{(v_h t)^2}{4c_f}(1 - \beta^2)$. At Tier 2, TP solves the following problem.

$$\max_{t,r} \quad \pi_I^s(t, r) = -c_t t^3 + r w_S(\beta)(1 - \alpha) + (w_I(\beta) - c_2)\alpha$$

$$\text{subject to} \quad 0 \leq w_S(1 - r) - c_1 \quad (\text{B.4})$$

$$w_S^{lh}(1 - r) - c_1 \leq (w_S(1 - r) - c_1)(1 - \alpha) \quad (\text{B.5})$$

$$r \in (0, 1)$$

Two constraints are S_1 's IR and IC respectively. (B.4) is binding as π_I^s is increasing in r . π_I^s increases in r . The royalty rate is $r^s(t, \beta) = 1 - \frac{4c_f c_1}{(v_l t \beta)^2}$. We obtain the optimal technology level $t^s(\beta) = \frac{\beta^2 v_l^2 + \alpha(1 - \beta^2)v_h^2}{6c_f c_t}$ from the first order condition. For the equilibrium royalty rate to be feasible, $r^s(t^s(\beta), \beta) > 0$ or $c_1 < \frac{v_l^2 \beta^2 (v_l^2 \beta^2 + \alpha(1 - \beta^2)v_h^2)^2}{144c_t^2 c_f^3}$.

Let us check if (t^s, r^s) satisfies (B.5) where S_1 's profit is zero. If S_1 's profit from deviation is positive, then (t^s, r^s) is not equilibrium. To be profitable, $w_S^{lh} > w_S$ or $c_2 > \frac{(v_h^2(1 - \beta^2) + v_l^2 \beta^2)(v_l^2 \beta^2 + \alpha(1 - \beta^2)v_h^2)^2}{144c_t^2 c_f^3}$. First, assume $v_l \leq \sqrt{\alpha}v_h$, $(v_l^2 \beta^2 + \alpha(1 - \beta^2)v_h^2)^2$ is decreasing in β . If $\beta = 1$, the deviation condition is $c_2 > \frac{v_l^6}{144c_t^2 c_f^3} > \frac{v_l^6}{432c_t^2 c_f^3} > c_2$, which is a contradiction. Next, assume $v_l > \sqrt{\alpha}v_h$. Since $(v_l^2 \beta^2 + \alpha(1 - \beta^2)v_h^2)^2$ is increasing in β , the deviation condition is non-monotonic, which is a polynomial of degree 3 with respect to β^2 . The highest degree coefficient is negative and β^2 has one negative and one positive solutions. Since $\beta^2 > 0$, the negative solution is infeasible. It is easy to see that the positive solution is greater than 1. The polynomial of degree 3 implies that the function has minimum at either boundary of $\beta \in [0, 1]$. We showed that when $\beta = 1$, the deviation condition is infeasible. If the condition is also infeasible at $\beta = 0$, we are done. When $\beta = 0$, $c_2 < \frac{\alpha^8 v_h^6}{432c_t^2 c_f^3} < \frac{\alpha^2 v_h^6}{144c_t^2 c_f^3} \equiv \frac{\alpha^8}{3} < \left(\frac{v_l^6}{v_h^6}\right)$ because $v_l > \sqrt{\alpha}v_h$ implies $\alpha^3 < (v_l/v_h)^6$ and $\frac{\alpha^8}{3} < \alpha^3$. Therefore, the deviation is not

profitable. In addition, the resulting profit π_I^s is increasing in β if $v_h \leq v_l/\sqrt{\alpha}$.

3. (Forego) If TP foregoes, there is one subsystem of quality β . S is the monopoly and set $w_S(t, \beta) = \frac{(v_l t \beta)^2}{4c_f}$ such that M_1 's IR is binding. TP sets r such that S 's IR is binding, $r^f(t, \beta) = 1 - \frac{4c_f c_1}{(v_l t \beta)^2}$. The first order condition gives the optimal technology level, $t^f(\beta) = \frac{(v_l \beta)^2}{6c_f c_t}$. *Forego* is feasible $c_1 \leq w_s(t^f(\beta), \beta)$ and $\beta_1^f \triangleq (432C_1)^{1/6}/v_l \leq \beta$. The latter is stricter. □

Proof of Lemma 2.3. We want to show that *Share* can be optimal for large enough v_h . That is $\pi_I^s(\beta) \geq \pi_I^d(\beta)$ and $\pi_I^s(\beta) \geq \pi_I^f(\beta)$. First, $\pi_I^s(\beta) \geq \pi_I^d(\beta)$ is equivalent to

$$\begin{aligned} \frac{(\beta^2 v_l^2 + \alpha(1 - \beta^2)v_h^2)^3}{432c_t^2 c_f^3} - (1 - \alpha)c_1 - \alpha c_2 &\geq \frac{v_l^6}{432c_t^2 c_f^3} - c_2 \\ 432c_t^2 c_f^3 (c_2 - c_1) &\geq \frac{v_l^6 - (\beta^2 v_l^2 + \alpha(1 - \beta^2)v_h^2)^3}{1 - \alpha}. \end{aligned} \quad (\text{B.6})$$

It is clear to see that the right hand side decreases in v_h . Similarly, $\pi_I^s(\beta) \geq \pi_I^f(\beta)$ can be written as

$$\begin{aligned} \frac{(\beta^2 v_l^2 + \alpha(1 - \beta^2)v_h^2)^3}{432c_t^2 c_f^3} - (1 - \alpha)c_1 - \alpha c_2 &\geq \frac{(v_l \beta)^6}{432c_t^2 c_f^3} - c_1 \\ \frac{(\beta^2 v_l^2 + \alpha(1 - \beta^2)v_h^2)^3 - \beta^6 v_l^6}{\alpha} &\geq 432c_t^2 c_f^3 (c_2 - c_1). \end{aligned} \quad (\text{B.7})$$

Let us define $\bar{\beta}$ such that (B.7) holds with equality. Then, (B.7) holds for $\beta \leq \bar{\beta}$.

(B.6) and (B.7) lead

$$\begin{aligned} \bar{K} \triangleq \frac{(\beta^2 v_l^2 + \alpha(1 - \beta^2)v_h^2)^3 - \beta^6 v_l^6}{\alpha} &\geq 432c_t^2 c_f^3 (c_2 - c_1) \\ 432c_t^2 c_f^3 (c_2 - c_1) &\geq \frac{v_l^6 - (\beta^2 v_l^2 + \alpha(1 - \beta^2)v_h^2)^3}{1 - \alpha} \triangleq \underline{K}. \end{aligned} \quad (\text{B.8})$$

As v_h increases, \bar{K} increases but \underline{K} decreases. Thus, for some given c_1 , c_2 , and $\beta \leq \bar{\beta}$, one can find v_h^{s1} .

In other words, if market inequality is sufficiently low, *Share* may not be optimal and the optimal competition strategy shifts from *Monopoly/Deter* to *Forego* as β increases.

If (B.8) does not hold, (B.6) or/and (B.6) should not hold. Observe that (B.6) holds for low β implying that *Monopoly/Deter* is more profitable than *Share*. Also notice that (B.7) holds for high β meaning that *Forego* is better than *Share*. Therefore, the optimal strategies shift from *Monopoly/Deter* to *Share* to *Forego* in β . In addition, (B.8) does not hold even at $v_h = v_h^{s2}$ implying that *TP*'s equilibrium profit is increasing even under *Share*.

□

Lemma B.8 (FSB *TP*'s Optimal Decisions For Each Strategy). *Let* $A = v_l^2 - \alpha v_l v_h + \alpha v_h^2$, $B = v_l^2 \beta^2 - \alpha v_l v_h \beta^2 + \alpha v_h^2$, $C = c_1 c_t^2 c_f^3$, and $D = (1 - \beta^2)v_h^2 + \beta^2 v_l^2$.

1. (*Monopoly*) If *TP* is the monopoly, her optimal decision and profit are

$$\begin{aligned} (T^M, R^M(T)) &= \left(\frac{A^2}{6c_f c_t (2A - v_l^2)}, \frac{\alpha v_h (v_h - v_l)}{2A - v_l^2} \right), \\ w_I^M(T, R) &= \frac{(v_l T)^2}{4c_f} (1 - R)^2, \\ \pi_I^M &= \frac{A^6}{432c_t^2 c_f^3 (2A - v_l^2)^3} - c_2. \end{aligned}$$

2. (*Deter*) If $\beta < \beta_1^D$, deterring is not feasible. Otherwise, the optimal deterring

decision and profit are

$$(T^D(\beta), R^D(T, \beta)) = \begin{cases} \left(\left(\sqrt{\frac{c_1}{c_f}} \frac{1}{3c_t} \frac{A}{v_l \beta} \right)^{1/2}, 1 - \frac{2\sqrt{c_f c_1}}{v_l \beta} \frac{1}{T} \right) & \text{if } \beta_1^D \leq \beta < \beta_2^D \\ \left(\frac{1}{6c_f c_t} \frac{A^2}{(2A - v_l^2(1 - \beta^2))}, \frac{A - v_l^2(1 - \beta^2)}{2A - v_l^2(1 - \beta^2)} \right) & \text{if } \beta_2^D \leq \beta \end{cases},$$

$$w_I^D(T, R, \beta) = \frac{(v_l T)^2}{4c_f} (1 - R)^2 (1 - \beta^2) + c_1,$$

$$\pi_I^D(\beta) = \begin{cases} \frac{2}{3\sqrt{3}} \frac{c_1}{C^{1/4}} \left(\frac{A}{v_l \beta} \right)^{3/2} - c_2 + \frac{c_1}{\beta^2} \left(1 - \frac{2A}{v_l^2} \right) & \text{if } \beta_1^D \leq \beta < \beta_2^D \\ \frac{A^6}{432c_t^2 c_f^3 (2A - v_l^2(1 - \beta^2))^3} - c_2 + c_1 & \text{if } \beta_2^D \leq \beta \end{cases}.$$

where $\beta_1^D = 12\sqrt{C}(2A - v_l^2)^2/v_l A^3$ and β_2^D solves $\frac{v_l \beta A^3}{(2A - v_l^2(1 - \beta^2))^2} = 12\sqrt{C}$. $\pi_I^D(\beta)$ is decreasing in β .

3. (Share) If $\beta < \beta_1^S$, sharing is not feasible. Otherwise, the optimal sharing decision and profit are

$$(T^S(\beta), R^S(T, \beta)) = \begin{cases} \left(\left(\sqrt{\frac{c_1}{c_f}} \frac{1}{3c_t} \frac{B}{v_l \beta} \right)^{1/2}, 1 - \frac{2\sqrt{c_f c_1}}{v_l \beta} \frac{1}{T} \right) & \text{if } \beta_1^S \leq \beta < \beta_2^S \\ \left(\frac{1}{6c_f c_t} \frac{B^2}{2B - \alpha D}, \frac{(A - \alpha v_l^2)\beta^2}{2B - \alpha D} \right) & \text{if } \beta_2^S \leq \beta \end{cases},$$

$$w_I^S(T, R, \beta) = \frac{(v_h^2(1 - \beta^2) + v_l^2\beta^2)T^2}{4c_f} (1 - R)^2,$$

$$\pi_I^S(\beta) = \begin{cases} \frac{2}{3\sqrt{3}} \frac{c_1}{C^{1/4}} \left(\frac{B}{v_l \beta} \right)^{3/2} - \frac{2B}{v_l^2 \beta^2} c_1 \\ + \left(c_1 - c_1 \frac{v_h^2}{v_l^2} \left(1 - \frac{1}{\beta^2} \right) - c_2 \right) \alpha & \text{if } \beta_1^S \leq \beta < \beta_2^S \\ \frac{B^6}{432c_t^2 c_f^3 (2B - \alpha D)^3} - \alpha c_2 & \text{if } \beta_2^S \leq \beta \end{cases}.$$

where β' , β'' , and β_2^S solve $\frac{1}{12} B v_l \beta = \sqrt{C}$, $\frac{4}{27} \frac{B^3}{(2B - \alpha D + \frac{c_2}{c_1} v_l^2 \alpha \beta^2)^2} v_l \beta = \sqrt{C}$ and $\frac{1}{12} \frac{B^3}{(2B - \alpha D)^2} v_l \beta = \sqrt{C}$ respectively and $\beta_1^S = \max(\beta', \beta'')$. If market inequality is small enough and $\beta_2^S < \beta$, $\pi_I^S(\beta)$ increases in β . Otherwise, it is decreasing in β .

4. (Forego) If $\beta < \beta_1^F$, foregoing is not feasible. Otherwise, the optimal foregoing decision and profit are

$$(T^F, R^F(T)) = \begin{cases} \left(\left(\frac{\sqrt{c_1}}{3\sqrt{c_f c_t}} \frac{A\beta}{v_l} \right)^{1/2}, 1 - \frac{2\sqrt{c_f c_1}}{v_l \beta} \frac{1}{T} \right) & \text{if } \beta_1^F \leq \beta < \beta_2^F \\ \left(\frac{A\beta^2}{12c_f c_t}, \frac{1}{2} \right) & \text{if } \beta_2^F \leq \beta \end{cases},$$

$$\pi_I^F(\beta) = \begin{cases} \frac{2}{3\sqrt{3c_t}} \left(\frac{c_1}{c_f} \right)^{3/4} \left(\frac{A}{v_l} \beta \right)^{3/2} - \frac{2A}{v_l^2} c_1 & \text{if } \beta_1^F \leq \beta < \beta_2^F \\ \frac{A^3 \beta^6}{3456c_f^3 c_t^2} & \text{if } \beta_2^F \leq \beta \end{cases}.$$

where β_1^F and β_2^F solve $27\sqrt{C} = Av_l\beta^3$ and $48\sqrt{C} = Av_l\beta^3$. $\pi_I^S(\beta)$ is increasing in β .

Proof of Lemma B.8. 1. (Monopoly) Since the demand would not change as long as M_1 and M_2 buy subsystem, TP 's profit increases in her subsystem price, w_I . She set w_I such that M_1 's IR is binding.

$$w_I^{F,0}(T, R) = p_1(\theta_1)(1 - R) - c_f \theta_1(T, R)^2$$

At the first stage, Innovator's profit function is

$$\pi_I(T, R) = -c_t T^3 + \underbrace{R(p_1(T, R)(1 - \alpha) + p_2(T, R)\alpha)}_{\text{Royalty profit}} + \underbrace{w_I^{F,0}(T, R) - c_2}_{\text{Sales profit}}.$$

First order condition gives the desired results.

2. Deter

(a) (Deter Strategy) She can deter the competitor by giving some discount on its subsystem, since her subsystem has superior quality. M_1 would

buy from Innovator if its profit is non-negative (B.9) and higher with the superior subsystem (B.10).

$$\begin{aligned} w_I(\beta) &\leq p_1(T, R)(1 - R) - c_f \theta_1(T, R)^2 & (B.9) \\ &= \frac{(v_l T)^2}{4c_f} (1 - R)^2 \end{aligned}$$

$$\begin{aligned} w_I(\beta) &\leq \pi_1^1(T, R) - \pi_1^\beta(T, R) & (B.10) \\ &= \frac{(v_l T)^2}{4c_f} (1 - R)^2 (1 - \beta^2) + c_1 \end{aligned}$$

For *Deter* to be feasible, $w_I^D \leq w_I^M$ at the same T and R , which gives $\beta \geq 12\sqrt{C}(2A - v_l^2)^2 / v_l A^3 \triangleq \beta_1^D$. If (B.9) is binding, $(T(\beta), R(T, \beta)) = \left(\left(\sqrt{\frac{c_1}{c_t}} \frac{1}{3c_t} \frac{A}{v_l \beta} \right)^{1/2}, 1 - \frac{2\sqrt{c_f c_1}}{v_l T \beta} \right)$. $R \in (0, 1)$ implies that $\beta \geq 12\sqrt{C}/Av_l$ but this is redundant since $\beta_1^D > 12\sqrt{C}/Av_l$. If (B.10) is binding, the first order conditions give T and R . By equating the optimal technologies from (B.9) and (B.10), we obtain β_2^D .

(b) $\pi_I^D(\beta)$ decreases in β .

Differentiate the first function $\pi_I^D(\beta)$ with respect to β .

$$\frac{\partial \pi_I^D(\beta)}{\partial \beta} \equiv -6 + \frac{A}{v_l^2} \left(12 - \frac{\sqrt{3Av_l \beta}}{C^{1/4}} \right)$$

which is negative if $\beta > \beta_1^D$. It is apparent that the second π_I^D is also decreasing in β since β has a positive coefficient in the denominator.

3. Share

(a) (Share Strategy) Suppose Innovator shares the subsystem market. It is apparent that Innovator takes High segment thanks to higher quality subsystem. That is M_1 uses the supplier's subsystem with quality β and

M_2 does the innovator's one with quality 1. Let us find the wholesale prices, (w_S, w_I) , in this subgame. Complementarity between technology and component leads M_1 ' to lower its quality choice, $\theta_1 = v_l T \beta (1 - R) / 2c_f$. Since M_2 uses the same quality subsystem, its component quality choice is the same, $\theta_2 = v_h T (1 - R) / 2c_f$. For M_1 not to deviate, Innovator's subsystem should be expensive. Similarly, for M_2 not to deviate, the higher quality subsystem should not be too expensive. This implies the following condition.

$$v_l^2 \frac{T^2(1-\beta^2)}{4c_f} (1-R)^2 + w_S < w_I \leq v_h^2 \frac{T^2(1-\beta^2)}{4c_f} (1-R)^2 + w_S$$

Given this, Innovator and Supplier set their prices.

$$w_S = (v_l \beta)^2 \frac{T^2}{4c_f} (1-R)^2,$$

$$w_I = (v_h^2 - (v_h^2 - v_l^2) \beta^2) \frac{T^2}{4c_f} (1-R)^2,$$

where $w_S \geq c_1$ and $w_I \geq c_2$. Innovator's problem is as follows.

$$\max_{T,R} \pi_I(T, R) = -c_t T^3 + R \left(p_1(T, R, \beta)(1-\alpha) + p_2(T, R, 1)\alpha \right) + (w_I(T, R) - c_2)\alpha$$

subject to $c_1 \leq w_S$,

$$c_2 \leq w_I.$$

Although two constraints give two upper bounds for R , Innovator is

constrained by $c_1 \leq w_S$ or $R \leq 1 - 2\sqrt{c_f c_1}/(v_l \beta T)$.

$$\begin{aligned} \max_{T,R} \pi_I(T, R) = & -c_t T^3 + \left((v_h^2 - (v_h^2 - v_l^2)\beta^2) \frac{T^2}{4c_f} (1-R)^2 - c_2 \right) \alpha \\ & + R(v_l \beta)^2 \frac{T^2}{2c_f} (1-R)(1-\alpha) \\ & + R(v_h^2 - (v_h - v_l)v_l \beta^2) \frac{T^2}{2c_f} (1-R)\alpha \end{aligned}$$

subject to $R \leq 1 - \frac{2\sqrt{c_f c_1}}{v_l \beta T}$.

If the constraint is binding, $(T, R(T)) = \left(\left(\frac{\sqrt{c_1}}{3\sqrt{c_f c_t}} \frac{B}{v_l \beta} \right)^{1/2}, 1 - \frac{2\sqrt{c_f c_1}}{v_l \beta} \frac{1}{T} \right)$.

To satisfy TP 's IR condition, $\beta' \leq \beta$ where β' solves the following equation.

$$\frac{4}{27} \frac{B^3}{(2B - \alpha D + \frac{c_2}{c_1} v_l^2 \alpha \beta^2)^2} v_l \beta = \sqrt{C}$$

To make $R \geq 0$, $\beta'' \leq \beta$ where β'' solves $Bv_l \gamma^3 = 12\sqrt{C}$. Define $\beta_1^S = \max(\beta', \beta'')$. Then, $\beta_1^S \leq \beta$ is necessary for feasible solutions. If the constraint is not binding, the first order conditions give the results.

- (b) There exists a threshold $\tilde{\alpha} v_h(\beta)$ such that for $\alpha v_h \leq \tilde{\alpha} v_h(\beta)$ and $\beta_2^S \leq \beta$, $\pi_I^S(\beta)$ increases in β .

Assume $\beta_2^S \leq \beta$.

$$\begin{aligned} \frac{\partial \pi_I^S}{\partial \beta} \equiv & \underbrace{(-\alpha v_h^2 - v_l(v_l - \alpha v_h)\beta^2)^5}_{(-)} \underbrace{(v_h^2(v_h^2 - v_l^2)\alpha^2)}_{(+)} \\ & + \underbrace{v_l(v_l - \alpha v_h)(-\alpha v_h^2 + 2\alpha v_l v_h - (2 - \alpha)v_l^2)\beta^2}_{(-)} \end{aligned}$$

The first parenthesis is negative. The first and second terms in the

second parenthesis have different signs. The sign of the derivative is determined by the second parenthesis. Let us divide both terms with v_l^4 and use $y = v_h/v_l$. The derivative is positive if

$$\alpha^2 y^2 (y^2 - 1) < (1 - \alpha y) \underbrace{(\alpha y^2 - 2\alpha y + 2 - \alpha)}_{(+)} \beta^2.$$

Notice that while LHS has a solution at $y = 0$ or $y = 1$, RHS has a solution at $y = 1/\alpha > 1$. Considering their degrees, it is apparent that there exists $1 < \tilde{y} < 1/\alpha$ such that for $y < \tilde{y}(\beta)$, $\partial \pi_I^h / \partial \beta > 0$. Let $\tilde{\alpha} v_h(\beta)$ denote the corresponding αv_h such that $\tilde{\alpha} v_h(\beta) = \tilde{y}(\beta) v_l$.

4. (Forego) Replace the subsystem quality with β and apply Proof of Lemma B.3.

□

Proof of Lemma 2.4. 1. *Deter* cannot be optimal when αv_h is large.

We prove this by showing that *Deter* is dominated by *Share* for $v_l = \alpha v_h$. Let $v_l = \alpha v_h$. $\Pi_I^D(\beta)$ is decreasing in β from Π_I^M . So does $\Pi_I^S(\beta)$. From the above, we know that $\beta_1^S < \beta_1^D$ when αv_h is large. This is also true for $v_l = \alpha v_h$. Similarly, $\beta_2^S < \beta_2^D$. There are two cases regarding these four threshold values. First, $\beta_1^S < \beta_1^D < \beta_2^S < \beta_2^D$. If $\beta \in [\beta_1^S, \beta_1^D)$, *Share* is clearly better than *Deter*. If $\beta \in [\beta_1^D, \beta_2^S)$,

$$\Pi_I^S(\beta) - \Pi_I^D(\beta) = (1 - \alpha)(c_1(1 - (1 + \alpha)\beta^2) + \alpha\beta^2 c_2) / \alpha\beta^2.$$

The difference is positive if $c_2 \geq c_1(1 + 1/\alpha - 1/\alpha\beta^2)$. We note that $c_2 \leq c_1/(1 - \alpha)$ is sufficient for the above condition. If $\beta \in [\beta_2^S, \beta_2^D)$, *Share* is better.

If $\beta \in [\beta_2^D, 1)$,

$$\begin{aligned} \Pi_I^S(\beta) - \Pi_I^D(\beta) &= \frac{\alpha^3 v_h^6}{432 c_t^2 c_f^3} \left(\frac{1}{(1 + (1 - \alpha^2)\beta^2)^3} - \frac{1}{(2 - \alpha(1 - \beta^2))^3} \right) \\ &\quad + c_2(1 - \alpha) - c_1. \end{aligned}$$

By comparing the denominators in the first parenthesis, $2 - \alpha(1 - \beta^2) > 1 + (1 - \alpha^2)\beta^2$. This tells the first term is positive. If $c_2(1 - \alpha) - c_1 > 0$, then the difference is positive.

Second, $\beta_1^S < \beta_2^S < \beta_1^D < \beta_2^D$. Similarly, if $\beta < \beta_1^D$, *Deter* is not feasible. Otherwise, although *Deter* is feasible but dominated by *Share* for the same reason above. Thus, *Deter* is dominated by *Share*.

2. *Deter* is optimal for small β when αv_h is small.

We want to show that $\beta_1^D < \beta_1^S$ when αv_h is small. We compare β_1^D and β' since if $\beta_1^D < \beta'$ then $\beta_1^D < \beta_1^S = \max(\beta', \beta'')$. Suppose $\beta = \beta_1^D$. Let us show $Bv_l\beta < 12\sqrt{C}$ which is equivalent to $B < \frac{A^3}{(2A - v_l^2)^2}$. While LHS is always increasing in v_h , RHS can decrease if $-v_l^2 + 2v_h(v_h - v_l)\alpha < 0$ or v_h is small enough. If $v_h = v_l$, the inequality becomes $v_l^2(\alpha + \beta^2 - \alpha\beta^2) < v_l^2$ and holds. This is also true for α . Similarly, one can show for $\beta_1^D < \beta_1^F$ when αv_h is small.

3. *Forego* is optimal if $c_2 \geq \underline{c}_I$ and β is large enough and v_h/v_l is small enough.

From 1 and 2 above, we know that *Deter* cannot be optimal for large enough β regardless of the market inequality ratio. We compare *Share* and *Forego*

profits for $\beta \geq \max\{\beta_2^S, \beta_2^F\}$.

$$\Pi_I^F(\beta) - \Pi_I^S(\beta) = \frac{1}{432c_t^2c_f^3} \left(\frac{A^3\beta^6}{8} - \frac{B^6}{(2B - \alpha D)^3} \right) + \alpha c_2.$$

The difference is positive if

$$c_2 \geq \frac{1}{\alpha} \frac{1}{432c_t^2c_f^3} \left(\frac{B^6}{(2B - \alpha D)^3} - \frac{A^3\beta^6}{8} \right) \triangleq \underline{c}_I.$$

We note that as v_h goes to infinity, \underline{c}_I goes to infinity too. Hence, *Forego* is only optimal for small v_h/v_l .

4. *TP* is better off with a more competitive supplier than a moderate one.

Suppose market inequality is low enough and β is large enough so that *Deter* is not optimal. *Forego* or *Share* is optimal. If *Forego* is optimal, $\Pi_I^F(\beta)$ is increasing in β . When *Share* is optimal, Lemma B.8.3 implies that $\Pi_I^S(\beta)$ is also increasing in β . Thus, *TP* is better off with a more competitive supplier. Consider the inequality is high. R1 rules out *Deter*. R3 shows when *Forego* is optimal. If *Forego* is optimal, the argument holds because $\Pi_I^F(\beta)$ is increasing in β .

□

Proof of Proposition 2.5. 1. Business model shift for low market inequality

We first prove if market inequality is low, the optimal business model changes from FSB to SSB in β . Note that regardless of market inequality and business models, *Monopoly* is optimal for small β . If so, it is clear that $\Pi_I^M \geq \pi_I^M$. The equality holds when $v_l = v_h$. Let $\beta \rightarrow 1$. While *Forego* is optimal under SSB, *Share* or *Forego* is optimal under FSB. In either case, there is a threshold, $\widehat{\alpha v_h/v_l}$, under which SSB is better than FSB according to Proposition 2.2 and

Lemma 2.4. Assume $\alpha v_h/v_l$ is less than $\widehat{\alpha v_h/v_l}$ and $\sqrt{\alpha}v_h/v_l < 1$. According to Lemma B.7, π_I^* is weakly increasing from $\pi_I(0)$ to $\pi_I(1)$. For FSB, there are two cases where *Deter* is optimal and not. First, suppose *Deter* is optimal for some β . *TP*'s profit is continuous. It weakly decreases and increases from $\Pi_I(0)$ to $\Pi_I(1)$ in β , which implies it cannot increase above $\Pi_I(1)$. $\Pi_I(0) > \pi_I(0) > \Pi_I(1)$ and $\pi_I(1) > \Pi_I(1)$ implies that Π_I and π_I cross once. Second, consider *Deter* is not optimal for any β . Although Π_I is not continuous and has a upward jump when the strategy changes from *Monopoly* to *Share*, the same reasoning works here since the profit under *Share* is decreasing to a constant less than or equal to $\pi_I(1)$. Thus, the optimal business model changes once from FSB to SSB.

2. Business model shift for high market inequality We show the optimal business model changes twice from FSB to SSB to FSB in β . Suppose $v_h = v_l/\alpha$. By the proof of Lemma 2.4, *Deter* cannot be optimal under FSB. For small enough α , FSB *Forego* dominates SSB *Forego* for all β . If SSB is optimal, SSB *Share* should be better than FSB *Share*. That is $\pi_I^s(\beta) > \Pi_I^s(\beta)$ for some β .

Claim 1: If $\frac{v_l^6}{432C} > 1$ and $v_h = \frac{v_l}{\alpha}$, $\beta_2^S < \beta_1^S < \sqrt{\frac{\alpha}{1-\alpha^2}}$.

Proof of Claim 1. If the claim is true, $12\sqrt{C} < v_l\beta(v_l^2\beta^2 + \alpha(1-\beta^2)v_h^2)$ at $\beta = \sqrt{\frac{\alpha}{1-\alpha^2}}$. We can rewrite the above using $v_h = \frac{v_l}{\alpha}$ as $\frac{12\sqrt{C}}{v_l^3} < \sqrt{\frac{\alpha}{1-\alpha^2}} \frac{1}{\alpha(1+\alpha)}$. $\frac{v_l^6}{432C} > 1$ implies $\frac{12\sqrt{C}}{v_l^3} < \frac{1}{\sqrt{3}}$. If $\frac{1}{\sqrt{3}} < \sqrt{\frac{\alpha}{1-\alpha^2}} \frac{1}{\alpha(1+\alpha)}$, we are done. By rearranging the terms, we get $\alpha(1-\alpha^2)(1+\alpha)^2 < 3$, which holds for $\alpha \in [0, 1]$.

Let us prove $\beta_2^S < \beta_1^S$. Let $\beta = \beta_1^S$. Then,

$$\begin{aligned} \frac{B^3}{(2B - \alpha D)^2} &< v_l \beta (v_l^2 \beta^2 + \alpha(1 - \beta^2)v_h^2) \\ g(\beta)^2 &= \frac{1}{(1 + (1 - \alpha^2)\beta^2)^2} < 1 - (1 - \alpha)\beta^2 = f(\beta) \\ g(\beta)^2 &< g(\beta) < f(\beta). \end{aligned}$$

□

Assume $\beta > \beta_1^S$. According to Claim 1, π_I^S and Π_I^S are feasible for $\beta > \beta_1^S$. $\pi_I^S \geq \Pi_I^S$ is equivalent to

$$(1 - (1 - \alpha)\beta^2)^3 - \frac{1}{(1 + (1 - \alpha^2)\beta^2)^3} \geq (1 - \alpha)\alpha^3 \frac{432C}{v_l^6}. \quad (\text{B.11})$$

First, we establish LHS is quasi-concave if it is positive. Second, we find the unique maximizer β^* such that the inequality holds. Third, we prove $\beta^* > \beta_1^S$. Let $f(\beta) = 1 - (1 - \alpha)\beta^2$, $g(\beta) = \frac{1}{1 + (1 - \alpha^2)\beta^2}$, and $\Delta(\beta) = f(\beta) - g(\beta)$.

(a) Quasi-concavity

$\Delta(\beta)$ is positive if $\beta < \sqrt{\frac{\alpha}{1 - \alpha^2}}$. So is LHS. Take a look at $\Delta'(\beta)$.

$$\Delta'(\beta) = 2\beta \left(-(1 - \alpha) + \frac{1 - \alpha^2}{(1 + (1 - \alpha^2)\beta^2)^2} \right).$$

The parenthesis term is decreasing from positive to negative in β . $\Delta'(\beta)$ increases from 0 to some positive then decreases to negative. It crosses zero at $\beta = \sqrt{\frac{\sqrt{1 + \alpha} - 1}{1 - \alpha^2}} < \sqrt{\frac{\alpha}{1 - \alpha^2}}$. Since its sign changes once from positive to negative for $\beta \in [0, \sqrt{\frac{\alpha}{1 - \alpha^2}}]$, $\Delta(\beta)$ is quasi-concave if it is positive. By Claim 2 below, LHS is also quasi-concave for $\beta < \sqrt{\frac{\alpha}{1 - \alpha^2}}$.

Claim 2: If $f(x)$ and $g(x)$ are decreasing in x and $f(x) - g(x)$ is quasi-concave, then $f(x)^3 - g(x)^3$ is also quasi-concave.

Proof. Proof of Claim 2 Let $\Delta(x) = f(x) - g(x)$ and $h(x) = f(x)^2 + f(x)g(x) + g(x)^2$. We can express $f(x)^3 - g(x)^3 = \Delta(x)h(x)$. Consider $x_1 < x_2 < x_3$. Assume $f(x)^3 - g(x)^3$ is not quasi-concave.

$$f(x_2)^3 - g(x_2)^3 = \Delta(x_2)h(x_2) < \min(\Delta(x_1)h(x_1), \Delta(x_3)h(x_3)).$$

Assume $\Delta(x_1) > \Delta(x_3)$. Since $h(\cdot)$ is decreasing, $\Delta(x_2)h(x_2) < \Delta(x_3)h(x_3)$ and $\Delta(x_2) < \Delta(x_3)$. However, $\Delta(x)$ is quasi-concave and $\min(\Delta(x_1), \Delta(x_3))$ is less than $\Delta(x_2)$. \square

(b) $\exists \beta^*$

Since $v_l^6/432C > 1$, $(1 - \alpha)\alpha^3 > (1 - \alpha)\alpha^3 \cdot v_l^6/432C$. We will prove the existence of β^* by showing that $f(\beta^*)^3 - g(\beta^*)^3 > (1 - \alpha)\alpha^3$ for $\alpha \in [0, 1]$. Let us investigate the value function of $f(\beta)^3 - g(\beta)^3$.

$$FOC(\beta) = \frac{\partial}{\partial \beta}(f(\beta)^3 - g(\beta)^3) = -6(1 - \alpha)\beta \cdot (f(\beta)^2 - (1 + \alpha)g(\beta)^4).$$

If $\beta = 0$, LHS is zero. The maximizer, β^* solves $f(\beta^*)^2 - (1 + \alpha)g(\beta^*)^4 = 0$.

By substituting this into LHS, we get

$$\begin{aligned} f(\beta^*)^3 - g(\beta^*)^3 &> (1 - \alpha)\alpha^3 \\ (1 + \alpha)^{3/2}g(\beta^*)^6 - g(\beta^*)^3 &> (1 - \alpha)\alpha^3. \end{aligned}$$

$g(\beta)$ is a positive and monotone decreasing function in β . So is $g(\beta)^3$.

We can replace $g(\beta^*)^3$ with x . The inequality can be rewritten as

$$(1 + \alpha)^{3/2}x^2 - x - (1 - \alpha)\alpha^3 > 0.$$

For this to hold, $x = g(\beta)^3 > \frac{\sqrt{1-4(\alpha-1)\alpha^3(\alpha+1)^{3/2}+1}}{2(\alpha+1)^{3/2}}$. It implies the existence of β^* such that $\beta^* < \left(\left(\left(\frac{1-\sqrt{1-4\alpha^3\sqrt{\alpha+1}(\alpha^2-1)}}{2(\alpha-1)\alpha^3} \right)^{1/3} - 1 \right) \frac{1}{1-\alpha^2} \right)^{1/2} \triangleq \bar{\beta}$, where $\bar{\beta}$ solves the above inequality.

(c) $\beta_1^s < \beta^*$

We infer a lower bound β_l from $\sqrt{\frac{\sqrt{1+\alpha}-1}{1-\alpha^2}}$. Let $\beta_l = (1 - \alpha)^{1/4} \sqrt{\frac{2\alpha/5}{1-\alpha^2}} < (1 - \alpha)^{1/4} \sqrt{\frac{\sqrt{1+\alpha}-1}{1-\alpha^2}} < \sqrt{\frac{\sqrt{1+\alpha}-1}{1-\alpha^2}}$. We claim that $\beta_1^s < \beta_l < \beta^*$.

Claim 3: $\beta_l < \beta^*$

Proof. Proof of Claim 3 We prove this by showing that $FOC(\beta_l) > 0$.

$$\frac{625(\alpha + 1)}{(2\alpha\sqrt{1-\alpha} + 5)^4} - \frac{\left((2\sqrt{1-\alpha} - 5)\alpha - 5 \right)^2}{25(\alpha + 1)^2} > 0$$

$$125(1 + \alpha)^{3/2} > \left(5(\alpha + 1) - 2\alpha\sqrt{1-\alpha} \right) \cdot \left(2\alpha\sqrt{1-\alpha} + 5 \right)^2$$

LHS is convex increasing. Let us analyze RHS.

$$\frac{\partial^3 RHS}{\partial \alpha^3} = \frac{3}{4} \left(20 \left(21\sqrt{1-\alpha} - 32 \right) \alpha - \frac{310}{\sqrt{1-\alpha}} - \frac{129}{(1-\alpha)^{3/2}} - \frac{75}{(1-\alpha)^{5/2}} + 320 \right)$$

It is a decreasing function in α and has the maximum -145.5 at $\alpha = 0$.

Thus, the third derivative of RHS is negative. This tells us that the

second derivative is also a decreasing function.

$$\begin{aligned} \frac{\partial^2 RHS}{\partial \alpha^2} &= \frac{\alpha \left(6\alpha \left(2\alpha \left(21\alpha + 40\sqrt{1-\alpha} - 49 \right) - 160\sqrt{1-\alpha} + 197 \right) \right)}{2(1-\alpha)^{3/2}} \\ &+ \frac{\alpha \left(6\alpha \left(-560\sqrt{1-\alpha} + 1221 \right) \right)}{2(1-\alpha)^{3/2}} - \frac{80\sqrt{1-\alpha} - 300}{2(1-\alpha)^{3/2}}. \end{aligned}$$

It is rather complex but one can easily check that its sign changes once from positive to negative as α increases. Define α_0 as the solution of the second order condition, i.e. $\frac{\partial^2 RHS}{\partial \alpha^2}|_{\alpha=\alpha_0} = 0$. The first order condition is increasing for $\alpha \leq \alpha_0$ and then decreasing afterward.

$$\begin{aligned} \frac{\partial RHS}{\partial \alpha} &= \frac{5(5\sqrt{1-\alpha} + 2) + \alpha \left(2(9\sqrt{1-\alpha} - 20)\alpha - 12\sqrt{1-\alpha} + 15 \right)}{\sqrt{1-\alpha}} \\ &\cdot \frac{2\sqrt{1-\alpha}\alpha + 5}{\sqrt{1-\alpha}}. \end{aligned}$$

When it is increasing, RHS is also convex as LHS. We note that LHS and RHS are equal at $\alpha = 0$ but LHS's derivative is 187.5 which is greater than RHS's 175. LHS is greater than RHS if RHS remains convex or $\alpha \leq \alpha_0$. Now consider RHS is concave or $\alpha > \alpha_0$. While LHS's derivative is still increasing, RHS's is decreasing. It is clear that LHS is also greater than RHS. Thus, we can conclude LHS is greater than RHS for all α and $FOC(\beta_l) > 0$. \square

Claim 4: $\beta_1^s < \beta_l$

Proof. Proof of Claim 4 If the claim is true, $12\sqrt{C} < v_l\beta_l(v_l^2\beta_l^2 + \alpha(1 - \beta_l^2)v_h^2)$. Since $v_l^6/432C > 1$ and $v_h = v_l/\alpha$, it is sufficient to show that

$\frac{1}{\sqrt{3}} < \beta_l f(\beta_l) / \alpha$. After some algebra, it is equivalent to

$$\frac{125}{6} \alpha \sqrt{1-\alpha} (1+\alpha)^3 < (5(1+\alpha) - 2\alpha \sqrt{1-\alpha})^2.$$

We use $25(1+\alpha)$ for a proxy between them.

$$\begin{aligned} \frac{125}{6} \alpha \sqrt{1-\alpha} (1+\alpha)^3 &< 25(1+\alpha) \\ \alpha \sqrt{1-\alpha} (1+\alpha)^2 &< \frac{6}{5} \end{aligned}$$

LHS has the maximum less than 1.16 at $(3 + \sqrt{65})/14 \approx 0.79$.

Let us show $25(1+\alpha) < (5(1+\alpha) - 2\alpha \sqrt{1-\alpha})^2$. Observe that both sides are 25 at $\alpha = 0$. $5(1+\alpha) - 2\alpha \sqrt{1-\alpha}$ is convex. So is RHS. The derivative of RHS at $\alpha = 0$ is 30 which is greater than LHS's. Hence, RHS is larger. As a result, we establish

$$\frac{125}{6} \alpha \sqrt{1-\alpha} (1+\alpha)^3 < 25(1+\alpha) < (5(1+\alpha) - 2\alpha \sqrt{1-\alpha})^2.$$

□

Therefore, there exists an interval around β^* such that SSB *Share* is preferred to FSB *Share*. So is SSB to FSB.

□

Proof of Proposition 2.6. Consider *TP* adopts FSB. For the partial coverage, the royalty rate is set such that both manufacturers are forced to compete for *h* segment and all the profits are extracted to *TP*. Thus, manufacturers are indifferent. For the full coverage, *TP* should decide whether to make M_1 's IR constraint binding. If the constraint is binding, M_1 is indifferent. Otherwise, M_1 is better off from the

integration since it can attain what the inferior supplier could have earned. In either case, M_2 is better off since the superior supplier S_2 sets its price w_2 competitively considering the price (c_1) and the quality (β) of the inferior subsystem so that M_2 procures from it. Moreover, TP 's technology investment and royalty rate decisions are not affected by the subsystem cost when M_1 's IR is not binding. M_2 earns the same revenue incurring lower procurement cost. Thus, both manufacturers are weakly better off by the backward-integration under FSB.

Suppose TP uses SSB. We show the case where M_2 is worse off from the backward-integration. Remind that manufacturers earn nothing under the partial coverage. Under the full coverage, we assume that only M_1 internally produces the inferior subsystem and M_2 procures from S_2 and derive the equilibrium. Later, we check if the assumption holds in equilibrium. A manufacturer's quality and price decisions are the same to those derived in Lemma B.12. The only supplier S_2 sets $w_2 = c_1 + \frac{(v_h t)^2}{4c_f}(1 - \beta^2)$ in order for M_2 to procure from it. M_1 's profit function with internal production is $\pi_1 = \frac{(v_l t \beta)^2}{4c_f} - c_1 - c_1 r$. We note that M_1 pays $c_1 r$ as the royalty payment. If it also buys the subsystem from S_2 , $\pi'_1 = \frac{(v_l t)^2}{4c_f} - w_2$. For M_1 to use its integrated subsystem production,

$$\pi_1 - \pi'_1 \equiv t^2(1 - \beta^2)(v_h^2 - v_l^2) \geq 4c_f c_1 r. \quad (\text{B.12})$$

Now, let $\pi_{2,n}$ and $\pi_{2,i}$ denote the profits of non-integrated and the integrated M_2 ,

which can be written as follows.

$$\begin{aligned}\pi_{2,n}(t_n) &= \left(\frac{(t_n^2 \beta^2 (v_h - v_l)^2)}{4c_f} \right) \alpha, \\ \pi_{2,i}(t_i) &= \left(\frac{t_i^2 \beta^2 ((v_h - v_l)^2 + v_l^2)}{4c_f} - c_1 \right) \alpha, \\ \pi_{2,n}(t_n) - \pi_{2,i}(t_i) &= \left(\frac{(t_n^2 \beta^2 (v_h - v_l)^2 - t_i^2 ((v_h - v_l)^2 + v_l^2))}{4c_f} \beta^2 + c_1 \right) \alpha\end{aligned}$$

where t_n and t_i are the optimal technology levels for the non-integrated and the integrated cases. Note that if $t_n^2 (v_h - v_l)^2 - t_i^2 ((v_h - v_l)^2 + v_l^2) \geq 0$, then $\pi_{2,n}(t_n) - \pi_{2,i}(t_i) > 0$. That is, if t_n is greater enough than t_i , $\pi_{2,n} > \pi_{2,i}$ and M_2 is better off when the backward-integration is not feasible. We obtained $t_n = \frac{v_l^2 \beta^2 + \alpha v_h^2 (1 - \beta^2)}{6c_f c_t}$ in Lemma B.10. Let us derive t_i . TP 's problem is

$$\begin{aligned}\max_{t,r} \pi_I(t,r) &= -c_t t^3 + (c_1(1 - \alpha) + w_2 \alpha) r \\ \text{s.t} \\ 0 &\leq \pi_{S2} \triangleq w_2(1 - r) - c_2 \\ 0 &\leq \pi_1\end{aligned}$$

where π_{S2} is S_2 's profit. This formulation means that TP can extract either M_1 or S_2 , which turns out not tractable. Instead, we employ $\tilde{\pi}_I = -c_t t^3 + \left(\frac{(v_l t \beta)^2}{4c_f} - c_1 \right) (1 - \alpha) + (w_2 - c_2) \alpha$, implying that TP hypothetically can extract all the profits of M_1 and S_2 . The optimal technology $\tilde{t}_i = \frac{\alpha v_h^2 + (v_l^2 - (v_h^2 + v_l^2) \alpha) \beta^2}{6c_f c_t}$. Notice that $t_n > \tilde{t}_i$ and $\lim_{v_h \rightarrow \infty} t_n^2 (v_h - v_l)^2 - t_i^2 ((v_h - v_l)^2 + v_l^2) = 0$. (B.12) also holds as v_h increases for \tilde{t}_i and $r \in (0, 1)$. Thus, $\pi_{2,n}(t_n) > \pi_2(\tilde{t}_i) > \pi_2(t_i)$. M_2 can be worse off from the backward-integration for large enough market inequality under SSB. \square

Lemma B.9. *Suppose TP and M_2 can integrate into S_2 after incurring the fixed*

integration cost. For $v_l = \alpha v_h$, if TP does not integrate into S_2 , then M_2 does not do so either.

Proof of Lemma B.9. In general, the complex forms of FSB profit functions hinder us to directly show the desired result. We show a special case instead. Consider $v_l = \alpha v_h$. Then, $M = \alpha v_h^2(1 - \beta^2) + v_l^2(-1 + (1 + \alpha)\beta^2)$ defined in Lemma B.14 is greater than 0, implying that both suppliers share the market for the non-integrated TP according to Lemma B.11. Its profit is $\frac{\alpha^3 v_h^6}{3456 c_t^2 c_f^3}$. The forward integrated TP 's profit is $\frac{\alpha^3 v_h^6}{432 c_t^2 c_f^3 (-1 + (-1 + \alpha)^2 \beta^2)^3 - \alpha c_2 - F}$, where F is the integration cost. Let us define F_I such that the integration is optimal if $F \leq F_I$ for TP .

$$F_I = \frac{\alpha^3 v_h^6}{3456 c_t^2 c_f^3} \left(-1 - \frac{8}{(1 + (1 - \alpha^2)\beta^2)^3} \right) - \alpha c_2.$$

Similarly, let F_2 denote a threshold such that the backward integration is optimal if $F \leq F_2$ for M_2 . We can do so by obtaining M_2 's profit under its backward integration and non-integration. Then, F_2 is written as follows.

$$F_2 = \frac{\alpha^3 v_h^6 (1 - (1 - \alpha^2)\beta^2)}{2304 c_t^2 c_f^3} - \alpha c_2.$$

If $F_I \geq F_2$, then we are done.

$$F_I - F_2 = \frac{\alpha^3 v_h^6 ((\alpha^2 - 1)\beta^2 + 1)^2}{6912 c_f^3 c_t^2 ((1 - \alpha^2)\beta^2 + 1)^3} ((1 - \alpha^2)\beta^2 (3(1 - \alpha^2)\beta^2 + 10) + 11) > 0.$$

□

B.1 Business Model Adaptation with Two Different Suppliers for the Non-Integrated Technology Provider

Suppose the technology provider faces two different suppliers, S_1 and S_2 , in their manufacturing capabilities. Recall that $\beta \in (0,1)$ denotes the inferior supplier's (S_1 's) relative subsystem quality compared to the superior subsystem quality 1. Let c_j denote S_j 's subsystem manufacturing cost. Without loss of generality and to maintain consistency with the previous case, we assume that c_1 is equal to $c_2\beta^2$, where neither supplier has an inherent advantage.² Later, we discuss the case in which they are not equal and continue analyzing an integrated technology provider to study how the subsystem manufacturing integration affects the technology business model. For ease of exposition, we adopt the common convention of quadratic system quality cost ($\delta_m = 2$, e.g. Moorthy and Png 1992; Mussa and Rosen 1978; Krishnan and Zhu 2006) and linear technology externalities in users ($\gamma = 1$, e.g. Lee and Mendelson 2008; Conner 1995; Sun et al. 2004) and put a mild convex increasing technology cost assumption of $\delta_i = 3$ to avoid trivial/corner cases.³

We consider SSB first and then FSB. Unlike the base case, the manufacturers in Tier 0 carefully weigh subsystem prices and qualities for their procurement decisions as described in Lemma B.12 in the Appendix. Knowing this, S_1 and S_2 compete in Tier 1 by following strategies in Lemma B.13 in the Appendix. S_2

²If $c_1 > c_2\beta^2$, S_2 has exogenous cost/quality advantages. Otherwise, S_1 does. In either case, TP should determine the technology investment and the royalty rate only for the supplier with advantages not to deviate.

³In Section 2.4, we obtain a mild convexity condition between δ_m and δ_i , namely $k = \delta_i\delta_m - \delta_i - \delta_m > 0$. If $\delta_m = 2$, then $\delta_i > 2$ for $k > 0$. By assuming $\delta_i = 3$, we have the simplest model for more complex cases.

excludes S_1 by setting a low price to be the monopoly only when market inequality and the royalty rate are low and S_1 is weak. Otherwise, it shares the market and becomes the local monopoly of h segment. Anticipating these suppliers' responses, TP decides the technology quality and the royalty rate. There are three ways to cover the market; one for partial coverage and two for full coverage. To achieve partial coverage, TP sets r high enough. For full coverage, TP should decide which suppliers to use. Specifically, the market is fully covered by only S_2 or by both suppliers. In any strategy, TP in Tier 2 must resolve misalignment/incentive incompatibility problems with Tiers 1 and Tier 0 to induce TP 's desired market coverage. The following lemma characterizes the optimal market coverage policy for TP under SSB.

Lemma B.10. *The SSB profit-maximizing market coverage policy with asymmetric subsystem suppliers shifts from full coverage to partial coverage as market inequality increases. Moreover, the technology provider induces S_2 to be the only supplier for full coverage, if $(v_h/v_l)^2 < (1 - (1 + \alpha)\beta^2)/(\alpha(1 - \beta^2))$. Otherwise, the technology provider prefers to have S_1 and S_2 to share the market.*

Corollary B.1. *When the market is fully covered by only S_2 , TP 's profit decreases as market inequality increases.*

Lemma B.10 not only verifies that a threshold policy is still optimal as in the base case (Lemma 2.1) but also reveals that TP may want only the superior subsystem to be available even for full coverage. Suppose both inferior and superior subsystems are available in the market, they are sold to each manufacturer, respectively. Because M_1 procures the inferior subsystem, M_2 with the superior subsystem can differentiate its product at a much higher price than M_1 's. Consider the case where only the superior subsystem is available. In this case, M_1 's full system

quality improves, leading M_2 to lower its price to make its product competitive. At the outset, having only the superior subsystem may seem to hurt TP 's profit. However, when l segment is large but β is low, improving M_1 's quality with the superior subsystem increases the royalty payment from l segment substantially and is indeed beneficial to TP . To achieve this single subsystem market, TP should set a lower royalty rate than under the diverse subsystem market with two different subsystems. As market inequality increases, S_2 has more incentive to share the market and become the local monopoly of h segment. To prevent this, TP should reduce the royalty rate even more. Consequently, TP can be worse off in market inequality (Corollary B.1). Nevertheless, if market inequality increases further, TP decides to have two suppliers and its profit increases.

Next, we turn our attention to FSB. While manufacturers' strategies in Tier 0 are similar to those under SSB, suppliers' strategies in Tier 1 are different since TP cannot directly influence the suppliers, which is characterized in Lemma B.14 in the Appendix. As we witnessed in SSB, FSB TP 's profit can be also greater with only the superior subsystem when both market inequality and β are low. Otherwise, TP prefers both subsystems to be adopted. However, FSB has different impacts on TP 's profit as the following lemma presents.

Lemma B.11. *The FSB profit-maximizing market coverage policy with asymmetric subsystem suppliers involves full coverage for all but the extreme proportion of h segment customers. Moreover, the technology provider induces S_2 to be the only supplier for full coverage, if $(v_h/v_l)^2 < (1 - (1 + \alpha)\beta^2)/(\alpha(1 - \beta^2))$. Otherwise, the technology provider prefers to have S_1 and S_2 to share the market.*

Corollary B.2. *When the market is fully covered by S_2 , TP 's profit may increase then decrease as market inequality increases.*

The above results again confirm that under FSB, full coverage (but using S_2)

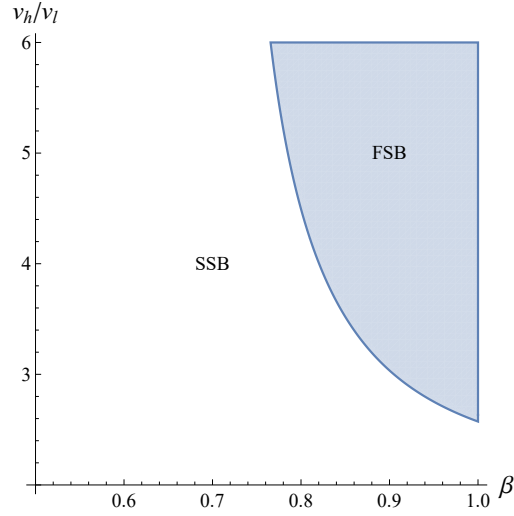


Figure B.2: Technology Provider's Business Model Preference with respect to β and v_h ⁴

would be optimal for a wide range of parameter settings. TP 's profit under FSB does increase when market inequality increases from low to intermediate, which is in sharp contrast to SSB. The rationale is as follows. To induce S_2 to compete with S_1 for M_1 , TP should make M_1 's profit large enough by charging a small royalty rate similar to SSB. Interestingly, M_2 responds to this royalty discount by increasing system quality investment, which is uniquely observed under FSB, leading more royalty profit from M_2 . If market inequality becomes intermediate, the royalty rate should be set much lower resulting in decreasing TP 's profit in market inequality. As market inequality becomes larger, TP decides to have two suppliers and its profit increases in market inequality. With optimal market coverages under SSB and FSB, we present the optimal business model for the technology provider with heterogeneous suppliers.

Proposition B.1. *In a competitive trilateral supply chain with heterogeneous subsystem suppliers, FSB is an increasingly more attractive business model option*

⁴Parameters are $\alpha = 0.2, c_t = 0.5, c_2 = 0.25$, and $c_f = 0.2$. Shaded regions are where FSB is preferred. Otherwise, SSB is preferred.

than SSB for higher and increasing levels of market inequality and inferior supplier's quality (β).

The above proposition generalizes the results of the previous section about the technology provider's comparative preference for SSB and FSB to the case of heterogeneous subsystem suppliers. TP generally wants to have more differentiated products when market inequality is high. The difference in subsystem qualities enables TP to receive different unit royalty payments from licensors under SSB as well as FSB. Since SSB TP can set a high royalty rate without discouraging manufacturer's system quality investment, SSB is superior for lower β . However, the difference in unit royalty payment decreases to zero as β increases to 1, implying that FSB is increasingly optimal in β as illustrated in Figure B.2. The FSB preference order between entities in the base case (Proposition 2.2) also holds in this region. The main results can be shown to hold if either of the suppliers has a cost advantage. Thus our results of the comparative attractiveness of the business model options from the previous section generalize to the case of asymmetric suppliers with quality and/or cost advantages.

Lemma B.12 (Tier 0 Strategy, SSB). *Let β_1 and β_2 be the subsystem procurement choices of M_1 and M_2 respectively.*

- (l, h) : *The full coverage equilibrium*

The optimal procurement choices are

$$(\beta_1, \beta_2) = \begin{cases} (\beta, \beta) & \text{if } w_1 \leq \min(w_2 - \frac{(v_h t)^2}{4c_f}(1 - \beta^2), \frac{(v_l t \beta)^2}{4c_f}), \\ (\beta, 1) & \text{if } w_1 + \frac{(v_l t)^2}{4c_f}(1 - \beta^2) < w_2 \leq w_1 + \frac{(v_h t)^2}{4c_f}(1 - \beta^2), \\ (1, 1) & \text{if } w_2 \leq \min(w_1 + \frac{(v_l t)^2}{4c_f}(1 - \beta^2), \frac{(v_l t)^2}{4c_f}). \end{cases}$$

The optimal qualities are $(\theta_1(\beta_1, \beta_2), \theta_2(\beta_1, \beta_2)) = (\frac{v_l t \beta_1}{2c_f}, \frac{v_h t \beta_2}{2c_f})$. The optimal prices are $(p_1(\theta_1, \theta_2), p_2(\theta_1, \theta_2)) = (\frac{(v_l t \beta_1)^2}{2c_f}, \frac{(\beta_1^2(v_l^2 - v_l v_h) + \beta_2^2 v_h^2)t^2}{2c_f})$.

- $(h/2, h/2)$: The partial coverage equilibrium

The optimal procurement choices are

$$(\beta_1, \beta_2) = \begin{cases} (\beta, \beta) & \text{if } \frac{(v_l t \beta)^2}{4c_f} < w_1 \leq w_2 - \frac{(v_h t \alpha^\gamma)^2}{4c_f} (1 - \beta^2) \\ & \text{and } \frac{(v_l t \beta)^2}{4c_f} < w_2 \leq \frac{(v_h t \alpha^\gamma)^2}{4c_f}, \\ (1, 1) & \text{if } \frac{(v_l t \beta)^2}{4c_f} < w_2 \leq w_1 + \frac{(v_h t \alpha^\gamma)^2}{4c_f} (1 - \beta^2) \\ & \text{and } \frac{(v_l t \beta)^2}{4c_f} < w_1 \leq \frac{(v_h t \beta \alpha^\gamma)^2}{4c_f}. \end{cases}$$

The optimal quality and price are $\theta^h = \frac{(v_h t \beta_1 \alpha^\gamma)}{2c_f}$ and $p^h = \frac{(v_h t \beta_1 \alpha^\gamma)^2}{4c_f} + w(\beta_1)$, where $w(\beta_1)$ is the subsystem price of quality β_1 .

Proof of Lemma B.12. 1. The full market coverage (l, h) : M_1 and M_2 have l and h segments respectively.

Let us assume that M_1 indeed can take l segment and analyze manufacturers' optimal decisions. Then, we specify the necessary condition. If M_1 uses $\beta_1 \in \{\beta, 1\}$ subsystem, $p_1(\beta_1) = v_l \cdot \theta_1(\beta_1) \cdot t \beta_1^\gamma$, $\theta_1(\beta_1) = \frac{v_l t \beta_1^\gamma}{2c_f}$, and $\pi_1(\beta_1) = (\frac{(v_l t \beta_1^\gamma)^2}{4c_f} - w_{\beta_1})(1 - \alpha)$. M_1 's IR condition using β_1 is

$$w_{\beta_1} \leq \frac{(v_l t \beta_1^\gamma)^2}{4c_f}. \quad (\text{B.13})$$

Its IC constraint for β is

$$\begin{aligned}\pi_1^\beta \geq \pi_1^1 &\equiv \frac{(v_l t \gamma)^2}{4c_f}(\beta^2 - 1) - (w_\beta - w_1) \geq 0, \\ w_\beta &\leq w_1 - \frac{(v_l t \gamma)^2}{4c_f}(1 - \beta^2).\end{aligned}$$

Therefore, M_1 's optimal subsystem choice is

$$\begin{cases} \beta & \text{if } w_\beta \leq \min\left(w_1 - \frac{(v_l t \gamma)^2}{4c_f}(1 - \beta^2), \frac{(v_l t \beta \gamma)^2}{4c_f}\right), \\ 1 & \text{if } w_1 \leq \min\left(w_\beta + \frac{(v_l t \gamma)^2}{4c_f}(1 - \beta^2), \frac{(v_l t \gamma)^2}{4c_f}\right). \end{cases} \quad (\text{B.14})$$

$$\quad (\text{B.15})$$

Similarly, M_2 also has two procurement options. There are four cases of manufacturers' procurement decisions: $(1, \beta)$, (β, β) , $(1, \beta)$, and $(1, 1)$.

(a) $(1, \beta)$: M_1 uses the superior subsystem but M_2 does the inferior one.

Hence, it cannot be an equilibrium.

For M_1 to use 1, (B.15) should hold. M_2 sets $p_2^\beta = v_h t \gamma (\theta^\beta - \theta_1) + p_1$ so that h segment's IC is binding. Then, $\theta_2^\beta = \frac{v_h t \beta \gamma}{2c_f}$ and $p_2^\beta(\theta_1, \theta_2^\beta) = (v_l^2 - v_l v_h + v_h^2 \beta^2) \frac{(t \gamma)^2}{2c_f}$. For M_2 to use β , the following must hold

$$\begin{aligned}\pi_2^\beta(\theta_1, \theta_2^\beta) &\geq \pi_2^1(\theta_1, \theta_2^1) \\ (2v_l^2 - 2v_l v_h + v_h^2 \beta^2) \frac{(t \gamma)^2}{4c_f} \alpha - w_\beta \alpha &\geq (2v_l^2 - 2v_l v_h + v_h^2) \frac{(t \gamma)^2}{4c_f} \alpha - w_1 \alpha \\ w_1 &\geq \frac{(v_h t \gamma)^2}{4c_f}(1 - \beta^2) + w_\beta,\end{aligned}$$

which contradicts to (B.15) for $v_l < v_h$.

(b) (β, β) : Both uses the inferior subsystem. EQ if $w_\beta \leq \min(w_1 - \frac{(v_h t \gamma)^2}{4c_f}(1 - \beta^2), \frac{(v_l t \beta \gamma)^2}{4c_f})$.

For M_1 to use β , (B.14) should hold. Then, M_2 's optimal decisions are

$\theta_2^\beta = \frac{v_h t \beta \gamma}{2c_f}$ and $p_2^\beta(\theta_1^\beta, \theta_2^\beta) = \beta^2(v_l^2 - v_l v_h + v_h^2) \frac{(t\gamma)^2}{2c_f}$. For M_2 to use β , the following must hold

$$\begin{aligned} \pi_2^\beta(\theta_1^\beta, \theta_2^\beta) &\geq \pi_2^1(\theta_1^\beta, \theta_2^1) \\ \beta^2(2v_l^2 - 2v_l v_h + v_h^2) \frac{(t\gamma)^2}{4c_f} \alpha - w_\beta \alpha &\geq (2v_l^2 \beta^2 - 2v_l v_h \beta^2 + v_h^2) \frac{(t\gamma)^2}{4c_f} \alpha - w_1 \alpha \\ w_\beta &\leq w_1 - \frac{(v_h t \gamma)^2}{4c_f} (1 - \beta^2). \end{aligned}$$

(c) $(\beta, 1)$: EQ if $w_\beta + \frac{(v_l t \gamma)^2}{4c_f} (1 - \beta^2) < w_1 \leq w_\beta + \frac{(v_h t \gamma)^2}{4c_f} (1 - \beta^2)$.

(B.14) holds. Then M_2 sets $\theta_2^1 = \frac{(v_h t \gamma)^2}{2c_f}$ and $p_2^1(\theta_1^\beta, \theta_2^1) = (\beta^2(v_l^2 - v_l v_h) + v_h^2) \frac{(t\gamma)^2}{2c_f}$.

$$\begin{aligned} \pi_2^1(\theta_1^\beta, \theta_2^1) &\geq \pi_2^1(\theta_1^\beta, \theta_2^\beta) \\ (\beta^2(2v_l^2 - 2v_l v_h) + v_h^2) \frac{(t\gamma)^2}{4c_f} \alpha - w_1 \alpha &\geq \beta^2(2v_l^2 - 2v_l v_h + v_h^2) \frac{(t\gamma)^2}{4c_f} \alpha - w_\beta \alpha \\ w_1 &\leq w_\beta + \frac{(v_h t \gamma)^2}{4c_f} (1 - \beta^2) \end{aligned}$$

(d) $(1,1)$: EQ if (B.15) holds

If M_1 use 1, then M_2 also uses 1 because $(1, \beta)$ is not optimal. (B.15) needs to hold.

2. The partial coverage $(h/2, h/2)$. Both manufacturers sell only to h segment.

If $\frac{(v_l t \beta \gamma)^2}{4c_f} < w_\beta$ and $\frac{(v_l t \gamma)^2}{4c_f} < w_1$, M_1 cannot take l and is forced to compete in h segment with M_2 . I will show that both manufacturers choose the same subsystem with respect to w_1 and w_β . Suppose M_1 uses β but M_2 does 1. Consumers buy from M_1 if $v_h \theta_1^\beta \cdot t \beta \cdot \gamma - p_1^\beta \geq v_h \theta_2^1 \cdot t \cdot \gamma - p_2^1$ (IC) and $v_h \theta_1^\beta \cdot t \beta \cdot \gamma \geq p_1^\beta$ (IR) hold. (IC) constraint implies that two firms are engaged

in price and quality competition. As a result, the price is set to the cost $p_1^\beta = c_f \theta_1^{\beta 2} + w_\beta$ and the quality is set as high as possible. h segment's IR gives the upper bound for the quality.

$$\begin{aligned} U_h &\geq p_1^\beta \\ v_h \theta_1^\beta \cdot t \beta \cdot \gamma \alpha &\geq c_f (\theta_1^\beta)^2 + w_\beta \\ \theta_1^{\beta*} &= \frac{v_h t \beta \gamma \alpha}{2c_f} \end{aligned}$$

Then, $p_1^\beta = \frac{(v_h t \beta \gamma \alpha)^2}{4c_f} + w_\beta$. Similarly, $p_2^1 = \frac{(v_h t \gamma \alpha)^2}{4c_f} + w_1$. For h consumer to buy from M_1 ,

$$\begin{aligned} \frac{(v_h t \beta \gamma \alpha)^2}{4c_f} - w_\beta &\geq \frac{(v_h t \gamma \alpha)^2}{4c_f} - w_1 \\ w_1 &\geq \frac{(v_h t \gamma \alpha)^2}{4c_f} (1 - \beta^2) + w_\beta. \end{aligned} \quad (\text{B.16})$$

If (B.16) holds, M_2 also uses β subsystem. Otherwise, M_1 switches for 1 subsystem. Therefore, manufacturers sells to h if

$$\begin{aligned} \frac{(v_l t \beta \gamma \alpha)^2}{4c_f} < w_\beta &\leq \frac{(v_h t \beta \gamma \alpha)^2}{4c_f}, \\ \frac{(v_l t \gamma \alpha)^2}{4c_f} < w_1 &\leq \frac{(v_h t \gamma \alpha)^2}{4c_f}. \end{aligned}$$

and uses the subsystem of quality

$$\begin{cases} \beta & \text{if (B.16) holds,} \\ 1 & \text{otherwise.} \end{cases}$$

□

Lemma B.13 (Tier 1 Strategy, SSB). *Let (β_1, β_2) be the procurement choices of M_1 and M_2 . S_1 and S_2 set the prices as follows.*

- If $r \leq r^{lh}$ and $\alpha v_h^2(1 - \beta^2) + v_t^2(-1 + (1 + \alpha)\beta^2) < 0$,

$$(w_1, w_2) = \begin{cases} \left(\frac{c_1}{1-r}, \frac{c_1}{1-r} + \frac{(v_t t)^2}{4c_f}(1 - \beta^2) \right) & \text{if } r \leq \tilde{r}(t), \\ \left(\frac{(v_t t \beta)^2}{4c_f}, \frac{(v_h t)^2}{4c_f}(1 - \beta^2) + w_1 \right) & \text{if } \tilde{r} < r \leq r^{lh}. \end{cases}$$

The procurement choice is

$$\begin{cases} (1, 1) & \text{if } r \leq \tilde{r}, \\ (\beta, 1) & \text{if } \tilde{r} < r \leq r^{lh}. \end{cases}$$

- If $r \leq r^{lh}$ and $\alpha v_h^2(1 - \beta^2) + v_t^2(-1 + (1 + \alpha)\beta^2) \geq 0$, $(w_1, w_2) = \left(\frac{(v_t t \beta)^2}{4c_f}, \frac{(v_h t)^2}{4c_f}(1 - \beta^2) + w_1 \right)$ and the procurement choice is $(\beta, 1)$.
- If $r^{lh} < r \leq r^h$, $(w_1, w_2) = \left(\frac{c_1}{1-r}, \frac{c_1}{1-r} + \frac{(v_h t \alpha^\gamma)^2}{4c_f}(1 - \beta^2) \right)$ and the procurement choice is $(1, 1)$.

, where $r^{lh} = 1 - \frac{4c_f c_1}{(v_t t \beta)^2}$, $r^h = 1 - \frac{4c_f c_1}{(v_h t \beta \alpha^\gamma)^2}$, $\tilde{r} = 1 - \frac{4c_2 c_f (-1 + \alpha + \beta^2)}{t^2 (\alpha v_h^2 (1 - \beta^2) + v_t^2 (-1 + (1 + \alpha)\beta^2))}$.

Proof of Lemma B.13. First, we prove that S_1 cannot be the monopoly. Assume S_1 takes both manufacturers. According to (β, β) case in Lemma B.12 and S_1 's IR condition,

$$\begin{aligned} \frac{c_1}{1-r} &\leq w_1 \leq w_2 - \frac{(v_h t)^2}{4c_f}(1 - \beta^2) \\ &= \frac{c_2}{1-r} - \frac{(v_h t)^2}{4c_f}(1 - \beta^2). \end{aligned}$$

The last equality follows from price competition. Since $c_1 = c_2 \beta^2$, for this inequality

to hold, $1 - \frac{4c_f c_2}{(v_h t)^2} \leq r$. However, M_1 's IR condition implies $r \leq 1 - \frac{4c_f c_2}{(v_h t)^2}$, which results in contradiction.

Next, consider $r \leq r^{lh}$. S_2 chooses between the monopoly (1,1) and the local monopoly $(\beta, 1)$. To be the monopoly, $w_2 = \frac{c_1}{1-r} + \frac{(v_l t)^2}{4c_f}(1 - \beta^2)$. If it is the local monopoly, it sells to only h segment at $w_2 = \frac{(v_h t)^2}{4c_f}(1 - \beta^2) + \frac{(v_l t)^2}{4c_f}$. Its profits are

$$\begin{aligned}\pi_2^{11} &= (1 - \beta^2) \left(\frac{(v_l t)^2}{4c_f}(1 - r) - c_2 \right), \\ \pi_2^{\beta 1} &= \alpha \left((v_h^2(1 - \beta^2) + v_l^2 \beta^2) \frac{t^2}{4c_f}(1 - r) - c_2 \right).\end{aligned}$$

Define $\tilde{r} = 1 - \frac{4c_2 c_f (-1 + \alpha + \beta^2)}{t^2 (\alpha v_h^2 (1 - \beta^2) + v_l^2 (-1 + (1 + \alpha)\beta^2))}$ as the royalty rate that equates both profits. Let us check the feasibility, $\tilde{r} \leq r^{lh}$.

$$r^{lh} - \tilde{r} > 0 \equiv \frac{-(1 - \beta^2)}{\alpha v_h^2 (1 - \beta^2) + v_l^2 (-1 + (1 + \alpha)\beta^2)} > 0.$$

Since the numerator is negative, the denominator should be negative, which implies market inequality and β are low. If $\alpha v_h^2 (1 - \beta^2) + v_l^2 (-1 + (1 + \alpha)\beta^2) < 0$, S_2 competes for (1,1) when $r \leq \tilde{r}$ but shares for $(\beta, 1)$ when $\tilde{r} < r \leq r^{lh}$. If $\alpha v_h^2 (1 - \beta^2) + v_l^2 (-1 + (1 + \alpha)\beta^2) > 0$, $(\beta, 1)$ is optimal for S_2 .

Lastly, consider $r^{lh} < r \leq r^h$. Both supplier cannot sell to l segment. They compete for h segment. For S_2 to win,

$$\begin{aligned}\frac{c_2}{1-r} &\leq \frac{c_1}{1-r} + \frac{(v_h t \alpha^\gamma)^2}{4c_f}(1 - \beta^2) \\ \frac{c_2}{1-r} &\leq \frac{(v_h t \alpha^\gamma)^2}{4c_f} \\ r &\leq r^h.\end{aligned}$$

That is S_2 always win the competition and $w_2 = \frac{c_1}{1-r} + \frac{(v_h t \alpha^\gamma)^2}{4c_f} (1 - \beta^2)$.

□

Proof of Lemma B.10. We consider the partial coverage first. Lemma B.13 tells us that S_2 wins the competition for h segment. The subsystem price increases in r . So does the royalty profit. The optimal royalty rate is set at the highest, $r^p = r^h$ with $t^p = \frac{(v_h \alpha^\gamma)^2 \alpha}{6c_f c_t}$.

$$\pi_I^p = \frac{(v_h \alpha^\gamma)^6 \alpha^3}{432 c_t^2 c_f^3} - \alpha c_2$$

For the full coverage, there are two ways to do it, $(\beta, 1)$ and $(1, 1)$. If $r^{lh} < \tilde{r}(t)$ or equivalently $\alpha v_h^2 (1 - \beta^2) + v_t^2 (-1 + (1 + \alpha) \beta^2) > 0$, then $(\beta, 1)$ is only feasible. Loosely speaking, when market inequality and β is high, TP is better off by price differentiation. Since the subsystem price is independent of r , TP sets the highest $r = r^{lh}$. The optimal technology is $t^{f\beta 1} = \frac{(v_t^2 \beta^2 + \alpha v_h^2 (1 - \beta^2))}{6c_f c_t}$ and the resulting profit is

$$\pi_I^{f\beta 1}(r^{lh}) = \frac{(v_t^2 \beta^2 + \alpha v_h^2 (1 - \beta^2))^3}{432 c_t^2 c_f^3} - \left(\beta^2 + \frac{\alpha v_h^2}{v_t^2} (1 - \beta^2) \right) c_2,$$

which is increasing in v_h if it is positive.

Otherwise, both are feasible. $(\beta, 1)$ is optimal for $\tilde{r} < r \leq r^{lh}$ and $(1, 1)$ for $r \leq \tilde{r}$. In either case, TP set the highest royalty rate. Notice that TP 's optimal decisions for $(\beta, 1)$ are the same as the above. The optimal technology for $(1, 1)$ is $t^{f11} = \frac{M}{6c_f c_t (-1 + \alpha + \beta^2)}$, where $M = v_h^2 \alpha \beta^2 (1 - \beta^2) + v_t^2 (-1 + \beta^2 + \alpha(1 - \beta^2 + \beta^4)) < 0$. The profit is

$$\pi_I^{f11} = \frac{M^3}{432 c_t^2 c_f^3 (-1 + \alpha + \beta^2)^3} - \frac{M}{\alpha v_h^2 (1 - \beta^2) + v_t^2 (-1 + (1 + \alpha) \beta^2)} c_2.$$

We show that $\pi_I^{f11} > \pi_I^{f\beta1}$ when market inequality is low enough. As $v_h \rightarrow v_l$,

$$\pi_I^{f11} - \pi_I^{f\beta1} > 0 \equiv \frac{v_l^6}{432c_t^2c_f^3}(1 + \alpha + \alpha^2 + (1 + \alpha - 2\alpha^2)\beta^2 + (1 - \alpha)^2\beta^4) - c_2 > 0.$$

If we assume $\pi_I^{f11} \geq 0$, the difference is greater than zero.

To prove that π_I^{f11} is decreasing in v_h , we claim that $\alpha v_h^2(1 - \beta^2) + v_l^2(-1 + (1 + \alpha)\beta^2) < 0$ implies $-1 + \alpha + \beta^2 < 0$. Let $v_h^2/v_l^2 = 1 + \delta$ where $\delta > 0$.

$$\begin{aligned} \alpha v_h^2(1 - \beta^2) &< -v_l^2(-1 + (1 + \alpha)\beta^2) \\ \alpha(1 + k)(1 - \beta^2) &< -(-1 + (1 + \alpha)\beta^2) \\ \alpha + \alpha k - \alpha\beta^2 - \alpha k\beta^2 &< 1 - \beta^2 - \alpha\beta^2 \\ \alpha k(1 - \beta^2) &< 1 - \alpha - \beta^2 \end{aligned}$$

By differentiating π_I^{f11} with respect to v_h , we get

$$\frac{\partial \pi_I^{f11}}{\partial v_h} = (-1 + \alpha + \beta^2) \frac{2\alpha c_2 v_h v_l^2}{(\alpha v_h^2(1 - \beta^2) + v_l^2(-1 + (1 + \alpha)\beta^2))^2} + \frac{\alpha v_h(1 - \beta^2)M^2}{72c_t^2c_f^3(-1 + \alpha + \beta^2)^3} < 0.$$

When market inequality is low, (1,1) is optimal. As market inequality increases, the optimal coverage changes to $(\beta, 1)$ and to the partial coverage.

□

Proof of Lemma B.11. In the partial coverage, both suppliers compete for h segment and S_2 wins by setting $w_2 = c_1 + \frac{(v_h T \alpha^\gamma)^2}{4c_f}(1 - R)^2(1 - \beta^2)$. TP solves the

following.

$$\begin{aligned} \max_{R,T} \quad & \pi_I^p(T, R) = -c_t T^3 + R \left(\frac{c_1}{1-R} + \frac{(v_h T \alpha^\gamma)^2}{4c_f} (1-R)(2-\beta^2) \right) \alpha \\ \text{subject to} \quad & R > 1 - \frac{2\sqrt{c_f c_2}}{v_l T} \triangleq R_l, \\ & R \leq 1 - \frac{2\sqrt{c_f c_2}}{v_h T \alpha^\gamma} \triangleq R_u. \end{aligned}$$

Observe that if $\beta = 1$ or $R = R_u$, the above profit function is the same as that in the identical suppliers. In addition, TP 's profit decreases more when $\beta < 1$ than when $\beta = 1$. Lemma B.4 still holds for the general suppliers but R^p changes faster.

Consider the full coverage by S_2 . TP 's problem is as follows.

$$\begin{aligned} \max_{T,R} \quad & \Pi_I^f(T, R) = -c_t T^3 + R(1-R) \left(v_l^2 \frac{T^2}{2c_f} (1-\alpha) + (v_h^2 - v_h v_l + v_l^2) \frac{T^2}{2c_f} \alpha \right) \\ \text{subject to} \quad & c_2 \leq \frac{(v_l T)^2}{4c_f} (1-R)^2. \end{aligned}$$

Observe that the optimal royalty rate is $R^f = 1/2$ without constraints. Let M denote $\alpha v_h^2 (1-\beta^2) + v_l^2 (-1 + (1+\alpha)\beta^2)$. According to Lemma B.14, if $M < 0$, $R^{f11} = \min(\tilde{R}, 1/2)$ is optimal for S_2 's full coverage. The optimal decisions for the full coverage by S_1 and S_2 follow the same reasoning. All of them can be obtained

applying the same analysis in Lemma B.3. The optimal decisions are

$$(T^{f11}, R^{f11}) = \begin{cases} (0, 1) & \text{if } Av_l \sqrt{\frac{M}{-1+\alpha+\beta^2}} < 27\sqrt{C}, \\ \left(\left(\sqrt{\frac{c_2}{c_f}} \frac{1}{3c_t} A \sqrt{\frac{-1+\alpha+\beta^2}{v_l}} \right)^{1/2}, \right. \\ \quad \left. 1 - \frac{2\sqrt{c_2 c_f}}{T} \sqrt{\frac{-1+\alpha+\beta^2}{M}} \right) & \text{if } 27\sqrt{C} \leq Av_l \sqrt{\frac{M}{-1+\alpha+\beta^2}} < 48\sqrt{C}, \\ \left(\frac{A}{12c_f c_t}, \frac{1}{2} \right) & \text{otherwise.} \end{cases}$$

$$(T^{f\beta 1}, R^{f\beta 1}) = \begin{cases} (0, 1) & \text{if } Bv_l < 27\sqrt{C}, \\ \left(\left(\sqrt{\frac{c_2}{c_f}} \frac{1}{3c_t} \frac{B}{v_l} \right)^{1/2}, 1 - \frac{2\sqrt{c_2 c_f}}{v_l T} \right) & \text{if } 27\sqrt{C} \leq Bv_l < 48\sqrt{C}, \\ \left(\frac{B}{12c_f c_t}, \frac{1}{2} \right) & \text{otherwise,} \end{cases}$$

where $A = v_l^2 - \alpha v_l v_h + \alpha v_h^2$, $B = (v_l^2 - \alpha v_l v_h)\beta^2 + \alpha v_h^2$, and $C = c_2 c_t^2 c_f^3$. When the market is covered by both suppliers, the profit function is

$$\Pi_I^{f\beta 1} = \frac{2}{9} \frac{B}{v_l^2} c_2 \left(-9 + \frac{\sqrt{3Bv_l}}{C^{1/4}} \right),$$

which resembles that in Lemma B.3 and increases in v_h .

However, if the market is covered by only S_2 , TP 's profit may decrease in v_h . Remind that \tilde{R} is only feasible if $M < 0$. As v_h increases, M increases to zero, which drives T to increase and \tilde{R} to decrease to zero. In short, as v_h increases, R^{f11} is non-increasing. If $R^{f11} = 1/2$, TP 's profit is increasing. Otherwise, it is decreasing.

Let us prove that the partial coverage is optimal within an interval where market inequality is high. Assume that (1,1) is feasible when the partial coverage is optimal. $M < 0$ or $\alpha < \frac{1-\beta^2}{\beta^2+v_h^2/v_l^2(1-\beta^2)}$. However, for the partial coverage to be optimal, $\left(\frac{\sqrt{B}}{v_h^{3/2}} \right)^{1/2} \leq \alpha$. We show that $\frac{1-\beta^2}{\beta^2+v_h^2/v_l^2(1-\beta^2)} < \left(\frac{\sqrt{B}}{v_h^{3/2}} \right)^{1/2}$ for contradiction.

We can normalize $v_l = 1$ without loss of generality. Take them to the power of 4.

$$\begin{aligned}
\frac{v_h^2 - v_h\beta^2 + (1 + (1 - v_h)v_h)\beta^4}{v_h^3(\beta^2 + v_h^2(1 - \beta^2))} &> \frac{(1 - \beta^2)^4}{(\beta^2 + v_h^2(1 - \beta^2))^4} \\
\frac{v_h^2 - v_h\beta^2 + (1 + (1 - v_h)v_h)\beta^4}{v_h^3} &> \frac{v_h^2 - v_h\beta^2 + (1 + (1 - v_h)v_h)\beta^4}{v_h^6} \\
\frac{v_h^2 - v_h\beta^2 + (1 + (1 - v_h)v_h)\beta^4}{v_h^6} &> \frac{(1 - \beta^2)^4}{(\beta^2 + v_h^2(1 - \beta^2))^3} \\
\frac{v_h^2 - v_h\beta^2 + (1 + (1 - v_h)v_h)\beta^4}{(1 - \beta^2)^4} &> 1 > \left(\frac{v_h^2}{\beta^2 + v_h^2(1 - \beta^2)}\right)^3 \\
v_h^2(1 - \beta^4) - v_h\beta^2(1 - \beta^2) + \beta^4 &> (1 - \beta^2)^2 > (1 - \beta^2)^4 \\
v_h(v_h(1 + \beta^2) - \beta^2) &> \frac{1 - 2\beta^2}{1 - \beta^2}
\end{aligned}$$

Thus, if the partial coverage is optimal, $\pi_I^p \geq \pi_I^{f\beta 1}$ must be the case. Since $\pi_I^{f\beta 1}$ is more convex increasing in v_h , $\pi_I^p \leq \pi_I^{f\beta 1}$ for large v_h . By applying the same technique in Lemma 2.2, one can find an interval for v_h with some high α .

□

Lemma B.14 (Tier 1 Strategy, FSB). S_1 and S_2 set the prices as follows.

- If $R \leq R^{lh}$ and $\alpha v_h^2(1 - \beta^2) + v_l^2(-1 + (1 + \alpha)\beta^2) < 0$,

$$(w_1, w_2) = \begin{cases} \left(c_1, c_1 + \frac{(v_l T)^2}{4c_f}(1 - \beta^2)(1 - R)^2 \right) & \text{if } R \leq \tilde{R}(t), \\ \left(\frac{(v_l T \beta)^2}{4c_f}(1 - R)^2, \right. \\ \left. w_1 + \frac{(v_h T)^2}{4c_f}(1 - \beta^2)(1 - R)^2 \right) & \text{if } \tilde{R}(t) < R \leq R^{lh}. \end{cases}$$

The procurement choice is

$$\begin{cases} (1, 1) & \text{if } R \leq \tilde{R}, \\ (\beta, 1) & \text{if } \tilde{R} < R \leq R^{lh}. \end{cases}$$

- If $R \leq R^{lh}$ and $\alpha v_h^2(1 - \beta^2) + v_l^2(-1 + (1 + \alpha)\beta^2) \geq 0$, $(w_1, w_2) = \left(\frac{(v_l T \beta)^2}{4c_f} (1 - R)^2, w_1 + \frac{(v_h T)^2}{4c_f} (1 - \beta^2)(1 - R)^2 \right)$ and the procurement choice is $(\beta, 1)$.
- If $R^{lh} < R \leq R^h$, $(w_1, w_2) = \left(c_1, c_1 + \frac{(v_l T)^2}{4c_f} (1 - \beta^2)(1 - R)^2 \right)$ and the procurement choice is $(1, 1)$.

, where $\tilde{R} = 1 - \frac{2\sqrt{c_f c_2}}{T} \sqrt{\frac{-1 + \alpha + \beta^2}{\alpha v_h^2(1 - \beta^2) + v_l^2(-1 + (1 + \alpha)\beta^2)}}$, $R^h = 1 - \frac{2\sqrt{c_f c_2}}{v_h T \alpha^\gamma}$, and $R^{lh} = 1 - \frac{2\sqrt{c_f c_2}}{v_l T}$.

Proof of Lemma B.14. Suppliers' profits are similar to those in Lemma B.13. The same proof can be applied. \square

Proof of Proposition B.1. Suppose market inequality is high enough so that the market is fully covered by both suppliers under both business models. Let $\pi_I^{f\beta 1}(r^{lh})$ denote TP 's profit under SSB. We define $\Pi_I^{f\beta 1}$ and $\Pi_I^{F\beta 1}\left(\frac{1}{2}\right)$ as FSB TP 's profit when M_1 's IR is binding (if $Bv_l < 48\sqrt{C}$) and not binding. Specifically,

$$\begin{aligned}\pi_I^{f\beta 1}(r^{lh}) &= \frac{(v_l^2 \beta^2 + v_h^2 \alpha (1 - \beta^2))^3}{432c_t^2 c_f^3} - \left(\beta^2 + \frac{\alpha v_h^2}{v_l^2} (1 - \beta^2) \right) c_2, \\ \Pi_I^{f\beta 1} &= \frac{2}{9} \frac{B}{v_l^2} c_2 \left(-9 + \frac{\sqrt{3Bv_l}}{C^{1/4}} \right), \\ \Pi_I^{F\beta 1}\left(\frac{1}{2}\right) &= \frac{B^3}{3456c_t^2 c_f^3}.\end{aligned}$$

First, observe that the all profit functions are increasing in v_h . Then, we compare $\pi_I^{f\beta 1}(r^{lh})$ and $\Pi_I^{F\beta 1}\left(\frac{1}{2}\right)$.

$$\begin{aligned}\Pi_I^{F\beta 1}\left(\frac{1}{2}\right) - \pi_I^{f\beta 1}(r^{lh}) &= \frac{1}{432c_t^2 c_f^3} \left(\frac{B^3}{8} - (v_l^2 \beta^2 + v_h^2 \alpha (1 - \beta^2))^3 \right) \\ &\quad + \left(\beta^2 + \frac{\alpha v_h^2}{v_l^2} (1 - \beta^2) \right) c_2,\end{aligned}$$

where $B = (v_l^2 - \alpha v_l v_h) \beta^2 + \alpha v_h^2$. Since $B > v_l^2 \beta^2 + v_h^2 \alpha (1 - \beta^2)$, the difference is positive. As B increases in market inequality, FSB is optimal in market inequality.

For high market inequality such as $v_l < \alpha v_h$, all profits decrease in β . We show that FSB is preferred for $\beta = 1$. Thus, there exists a threshold in β under (over) which SSB (FSB) is optimal.

□

B.2 Analysis of Multiple Technology Providers and Proof of Proposition 2.7

Consider the base case where the subsystem suppliers are identical. Let us introduce one more technology provider that develops either a substitutable or complementary technology. TP_1 and TP_2 denote each TPs. They can choose the business model between SSB and FSB, resulting in four combinations of business models. We are interested in what the optimal business model in equilibrium. We analyze the substitutable technology case followed by the complementary case. As there are two market segments, a technology provider should decide whether to compete with the other TP for both segments. If they compete, they are essentially engaged in price competition, resulting in zero profits in the symmetric equilibrium regardless of a business model. Let us consider the case where TPs are local monopolies, or equivalently, their decisions are asymmetric.

B.2.1 Substitutable Technology Providers

Suppose both TPs adopts SSB. We define (t_i, r_i) as the technology quality and the royalty rate for TP_i , where $t_1 < t_2$ without loss of generality. A supplier should also decide whether to compete for both manufacturers. It can do so by

embedding the superior technology (t_2) and sell the subsystem at a competitive price. However, this strategy is not profitable in equilibrium, which will be shown. First, suppose each supplier embeds a different technology, saying S_i uses TP_i 's technology. That is, S_1 embeds the inferior technology t_1 , sets the price w_1 and pays the royalties $w_1 r_1$. For any w_1 , S_2 can set $w_2 = \frac{(t_2^2 - t_1^2)v_h^2}{4c_f} + w_1$ such that M_2 is better off by procuring from S_2 . Knowing this, S_1 sells to M_1 at $w_1 = \frac{(v_l t_1)^2}{4c_f}$. Both suppliers' profits can be expressed as follows.

$$\pi_{S1} = (w_1(1 - r_1) - c_s)(1 - \alpha),$$

$$\pi_{S2} = (w_2(1 - r_2) - c_s)\alpha.$$

Each supplier's profit is binding at $r_1^* = 1 - \frac{4c_f c_s}{(v_l t_1)^2}$ and $r_2^* = 1 - \frac{4c_f c_s}{(v_h t_2)^2 - (v_h^2 - v_l^2)t_1^2}$. One can verify that $r_1 < r_2$ for $t_1 < t_2$ and S_2 's deviation of selling to both M_1 and M_2 is not profitable. Therefore, for given technologies t_i and r_i^* , S_i sells to M_i and TP_i extracts all the profits of S_i in equilibrium. In short, $TP_1 - S_1 - M_1$ and $TP_2 - S_2$ are integrated in this asymmetric equilibrium. We note that SSB is the optimal business model for TP_1 , because TP_1 can integrate its own supply chain. The profits of TP_1 and TP_2 in equilibrium are

$$\pi_{I1} = \left(\frac{v_l^6(1 - \alpha)^2}{432c_t^2c_f^3} - c_s \right) (1 - \alpha),$$

$$\pi_{I2} = \left(\frac{\alpha^2 v_h^6 - 3(1 - \alpha)^2 v_l^4 v_h^2 + 3(1 - \alpha)^2 v_l^6}{432c_t^2c_f^3} - c_s \right) \alpha.$$

Notice that each technology provider has a different IR constraint. To focus on more interesting cases, we let $c_s = \frac{v_l^6(1-\alpha)^2}{432c_t^2c_f^3}$ and $v_l = \alpha v_h$. Then,

$$\begin{aligned}\pi_{I1} &= 0, \\ \pi_{I2} &= \frac{\alpha^3 v_h^6}{432c_t^2c_f^3} (1 + (1-\alpha)^2 \alpha^2 (2\alpha^2 - 3)) > 0.\end{aligned}$$

Therefore, (SSB, SSB) is individually rational for each technology provider.

Next, we check TP_2 's incentive to deviate to FSB. Assume TP_1 and TP_2 adopts SSB and FSB, respectively. When M_2 procures from S_1 , it uses the inferior subsystem but does not need to pay royalties. If it buys from S_2 , it pays royalties. M_2 's profit function for each case can be written as follows.

$$\begin{aligned}\pi_{2|s1} &= (p_2 - c_f \theta_2^2 - w_1) \alpha \\ &= \left(\frac{t_1^2}{4c_f} (v_h^2 - 2v_h v_l + 2v_l^2) - w_1 \right) \alpha, \\ \pi_{2|s2} &= (p_2(1-R) - c_f \theta_{2|s2}^2 - w_2) \alpha \\ &= \left(\frac{(v_h t_2)^2 (1-R)^2 - 2(1-R)v_l(v_h - v_l)t_1^2}{4c_f} - w_2 \right) \alpha\end{aligned}$$

S_2 can set w_2 low enough such that $\pi_{2|s2} \geq \pi_{2|s1}$ and M_2 buys the superior subsystem from S_2 . Then, TP_2 's profit is written as

$$\begin{aligned}\Pi_{I2} &= -c_t t_2^3 + R p_2 \alpha \\ &= -c_t t_2^3 + R \frac{(1-R)(v_h t_2)^2 - v_l(v_h - v_l)t_1^2}{2c_f} \alpha.\end{aligned}$$

The first order condition with respect to R gives $R^* = \frac{1}{2} - \frac{v_l(v_h - v_l)}{2(v_h t_2)^2} t_1^2$, which hinders us from obtaining a closed form solution for t_2 and checking TP_2 's deviation incentive. To bypass this issue, we introduce a pseudo profit function

for TP_2 . Observe that if TP_1 adopted FSB and M_1 uses TP_1 's technology, $\tilde{p}_2 = (1 - R) \frac{(v_h t_2)^2 - v_l(v_h - v_l)t_1^2}{2c_f} > p_2$. The resulting profit function is $\tilde{\Pi}_{I2} = -c_t t_2^3 + R(1 - R) \frac{(v_h t_2)^2 - v_l(v_h - v_l)t_1^2}{2c_f} \alpha > \Pi_{I2}$. Since the optimal royalty rate is $\tilde{R} = 1/2$, $\tilde{\Pi}_{I2}(t_2) = -c_t t_2^3 + \frac{(v_h t_2)^2 - v_l(v_h - v_l)t_1^2}{8c_f} \alpha$ and we obtain the optimal technology level $\tilde{t}_2 = \frac{\alpha v_h^2}{12c_f c_t}$. We compare this to $\pi_{I2}(t_2) = -c_t t_2^3 + \frac{(v_h t_2)^2 - (v_h^2 - v_l^2)t_1^2}{4c_f} \alpha$. Assume SSB TP_2 mimics FSB TP_2 's technology investment, which is suboptimal for SSB TP_2 . Then,

$$\begin{aligned}
\pi_{I2}(\tilde{t}_2) - \tilde{\Pi}_{I2}(\tilde{t}_2) &\equiv \frac{(v_h \tilde{t}_2)^2 - (v_h^2 - v_l^2)t_1^2}{4c_f} - \frac{(v_h \tilde{t}_2)^2 - v_l(v_h - v_l)t_1^2}{8c_f} \\
&\equiv (v_h \tilde{t}_2)^2 - t_1^2(2v_h^2 - v_h v_l - v_l^2) - 8c_f c_s \\
&\equiv -1152c_f^3 c_s c_t^2 + \alpha^2 v_h^6 - 8(1 - \alpha)^2 v_h^2 v_l^4 + 4(1 - \alpha)^2 v_h v_l^5 \\
&\quad + 4(1 - \alpha)^2 v_l^6. \tag{B.17}
\end{aligned}$$

The last equation, obtained by substituting t_1 and \tilde{t}_2 with their values, implies that TP_2 is generally better off under SSB if v_h/v_l is large enough and $c_s c_t^2 c_f^3$ is small enough. To obtain a clearer insight, we apply the conditions defined above when (SSB, SSB) is IR. Then, (B.17) becomes

$$\pi_{I2}(\tilde{t}_2) - \tilde{\Pi}_{I2}(\tilde{t}_2) \equiv \frac{1}{3} \alpha^2 v_h^6 (3 + 4(1 - \alpha)^2 \alpha^2 (-6 + \alpha(3 + \alpha))) > 0.$$

Therefore, TP_2 's SSB is incentive compatible and (SSB, SSB) is the equilibrium strategy. Since (B.17) > 0 as $c_s c_t^2 c_f^3$ decreases and v_h increases, $c_s \leq \frac{v_l^6 (1 - \alpha)^2}{432 c_t^2 c_f^3}$ and $v_l \leq \alpha v_h$ are the sufficient conditions for (SSB, SSB) to be the equilibrium strategy.

B.2.2 Complementary Technology Providers

Suppose there are equally important complementary technologies T_i from TP_i for $i \in \{1, 2\}$ such that the product quality is $Q = (T_1 T_2)^{1/2} \theta$. Assume that there are two identical suppliers for each TP , leading the subsystem competition simple.

M_i 's profit function under different technology business models can be written as follows.

$$\pi_i = \begin{cases} (p_i(1 - R_1 - R_2) - c_f \theta_i^2 - w_{s1} - w_{s2}) D_i & (FSB, FSB), \\ (p_i(1 - R_1) - c_f \theta_i^2 - w_{s1} - w_{s2}) D_i & (FSB, SSB), \\ (p_i - c_f \theta_i^2 - w_{s1} - w_{s2}) D_i & (SSB, SSB). \end{cases}$$

We note that two subsystems should be procured at w_{s1} and w_{s2} . Since these subsystem prices affect M_i 's participation decision, we can use $w_s = w_{s1} + w_{s2}$. The manufacturer's quality and price decisions can be analogously obtained for the cases of (FSB, FSB) and (SSB, SSB).

For example, both TPs adopt SSB and the full market coverage strategy. $\theta_1 = \frac{v_l \sqrt{T_1 T_2}}{2c_f}$ and $p_1 = \frac{v_l^2 T_1 T_2}{2c_f}$. In equilibrium, $w_s = p_1 - c_f \theta_1^2 = \frac{T_1 T_2 v_l}{4c_f}$. Since two technologies are equally important, each TP sets its royalty rate such that it has a half of w_s . This leads $T_i = \frac{v_l^2}{24c_f c_s^{1/3} c_t^{2/3}}$ and $\pi_{Ii}^{SS} = \frac{v_l^6}{6912c_t c_s c_f^3} - c_s$. When both TPs use FSB, they have two forms of profit functions depending on whether M_1 's IR is binding. We know that for large market inequality, it is optimal for TP to maintain a low royalty rate where M_1 's IR is not binding. In such case, $\Pi_{Ii}^{FF} = \frac{(v_l^2 - \alpha v_l v_h + \alpha v_h^2)^3}{78732c_t^2 c_f^3}$. By comparing π_{Ii} and Π_{Ii} , it is clear that (SSB,SSB) is optimal for low market inequality and (FSB, FSB) is for high market inequality. The remaining question is if (SSB, FSB) or (FSB, SSB) can be optimal.

Suppose TP_1 adopts SSB and TP_2 does FSB. To avoid confusion from small and large letters, we define π_{I1}^{xy} as the profit of TP_i when TP_1 and TP_2 adopt x and y , respectively. Their profit functions can be expressed as

$$\begin{aligned}\pi_{I1}^{SF} &= -c_t T_1^3 + w_1 r, \\ \pi_{I2}^{SF} &= -c_t T_2^3 + (p_1(1 - \alpha) + p_2 \alpha) R.\end{aligned}$$

The competition between TP_1 's suppliers drives their profits zero, resulting in $w_1 = \frac{c_s}{1-r}$. It implies TP_1 can set w_1 via r . For the full market coverage, it is optimal to set $r(R)$ such that M_1 's IR is binding, i.e. $w_1 = \frac{T_1 T_2 v_l^2}{4c_f} (1 - R)^2 - c_s$. Since TP_1 's royalty rate under SSB does not affect the system quality investment θ_1 and θ_2 , TP_2 can set the optimal royalty rate $R^* = 1/2$ without considering r . Responding to that, TP_1 sets its royalty rate $r^* = 1 - \frac{16c_f c_s}{T_1 T_2 v_l^2 - 16c_f c_s}$ or equivalently has $w_1 = \frac{T_1 T_2 v_l^2}{16c_f} - c_s$. Anticipating these royalty rates, the optimal technologies are $T_1 = \frac{v_l^{4/3} (v_l^2 - \alpha v_l v_h + \alpha v_h^2)^{1/3}}{24 \cdot 2^{2/3} c_f c_t}$ and $T_2 = \frac{v_l^{2/3} (v_l^2 - \alpha v_l v_h + \alpha v_h^2)^{2/3}}{24 \cdot 2^{1/3} c_f c_t}$. Consequently, the optimal profits of TPs are

$$\begin{aligned}\pi_{I1}^{SF} &= \frac{v_l^6 + v_l^4 v_h (v_h - v_l) \alpha}{27648 c_t^2 c_f^3} - 2c_s, \\ \pi_{I2}^{SF} &= \frac{v_l^2 (v_l^2 - \alpha v_l v_h + \alpha v_h^2)^2}{13824 c_t^2 c_f^3}.\end{aligned}$$

We want to check that there exists a range of v_h/v_l such that (SSB, FSB) is an equilibrium, which is equivalent to

$$\begin{aligned}\pi_{Ii}^{SS} &\leq \pi_{Ii}^{SF}, \\ \Pi_{Ii}^{FF} &\leq \pi_{Ii}^{SF}.\end{aligned}$$

Let us normalize $\pi_{I_i}^{SS} = 0$ by setting $c_s = v_l^6/6912c_t^2c_f^3$. One can derive a threshold $v_{h1} = \frac{\alpha + \sqrt{28\alpha + \alpha^2}}{2\alpha}v_l$ such that for $v_{h1} \leq v_h$, $\pi_{I_1}^{SS} \leq \pi_{I_1}^{SF}$. We remind that $\Pi_{I_1}^{FF}$ can have two forms depending on whether M_1 's IR is binding. Consider $\Pi_{I_1,b}^{FF}$ which is constrained by M_1 's IR constraint. It is evident that $\Pi_{I_1,b}^{FF}$ is increasing in v_h . Although its form is quite complicated, one can verify that $\Pi_{I_1,b}^{FF} = \frac{(3-5 \cdot 6^{1/4})v_l^6}{1296c_t^2c_f^3} > 0$ at $v_h = v_{h1}$. For TP_2 's FSB and $v_h = v_{h1}$, while TP_1 's profit is zero under SSB but strictly positive under FSB. Moreover, one can verify that $\Pi_{I_1,b}^{FF}$ is convexly increasing faster than $\pi_{I_1}^{SF}$ at $v_h = v_{h1}$. Hence, FSB is still optimal for TP_1 for $v_{h1} \leq v_h$ and (SSB, FSB) cannot be optimal.

Appendix C

Proofs for Chapter 3

Proof. Proof of Proposition 3.1

We remind that if t_i follows exponential distribution with parameter λ_i and t_1, t_2, \dots, t_n are independent random variables, then $\min\{t_1, t_2, \dots, t_n\}$ follows exponential distribution with parameter $\sum_{i=1}^n \lambda_i$. Since all the $n - 1$ competitors are identical, t_c in (3.2) follows exponential distribution with parameter $\sum \lambda_{-i} = (n - 1)\lambda_j$ for $j \neq i$. From the first order condition, i 's best response is given as follows.

$$\lambda_i(\lambda_{-i}) = \frac{\sqrt{k(n)P(n)r(r + (n - 1)\lambda_j)}}{k(n)r} - (n - 1)\lambda_j - r.$$

By using the symmetry between Firm i and Firm j , $\lambda_i = \lambda_j$ and we obtain the desired result. \square

Proof. Proof of Proposition 3.2 Note that the monopoly's optimal investment is $\lambda_i^*(1) = \sqrt{\frac{P(1)}{k(1)}} - r$. We replace $P(1)$ with $k(1)r^2P$ for $P > 1$. Then, $\lambda_i^*(1) = r(\sqrt{P} - 1)$. Similarly, we can obtain the optimal investments for a duopoly and a three-firm oligopoly by replacing n and $P(n)$ in Proposition 3.1 with proper

parameters. As a result, one can derive the following.

$$\lambda_i^*(2) = \frac{r}{8k(2)}(-4k(2) + k(1)P\theta_{12} + \sqrt{k(1)P\theta_{12}}\sqrt{8k(2) + k(1)P\theta_{12}}),$$

$$\lambda_i^*(3) = \frac{r}{9k(3)}(-3k(3) + k(1)P\theta_{13} + \sqrt{k(1)P\theta_{13}}\sqrt{3k(3) + k(1)P\theta_{13}}).$$

By equating $\lambda_i^*(n) = \lambda_i^*(m)$, we derive the threshold $\bar{\theta}_{nm}$. Specifically,

$$\bar{\theta}_{12} = \frac{k(2)}{k(1)} \frac{(1 - 2\sqrt{P})^2}{P^{3/2}},$$

$$\bar{\theta}_{13} = \frac{k(3)}{k(2)} \frac{(2 - 3\sqrt{P})^2}{P(-1 + 2\sqrt{P})},$$

$$\bar{\theta}_{23} = \frac{k(3)}{k(1)^2 k(2)} \cdot \left(\frac{9\theta_{12}^2 k(1)^2 P^2 + 9(\theta_{12} k(1) P)^{3/2} \sqrt{\theta_{12} k(1) P + 8k(2)}}{16\theta_{12} P^2} + \frac{2k(2) \sqrt{\theta_{12} k(1) P} \sqrt{\theta_{12} k(1) P + 8k(2)} - 26\theta_{12} k(1) k(2) P}{16\theta_{12} P^2} \right).$$

□

Bibliography

- Altug, Mehmet Sekip, and Garrett van Ryzin. 2013. “Product quality selection: Contractual agreements and supplier competition in an assemble-to-order environment”. *International Journal of Production Economics* 141 (2): 626–638.
- Aronsson, Thomas, Mats A Bergman, and Niklas Rudholm. 2001. “The impact of generic drug competition on brand name market shares—evidence from micro data”. *Review of Industrial Organization* 19 (4): 423–433.
- Arrow, Kenneth. 1962. “Economic welfare and the allocation of resources for invention”. In *The rate and direction of inventive activity: Economic and social factors*, 609–626. Princeton University Press.
- Bartz, Diane. 2009. “U.S. battle over patent reform headed for compromise?” *Reuters*.
- Bartz, Diane, and Stephen Nellis. 2017. “Apple files \$1 billion lawsuit against chip supplier Qualcomm”. *Reuters*.
- Berndt, Ernst R, Richard Mortimer, Ashoke Bhattacharjya, Andrew Parece, and Edward Tuttle. 2007. “Authorized generic drugs, price competition, and consumers’ welfare”. *Health Affairs* 26 (3): 790–799.
- Berndt, Ernst R, Rena M Conti, and Stephen J Murphy. 2017. *The Landscape of US Generic Prescription Drug Markets, 2004-2016*. Tech. rep. National Bureau of Economic Research.

- Bernstein, Fernando, and A Gürhan Kök. 2009. "Dynamic cost reduction through process improvement in assembly networks". *Management Science* 55 (4): 552–567.
- Bhaskaran, Sreekumar R, and Vish Krishnan. 2009. "Effort, revenue, and cost sharing mechanisms for collaborative new product development". *Management Science* 55 (7): 1152–1169.
- Bhattacharya, Jayanta, and William B Vogt. 2003. "A simple model of pharmaceutical price dynamics". *The Journal of Law and Economics* 46 (2): 599–626.
- Bhattacharya, Shantanu, Vish Krishnan, and Vijay Mahajan. 2003. "Operationalizing technology improvements in product development decision-making". *European Journal of Operational Research* 149 (1): 102–130.
- Bimpikis, Kostas, Douglas Fearing, and Alireza Tahbaz-Salehi. 2014. "Multi-sourcing and miscoordination in supply chain networks": Working paper, Stanford University, CA.
- Bonanno, Giacomo. 1986. "Vertical differentiation with Cournot competition". *Economic Notes* 15 (2): 68–91.
- Bousquet, Alain, Helmuth Cremer, Marc Ivaldi, and Michel Wolkowicz. 1998. "Risk sharing in licensing". *International Journal of Industrial Organization* 16 (5): 535–554.
- Bresnahan, Timothy F, and Peter C Reiss. 1991. "Entry and competition in concentrated markets". *Journal of political economy* 99 (5): 977–1009.
- Bullis, Kevin. 2015. "Why we don't have battery breakthroughs". *MIT Technology Review*.
- Cachon, Gérard P, and Martin A Lariviere. 2005. "Supply chain coordination with revenue-sharing contracts: Strengths and limitations". *Management science* 51 (1): 30–44.

- Coad, Alex. 2009. "On the distribution of product price and quality". *Journal of Evolutionary Economics* 19 (4): 589–604.
- Conner, Kathleen R. 1995. "Obtaining strategic advantage from being imitated: When can encouraging "Clones" pay?" *Management Science* 41 (2): 209–225.
- Corbett, Charles J, and Uday S Karmarkar. 2001. "Competition and structure in serial supply chains with deterministic demand". *Management Science* 47 (7): 966–978.
- Cvsa, Viswanath, and Stephen M Gilbert. 2002. "Strategic commitment versus postponement in a two-tier supply chain". *European Journal of Operational Research* 141 (3): 526–543.
- Dasgupta, Partha, and Joseph Stiglitz. 1980. "Industrial structure and the nature of innovative activity". *The Economic Journal* 90 (358): 266–293.
- Elmer-DeWitt, Philip. 2013. "J.P. Morgan takes a deep look at a low-end iPhone". *Fortune*.
- Erat, Sanjiv, and Stylianos Kavadias. 2006. "Introduction of new technologies to competing industrial customers". *Management Science* 52 (11): 1675–1688.
- Fairless, Tom, and Don Clark. 2015. "EU Launches Antitrust Investigations Into Qualcomm". *The Wall Street Journal*.
- Fehrenbacher, Katie. 2016. "Why Tesla Is Making a New Battery Format at the Gigafactory". *Fortune*.
- Fink, Sheri. 2016. "Drug Shortages Forcing Hard Decisions on Rationing Treatments". *The New York Times*.
- Fox, Erin R, Burgunda V Sweet, and Valerie Jensen. 2014. "Drug shortages: a complex health care crisis". In *Mayo Clinic Proceedings*, 89:361–373. 3. Elsevier.

- Frank, Richard G, and David S Salkever. 1997. “Generic entry and the pricing of pharmaceuticals”. *Journal of Economics & Management Strategy* 6 (1): 75–90.
- Gabszewicz, J Jaskold, and J-F Thisse. 1980. “Entry (and exit) in a differentiated industry”. *Journal of Economic Theory* 22 (2): 327 –338. ISSN: 0022-0531.
- . 1979. “Price competition, quality and income disparities”. *Journal of economic theory* 20 (3): 340–359.
- Gal-Or, Esther. 1983. “Quality and quantity competition”. *Bell Journal of Economics* 14 (2): 590–600.
- Gilbert, Stephen M, and Viswanath Cvsa. 2003. “Strategic commitment to price to stimulate downstream innovation in a supply chain”. *European Journal of Operational Research* 150 (3): 617–639.
- Girotra, Karan, and Serguei Netessine. 2014. “Four paths to business model innovation”. *Harvard business review* 92 (7): 96–103.
- Girotra, Karan, Christian Terwiesch, and Karl T Ulrich. 2010. “Idea generation and the quality of the best idea”. *Management science* 56 (4): 591–605.
- Goldscheider, Robert. 1995. “The negotiation of royalties and other sources of income from licensing”. *IDEA: The Journal of Law and Technology* 36:1–17.
- Grabowski, Henry G, and John M Vernon. 1992. “Brand loyalty, entry, and price competition in pharmaceuticals after the 1984 Drug Act”. *The journal of law and economics* 35 (2): 331–350.
- Grahovac, Jovan, and Geoffrey Parker. 2003. “Component modularity, external economies of scale, and outsourcing decisions in the supply chain.”: Working paper, Tulane University, New Orleans, LA.
- Greenwald, Ted. 2017. “Qualcomm Sues iPhone Manufacturers Over Royalties”. *The Wall Street Journal*.

- Gupta, Sudheer, and Richard Loulou. 1998. "Process innovation, product differentiation, and channel structure: Strategic incentives in a duopoly". *Marketing Science* 17 (4): 301–316.
- Hagel III, John, and Marc Singer. 2000. "Unbundling the corporation". *McKinsey Quarterly*.
- Heywood, John S, Jianpei Li, and Guangliang Ye. 2014. "Per unit vs. ad valorem royalties under asymmetric information". *International Journal of Industrial Organization* 37:38–46.
- Holmes, Thomas J, and Sanghoon Lee. 2012. "Economies of density versus natural advantage: Crop choice on the back forty". *Review of Economics and Statistics* 94 (1): 1–19.
- Hu, Bin, Ming Hu, and Yi Yang. 2017. "Open or Closed? Technology Strategy, Supplier Investment, and Competition". *Forthcoming to Manufacturing & Service Operations Management*.
- Hu, Xinxin, Haresh Gurnani, and Ling Wang. 2013. "Managing risk of supply disruptions: Incentives for capacity restoration". *Production and Operations Management* 22 (1): 137–150.
- Hull, Dana. 2017. "Tesla Deliveries Miss Forecasts Again on Production Delays". *Bloomberg*.
- Iyer, Ananth V, Vinayak Deshpande, and Zhengping Wu. 2005. "Contingency management under asymmetric information". *Operations Research Letters* 33 (6): 572–580.
- Jain, Nitish, Karan Girotra, and Serguei Netessine. 2016. "Recovering from Supply Interruptions: The Role of Sourcing Strategy". *Working aper*. <https://ssrn.com/abstract=2682522>.
- Jensen, Richard, and Marie Thursby. 2001. "Proofs and prototypes for sale: The licensing of university inventions". *The American Economic Review* 91 (1): 240–259.

- Jensen, Valerie, and Bob A Rappaport. 2010. "The reality of drug shortages-the case of the injectable agent propofol". *New England Journal of Medicine* 363 (9): 806–807.
- Jensen, Valerie, Lorene M Kimzey, and Mark J Goldberger. 2002. "FDA's role in responding to drug shortages". *American journal of health-system pharmacy* 59 (15): 1423–1425.
- Jerath, Kinshuk, Serguei Netessine, and Z John Zhang. 2007. "Can we all get along? Incentive contracts to bridge the marketing and operations divide". *SSRN*.
- Jeuland, Abel P, and Steven M Shugan. 1983. "Managing channel profits". *Marketing science* 2 (3): 239–272.
- Jia, Justin, and Hui Zhao. 2017. "Mitigating the US Drug Shortages Through Pareto-Improving Contracts". *Production and Operations Management* 26 (8): 1463–1480.
- Jones, Roy, and Haim Mendelson. 2011. "Information goods vs. industrial goods: Cost structure and competition". *Management Science* 57 (1): 164–176.
- Kaiser, Jocelyn. 2011. "Shortages of Cancer Drugs Put Patients, Trials at Risk". *Science* 332 (6029): 523–523. ISSN: 0036-8075. eprint: <http://science.sciencemag.org/content/332/6029/523.full.pdf>.
- Kamien, Morton I, and Yair Tauman. 1986. "Fees versus royalties and the private value of a patent". *The Quarterly Journal of Economics* 101 (3): 471–491.
- Katz, Michael L, and Carl Shapiro. 1986. "How to license intangible property". *The Quarterly Journal of Economics* 101 (3): 567–589.
- . 1985. "On the licensing of innovations". *The RAND Journal of Economics* 16 (4): 504–520.
- Kessler, Aaron M. 2015. "Losses Widen at Tesla, but Company Says Production Is on Track". *New York Times*.

- Kim, Sang-Hyun, and Fiona Scott Morton. 2015. "A Model of Generic Drug Shortages: Supply Disruptions, Demand Substitution, and Price Control". *Working paper*.
- Kim, Sang-Hyun, and Brian Tomlin. 2013. "Guilt by association: Strategic failure prevention and recovery capacity investments". *Management Science* 59 (7): 1631–1649.
- Kremer, Michael. 1993. "The O-ring theory of economic development". *The Quarterly Journal of Economics* 108 (3): 551–575.
- Krishnan, Vish, and Saurabh Gupta. 2001. "Appropriateness and impact of platform-based product development". *Management Science* 47 (1): 52–68.
- Krishnan, Vish, and Karl T Ulrich. 2001. "Product development decisions: A review of the literature". *Management science* 47 (1): 1–21.
- Krishnan, Vish, and Wenge Zhu. 2006. "Designing a family of development-intensive products". *Management Science* 52 (6): 813–825.
- Kulatilaka, Nalin, and Lihui Lin. 2006. "Impact of licensing on investment and financing of technology development". *Management Science* 52 (12): 1824–1837.
- Lambert, Fred. 2017. "Tesla is starting Model 3 battery cell production at Gigafactory 1 'right now'". *eletrek*.
- Lee, Deishin, and Haim Mendelson. 2008. "Divide and conquer: Competing with free technology under network effects". *Production and Operations Management* 17 (1): 12–28.
- Lee, Eunkyu, and Richard Staelin. 1997. "Vertical strategic interaction: Implications for channel pricing strategy". *Marketing Science* 16 (3): 185–207.
- Lee, Junghee, Vish Krishnan, and Hyoduk Shin. 2018a. "Business Models for Technology-Intensive Supply Chains". *Working paper*.

- . 2018b. “Product innovation in technology supply chains”. *Working paper*.
- Lee, Min-Jeong. 2015. “Samsung Facing Supply Shortages for Curved-Screen Galaxy S6 Edge”. *The Wall Street Journal*.
- Lee, Se Young, and Stephen Nellis. 2016. “South Korea Fines Qualcomm \$854 million for violating competition laws”. *Reuters*.
- Lim, Michael K, Ho-Yin Mak, and Ying Rong. 2015. “Toward mass adoption of electric vehicles: Impact of the range and resale anxieties”. *Manufacturing & Service Operations Management* 17 (1): 101–119.
- Llobet, Gerard, and Jorge Padilla. 2016. “The optimal scope of the royalty base in patent licensing”. *The Journal of Law and Economics* 59 (1): 45–73.
- Majumder, Pranab, and Ashok Srinivasan. 2008. “Leadership and competition in network supply chains”. *Management Science* 54 (6): 1189–1204.
- Maynard, Micheline. 2014. “Tesla Shows Signs It’s Struggling With Manufacturing”. *Forbes*.
- Moorthy, K Sridhar, and Ivan PL Png. 1992. “Market segmentation, cannibalization, and the timing of product introductions”. *Management Science* 38 (3): 345–359.
- Mozur, Paul, and Quentin Hardy. 2015. “China Hits Qualcomm With Fine”. *The New York Times*.
- Murai, Reiji. 2014. “Apple iPhone 6 screen snag leaves supply chain scrambling”. *Reuters*.
- Mussa, Michael, and Sherwin Rosen. 1978. “Monopoly and product quality”. *Journal of Economic Theory* 18 (2): 301–317.

- Orsdemir, Adem, Bin Hu, and Vinayak Deshpande. 2016. "Ensuring Corporate Social and Environmental Responsibility through Vertical Integration and Horizontal Sourcing". *SSRN*.
- Pettersson, Edvard, Tim Higgins, and Adam Ewing. 2015. "Apple, Ericsson Sue Each Other Over Phone Patent Royalties". *Bloomberg Business*.
- Reiffen, David, and Michael R Ward. 2005. "Generic drug industry dynamics". *Review of Economics and Statistics* 87 (1): 37–49.
- Roels, Guillaume, Uday S Karmarkar, and Scott Carr. 2010. "Contracting for collaborative services". *Management Science* 56 (5): 849–863.
- Rostoker, Michael D. 1983. "A Survey of Corporate Licensing". *IDEA: The Journal of Law and Technology* 24:59–92.
- San Martín, Marta, and Ana I Saracho. 2010. "Royalty licensing". *Economics Letters* 107 (2): 284–287.
- Savva, Nicos, and Niyazi Taneri. 2015. "The Role of Equity, Royalty, and Fixed Fees in Technology Licensing to University Spin-Offs". *Management Science* 61 (6): 1323–1343.
- Scott Morton, Fiona M. 1999. "Entry decisions in the generic pharmaceutical industry". *The Rand journal of economics*: 421–440.
- Sen, Debapriya. 2005. "Fee versus royalty reconsidered". *Games and Economic Behavior* 53 (1): 141–147.
- Shaked, Avner, and John Sutton. 1982. "Relaxing price competition through product differentiation". *Review of Economic Studies* 49 (1): 3–13.
- Shrout, Ryan. 2018. "Opinion: Apple loses in Qualcomm-Samsung license agreement". *MarketWatch*.

- Spengler, Joseph J. 1950. "Vertical integration and antitrust policy". *Journal of Political Economy* 58 (4): 347–352.
- Sun, Baohong, Jinhong Xie, and H Henry Cao. 2004. "Product strategy for innovators in markets with network effects". *Marketing Science* 23 (2): 243–254.
- Tesla. 2010. "Tesla and Panasonic Collaborate to Develop Next-Generation Battery Cell Technology".
- Tunca, Tunay I, and Qiong Wu. 2009. "Multiple sourcing and procurement process selection with bidding events". *Management Science* 55 (5): 763–780.
- Ulrich, Karl T, and David J Ellison. 2005. "Beyond make-buy: Internalization and integration of design and production". *Production and Operations Management* 14 (3): 315–330.
- U.S. Food and Drug Administration. 2011. "A review of FDA's approach to medical product shortages". *FDA Report* ().
- . 2013. "Strategic Plan for Preventing and Mitigating Drug Shortages". *FDA Report*. <https://www.fda.gov/downloads/Drugs/DrugSafety/DrugShortages/UCM372566.pdf>.
- U.S. Government Accountability Office. 2014. "Drug Shortages: Public health threat continues, despite efforts to help ensure product availability". *GAO Report* GAO-14-194.
- Villas-Boas, J Miguel. 1998. "Product line design for a distribution channel". *Marketing Science* 17 (2): 156–169.
- Wang, Jingqi, Xiaole Wu, and Vish Krishnan. 2017. "Decision Structure and Outcomes in Technology Supply Chains". *Forthcoming to Manufacturing & Service Operations Management*.

- Wang, X Henry. 1998. "Fee versus royalty licensing in a Cournot duopoly model". *Economics letters* 60 (1): 55–62.
- Wells, Peter. 2017. "Nissan/NEC sell rechargeable electric battery business". *Financial Times*.
- Wiggins, Steven N, and Robert Maness. 2004. "Price Competition in Pharmaceuticals: The Case of Anti-infectives". *Economic Inquiry* 42 (2): 247–263.
- Woodcock, Janet, and Marta Wosinska. 2013. "Economic and technological drivers of generic sterile injectable drug shortages". *Clinical Pharmacology & Therapeutics* 93 (2): 170–176.
- Yurko, Anna V. 2011. "How does income inequality affect market outcomes in vertically differentiated markets?" *International Journal of Industrial Organization* 29 (4): 493–503.
- Yurukoglu, Ali, Eli Liebman, and David B Ridley. 2017. "The role of government reimbursement in drug shortages". *American Economic Journal: Economic Policy* 9 (2): 348–82.