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ESSAYS ON CONTRACT MANUFACTURING

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Essays on Contract Manufacturing

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A thesis submitted in partial fulfillment of the requirements for the
degree of Doctor of Philosophy

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Abstract

In recent decades, contract manufacturing has been increasingly adopted in industries such as telecommunication and personal computer industry. By outsourcing the production to the contract manufacturers (CMs), the original equipment manufacturers (OEMs) can better focus on their core competencies such as product design and marketing and at the same time enjoy the benefits of reduced labor costs, freed-up capital, and improved worker productivity (Arruñda and Vázquez 2006).

This dissertation consists of three parts, each investigating a decision-making issue on contract manufacturing: (1) The outsourcing structure selection, (2) the price negotiation, quantity commitment and capacity installing, (3) the choice over quantity leadership/followship when the CM becomes a downstream competitor of the OEM.

In the first essay, we consider a multi-tier supply chain consisting of an OEM, a CM and a supplier and study two outsourcing structures, control and delegation. Under control, the OEM takes a direct control over procurement of raw materials/components and the CM is only responsible for manufacturing. Under delegation, the CM performs both manufacturing and the procurement functions for the OEM. Which structure is more beneficial for the OEM, the CM or the supplier? Towards this question, we study the performance of supply chain parties under the two sourcing structures and we consider different supply chain contracts such as push, pull and two-wholesale-price (TWP) contracts. We derive the equilibrium ordering quantities

and capacities for all the combinations of the outsourcing structures and contracts. We show that under the push contract, the OEM prefers delegation to control if the wholesale price it pays to the CM under delegation is no more than the sum that it pays to the CM and the supplier under control. As to the pull contract, we find that the OEM is more likely to prefer delegation if the wholesale price under delegation is in a moderate range and the customer demand has low uncertainty. For the TWP contract, we find that the preference of the OEM between control and delegation depends on the wholesale price and cost structures. And delegation is also more likely to be preferred under the TWP contract if the customer demand has low uncertainty. Lastly, we find that for any given vertical outsourcing structure, the OEM prefers the pull contract to the push contract if the prebook prices are very high or at-once wholesale prices are in a moderate range.

Based on the work on the first issue, we continue to investigate the comparison of outsourcing structures when the wholesale prices are endogenized. The second essay assumes that wholesale prices are decided via a cooperative generalized Nash bargaining (GNB) game. We examine price negotiation, quantity commitment and capacity installing issues under four scenarios classified according to the vertical outsourcing structure and the timing of quantity ordering. Similar with essay 1, we consider two outsourcing structures, control and delegation. On the timing of quantity ordering, we consider two inventory/capacity risk allocation contracts: Push and pull. For each scenario, we derive the negotiation-induced wholesale prices and equilibrium ordering/capacity decisions. We find that compared with control, delegation always

generates a lower procurement price for the OEM, which, however, may reduce the supplier's capacity building-up incentives. We also find that push contract plays an important role in coordinating the supply chain when the CM and the supplier have unbalanced capacity set-up incentives and/or the demand uncertainty is large. We show the company shall adopt control strategy over the key components while delegate the procurement of commodity components to the CM.

The third essay is quite different from the above two. This part studies a supply chain that consists of an OEM and a CM, where the CM is both an upstream partner and a downstream competitor of the OEM. They can engage in one of the following Cournot competition games: a “simultaneous”-move game, a sequential game with the OEM as the Stackelberg leader and a sequential game with the CM as the Stackelberg leader. Based on these three basic games, we then investigate the two parties' decisions on choosing Stackelberg leadership or followership. When the outsourcing quantity and the wholesale price are exogenously given, both the Stackelberg leadership and followership can be preferred by either party. In particular, when the wholesale price or the proportion of the production outsourced to the CM is lower than a threshold value, both parties prefer Stackelberg leadership and consequently, a “simultaneous”-move game is played in the consumer market. When the outsourcing quantity and the wholesale price are decision variables, the OEM prefers outsourcing entirely from the competitive CM and the competitive CM will set a wholesale price low enough to allow both parties to coexist in the market. We find that a Stackelberg equilibrium is sustained when the competitive CM has a large bargaining power and

the non-competitive CMs' wholesale price is high enough.

Publications arising from this thesis

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Chapter 1

Introduction

These days, contract manufacturing is becoming increasingly popular in many industries. In electronic industry, contract manufacturing service providers contributed over \$ 300 billion to the world GDP in 2008, compared with only a few billion dollars in the early 1990's (Ozkan and Wu 2009a). In this trend, two largest contract manufacturers (CMs) rise in the world, Foxconn and Flextronics, with hundreds of manufacturing plants located in China, Mexico, Indian, Malaysia and other developing countries or regions. The growth of contract manufacturing business can be reflected by some statistics data on the main CMs in Figure 1 (iSuppli Corp. 2008).

| Company Name | 2007 Annual Revenue (000) | 2006 Annual Revenue (000) | Change | 2007 Rank | 2006 Rank |
|--------------|---------------------------|---------------------------|--------|-----------|-----------|
| Foxconn | \$54,706 | \$39,253 | 39% | 1 | 1 |
| Flextronics | \$33,346 | \$28,876 | 15% | 2 | 2 |
| Quanta | \$23,259 | \$14,170 | 64% | 3 | 4 |
| Asustek | \$23,033 | \$17,348 | 33% | 4 | 3 |
| Compal | \$13,634 | \$9,410 | 45% | 5 | 7 |
| Jabil | \$12,432 | \$11,087 | 12% | 6 | 5 |
| Sanmina-SCI | \$10,138 | \$10,872 | -7% | 7 | 6 |
| Wistron | \$8,658 | \$6,603 | 31% | 8 | 11 |
| TPV | \$8,419 | \$7,238 | 16% | 9 | 9 |
| Celestica | \$8,069 | \$8,811 | -8% | 10 | 8 |
| Inventec | \$7,191 | \$7,167 | 0% | 11 | 10 |
| Lite-On | \$5,760 | \$5,048 | 14% | 12 | 13 |
| Elcoteq | \$5,740 | \$5,139 | 11% | 13 | 12 |
| Innolux | \$4,806 | \$3,207 | 50% | 14 | 15 |
| Benchmark | \$2,915 | \$2,907 | 0% | 15 | 16 |
| Venture | \$2,617 | \$1,971 | 33% | 16 | 18 |
| Mitac Intl | \$2,558 | \$2,540 | 1% | 17 | 17 |
| Inventec App | \$2,378 | \$3,389 | -30% | 18 | 14 |
| USI | \$2,046 | \$1,676 | 22% | 19 | 19 |
| Plexus | \$1,624 | \$1,513 | 7% | 20 | 20 |

Figure 1.1: Statistics Data of Main CMs

By outsourcing the assembling function to the CMs, the OEMs can be involved

primarily in high-value-added businesses, such as new product introduction, market analysis, brand management, professional service and so on. On the other hand, the CMs who own many factories all over the world can make use of the low labor cost to achieve economies of scale and other benefits in production quality control, materials/components procurement and logistics service.

However, contract manufacturing also brings big risks for the OEMs. With outsourcing, the OEM may lose control over the production of their products. Amaral et al. (2006) summarize the benefits and risks in contract manufacturing, among which the wholesale prices, the supply risk, the information asymmetry and the procurement strategies are some of the most critical ones. Arruñda and Vázquez (2006) investigate another important risk, that is, the CMs may develop their self-brand businesses and hence become the OEMs' downstream competitors. These risk issues motivate this study.

In Chapter 2, we focus on the supply chain parties' capacity/prebook decisions under different outsourcing structures and risk allocation contracts. We mainly discuss the supply chain risk due to demand uncertainty. In our context, it is referred as the inventory/capacity risk. Essentially, how to allocate the inventory/capacity risk among the supply chain parties motivates us to consider control and delegation outsourcing structures together with push and pull contracts. We consider a three-tier supply chain consisting of an OEM, a CM and a supplier. We first introduce the definition of two vertical outsourcing structures: Control and delegation. Under control, it is the OEM who procures raw materials/components from the supplier while under delegation the CM is authorized to conduct the procurement function on the OEM's behalf. We then consider three risk allocation contracts: Push, pull and two-wholesale-price contract (TWP). Push contract means that the downstream supply chain parties prebook before the demand is observed. Pull contract means the

orders happen after demand is realized. Two-wholesale-price proposed by Dong and Zhu (2007) is an united one of push and pull. Under such a contract, there exist two ordering opportunities, one is before demand realization and the other one is not. We consider a newsvendor setting and assume the demand has an increasing generalized failure rate (IGFR). In total, we consider six scenarios combined by two outsourcing structures and three risk allocation contracts. Under each contract, we first derive the equilibrium ordering quantities and then conduct the comparison of the OEM's profit under control and delegation. We find that the wholesale prices paid by the OEM to purchase the CM and the supplier's service/products are important. Under push contract, if the total unit wholesale price with control structure is higher than that with delegation structure, delegating the component procurement function to the CM is more beneficial for the OEM. However, under pull contract, only when the wholesale price paid to the CM under delegation structure falls into a moderate range, delegation can be preferred by the OEM. This finding is mainly due to the tradeoff between the OEM's total procurement cost saving and the reduction of the CM's capacity building incentive. Under TWP contract, we derive the corresponding condition in which delegation is more preferable for the OEM and then numerically test the impact of the coefficient of variance.

In Chapter 3, we introduce the generalized Nash bargaining (GNB) scheme into our model to study the comparison of outsourcing structures with endogenized wholesale prices. GNB scheme is a cooperative price negotiation game, which is different with the commonly used take-it-or-leave-it wholesale price contract. Under the GNB scheme, we assume the supply chain parties have their bargaining powers respectively, based on which they divide the total trade gains. The wholesale prices become the functions of the bargaining powers. Under control and delegation outsourcing structures, the bargaining powers of the OEM and the CM facing the supplier are different,

so the negotiated component prices are different, too. For tractability, we consider push and pull contracts. We derive the negotiated wholesale prices and the corresponding equilibrium ordering quantities and capacities. Based on these, we compare the OEM's performance under control and delegation. We also discuss the impact of the capacity installing costs, the bargaining powers and the coefficient of variance.

In Chapter 4, we study an interesting phenomenon in which the CM becomes the OEM's downstream competitor by having its self-branded business. In practice we can find many such examples. For example, Asustek, BenQ and HTC are famous CMs for Apple, Motorola and Google-mobile, respectively, but they all produce and sell their self-branded products which are substitutable to their OEMs'. This motivates us to think over the question: Which party has the motivation to be the quantity leader in the end-product market? If one party makes its quantity decision earlier than its competitor, then it acts as the quantity leader. Otherwise, it is the quantity follower. We study three basic games, a "simultaneous"-move game, a sequential game with the OEM as the Stackelberg leader and a sequential game with the CM as the Stackelberg leader. Here, a "simultaneous"-move game need not mean that the players make their decisions exactly at the same time. If there is no any communication when the players make the decisions, then the game can also be viewed as a "simultaneous"-move game. We then compare the OEM and the competitive CM's profits and find that either Stackelberg leadership or followership can be preferred by both of them. When the wholesale price or the proportion of production outsourced to the competitive CM is lower than a threshold value, both parties will prefer leadership. We also take the wholesale price and outsourcing proportion as decision variables and show that the competitive CM's optimal choice is to set a low price allowing both parties coexist in the end market. Meanwhile, the OEM tends to source solely from the competitive CM given the wholesale price of the non-competitive CM is higher than that of the

competitive CM. When the wholesale price is negotiated, a powerful CM and non-favorable outside option for the OEM will intensify the competition and generates the simultaneous game.

Chapter 2

Comparison of Two Vertical Outsourcing Structures under Push, Pull and Two-wholesale-Price Contracts

2.1 Introduction

Nowadays, there are unprecedented opportunities for original equipment manufacturers (OEMs) to outsource all of the assembling function to contract manufacturers (CMs). By doing so, the OEMs can enjoy the benefits of reduced labor costs, freed-up capital and improved worker productivity. Facilitating these gains are the CM's special strengths, which may include location in a low-wage area, economies of scale, and exposure to the engineering and development processes of the products it handles for other OEMs (Arruñda and Vázquez 2006).

The relocation of manufacturing processes to low-cost destinations has driven countries such as China to become the “world's factory”. By 2007, China has accounted for 13.2% of all the manufacturing in the world and is set to overtake the USA as the number one destination for manufacturing (Jayaraman 2009). In today's global economy, the CM networks in those areas serve as an important manufacturing base for numerous goods, ranging from garments, toys, mobile handsets, and computers to household appliances and even musical instruments. For instance, more than 90% of Chinese home electronics companies are engaged in the CM business (Yang and Wu 2008). And in another example, the Chinese microwave manufacturer Galanz produces microwave ovens for more than 250 international brands, holding a market share of more than 40% of all microwaves sold worldwide (Yang and Wu

2008). In an AMR research report based on an extensive survey of more than 700 brand-owners/OEMs and CMs located primarily in North America, about 65% of the respondents frequently used CMs in mainland China and Taiwan (Swanton et al. 2005).

However, outsourcing activities enlarge the distance between the supply chain parties and lengthen the lead time. This gives rise to greater risks in production planning and capacity decisions for those CMs and suppliers, as such decisions need to be made well before demand is observed. It is therefore interesting to consider risk-sharing mechanisms among the supply chain parties such that the supply chain capacity can be increased. In particular, it is interesting to explore whether the OEM can be better off by bearing some inventory/capacity risks. The sharing of inventory/capacity risks can be affected by multiple factors which are associated with three basic questions: Who shall order? when to order? and how much to order?

Who shall order? Consider a serial three-tier supply chain consisting of an OEM, a CM and a supplier. Compared with a two-tier supply chain, this multi-tier supply chain provides one more layer of flexibility to the OEM by allowing the OEM not only deciding how to share the inventory/capacity with the upstream parties but also choosing the way how it outsources the manufacturing: the OEM can either outsource just the product manufacturing function to the CM and control the procurement of components from the supplier, or it can outsource both the product manufacturing and component procurement functions to the CM and let the CM handle the component procurement. We call these two outsourcing structures *control* (C for the superscript) and *delegation* (D for the superscript), respectively, and they are depicted in Figure 2.1. Note that under both outsourcing structures the material flow is assumed to be the same: First, the supplier produces one unit of component,

which is then shipped to the CM. Second, the CM processes the received component into one unit of semi-product, which is then shipped to the OEM. Finally, the OEM customizes the end product by adding the label, determining the specific package and so on. The main difference between control and delegation outsourcing structure is the ownership of the component inventory. In other words, under delegation, it is the CM rather than the OEM who owns the components and bears the component inventory risk.

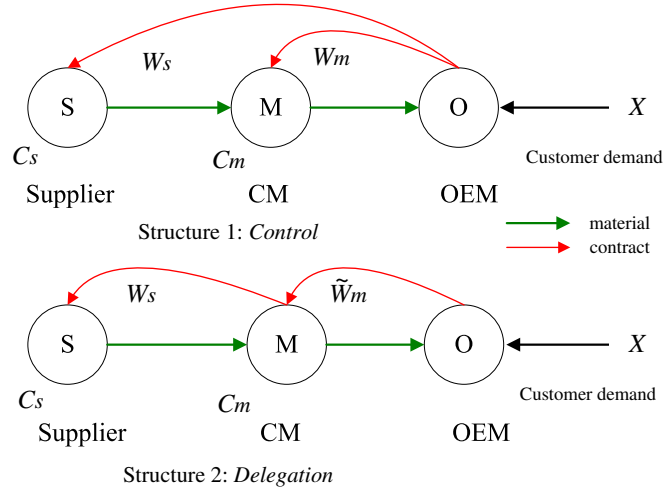


Figure 2.1: Control and Delegation

In practice, Dell delegated the procurement of some key components for its notebook personal computers, including keyboards, cases, and printed circuit boards to its Taiwan CMs but took a direct control over the procurement of CPUs, hard-disk drives, memory chips, panels and batteries (Liu 2007). Hewlett-Packard (HP) maintains the strategic sourcing of key components but delegates the procurement of commodity components (Smock 2004, Amaral et al. 2006). In automobile industry, General Motors (GM), Ford, Chrysler and some European automobile companies have increasingly delegated the component procurement responsibility to the manufacturers over the past two decades (Kayaş et al. 2009). In contrast, Motorola, who

once delegated the component purchasing function to its CMs in the 1990s, resorted to control structure after 2003 (Jorgensen 2004, Smock 2004).

When to order? The sharing of inventory/capacity risks is also affected by the timing of orders. In practice, some downstream OEMs ease the uncertainty of their upstream CMs and suppliers by adopting a *push* contract; that is, they place the order with the upstream CMs and the suppliers before the selling season and hence bear all the inventory risk. Take the fireworks industry as an example. It usually takes about four to six weeks to ship the fireworks from China, where most of the fireworks are made, to the US (Quint and Shorten 2005). However, about 95% of US fireworks sales occur between May 15th and July 4th, which is a very short selling season. Given this, firework retailers in US have to purchase before the selling season and hence, a push contract is adopted (Prasad et al. 2009).

In contrast to the push contract under which the OEMs bear all inventory risks, there exists another type of contract, the *pull* contract, under which OEMs place the order in the selling season, and the upstream CMs and suppliers have to bear all the inventory risk. Vendor Managed Inventory (VMI) agreement is just a typical pull contract, in which the suppliers commit capacities/resources for the OEMs and make capital investment without receiving payment until after the resources are used (Li and Scheller-Wolf 2010). For example, Flextronics customizes its service to Lenovo, a world leading Chinese personal computer provider, by providing VMI service to Lenovo (Ligan et al. 2009). Another example is CEPA, who makes sheet metal components for the OEMs such as ABB, Alfa Laval and Hasselblad, and holds all the inventory in the warehouse and delivers the components to the OEM only when the OEM receives a firm customer order (Jukka et al. 2007).

Besides the foregoing two extremes of risk-allocation contracts, we have the advance-purchase contract where the downstream OEMs partially share the inventory/capacity

risk with the upstream supply chain parties. For example, Motorola, a big OEM in telecommunications industry, buys a percentage of its component requirements from its Taiwan suppliers (e.g., Foxconn, BenQ, and Compal) using the advance-purchase commitment contract (Carbone 2004). And HP promised a volume commitment to its suppliers on some components (Smock 2004). And in LCD industry, OEM manufacturers such as Innolux Display, TPV Technology and LG signed the advance commitment with their LCD panel supplier– Taiwan Chunghwa Picture Tubes (Hayes 2007).

How much to order? The inventory responsibility of the supply chain parties is also affected by the quantity of orders. Ordering too much or too little may both bring big cost for the OEM. Hence, the questions here we are interested in are the supply chain parties' *optimal* decisions on quantities:

- (1) What are the OEM's optimal ordering quantities under the different combinations of the outsourcing structures and contracts?
- (2) What are best responses for the CM and the supplier in capacity decision?

To summarize, we consider six scenarios according to the combinations of two vertical outsourcing structures (control and delegation) and three contracts (push, pull and TWP). Under each scenario, we analyze the performance of three supply chain parties, the OEM, the CM and the supplier. To draw some managerial insights, we conduct two types of comparison among the results in different scenarios aiming to answer two questions: For each contract, which outsourcing structure is more beneficial to the OEM and under what conditions? For each outsourcing structure, what is the best timing of ordering for the OEM and under what conditions?

We first study the two extreme contracts, push and pull and later extend to the more general setting, TWP. For each of these contracts, we derive the equilibrium

ordering quantities and the capacities of the CM and the supplier under both control and delegation outsourcing structures. Through our analysis, we find that under the push contract, as long as the sum of wholesale prices paid by the OEM to the CM and the supplier under control is higher than that paid by the OEM to the CM under delegation, the OEM prefers delegation to control; otherwise, it prefers control to delegation.

Under the pull contract, we find that if the wholesale price paid by the OEM to the CM under delegation falls in a moderate range, then delegating the procurement function to the CM is more beneficial to the OEM. That means, a too high or a too low wholesale price both can reduce the benefit of delegation. It is easy to understand the first part: a high wholesale price under delegation hurts the OEM's profit margin and reduces the OEM's incentives on adopting the delegation structure. But why does a low wholesale price also hurt the OEM? The reason is that a low wholesale price hurts the CM and reduces its incentives to build up a large capacity, which eventually hurts the OEM.

Under the TWP contract, we find that the isolated Newsvendor capacity building incentives of the CM and the supplier (the isolated decision means that the supply chain party makes its own optimal capacity decision assuming that the other supply chain parties' capacities are infinite) has a strong impact on the performance of the outsourcing structure. If the CM's isolated Newsvendor quantity is smaller than that of the supplier, control is more beneficial to the OEM than delegation. Otherwise, delegation may be preferable. The potential reason behind is as follows: Under delegation, if the CM has incentives to build a larger capacity than the supplier, the CM may prebook more to the supplier than what it receives from the OEM so as to push the supplier to build more capacity. In other words, the OEM can benefit from delegation when the CM has high incentives to bear capacity/inventory risks.

Through our numerical study, we observe that under both pull and TWP contracts, delegation is more likely to be preferred if the market demand has low uncertainty. On the other hand, if the market is risky, the OEM is more likely to adopt control instead of delegation.

Lastly, we compare the performance of the three contracts under the two outsourcing structures. We find that the TWP contract leads to a higher supply chain capacity than that under the pull contract. And we also show that the pull contract is more likely to be preferred over the push contract by the OEM if the prebook wholesale prices are high or the at-once wholesale prices are in a moderate range.

The remainder of this chapter is organized as follows. Section 2 reviews the related literature. Section 3 introduces the model and preliminaries. Sections 4-6 study performance of push, pull and TWP contracts, respectively. In each section, we consider the supply chain parties' quantity ordering and capacity building decisions under both control and delegation. Section 7 compares the supply chain capacities and the OEM's profits under three contracts. Section 8 summarizes and concludes the chapter. All the proofs are relegated to the appendix.

2.2 Literature Review

Our work is closely related to the literature on quantity commitment and advance purchase in supply chain management. Push, pull and advance-purchase contracts are first studied in Cachon (2004). Later Dong and Zhu (2007) consider an unified two-wholesale-price (TWP) contract under which the OEMs place both early and late orders. These early orders are quantity committed by the OEMs and are given some price discounts. Notice that TWP with a null early order is reduced to pull contract and TWP with only an early order and no at-once orders during the selling season is push contract. Both Cachon (2004) and Dong and Zhu (2007) consider

a two-tier supply chain while we consider a three-tier supply chain. Besides these two work, Cachon and Lariviere (2001) characterize a contract composed of firm commitments and options, to convey demand information. Lariviere and Porteus (2001) study a price-only contract where the retailer buys before the random demand is realized. Ferguson (2003) and Ferguson et al. (2005) focus on the manufacturer's commitment time decision (i.e., before or after demand realization). They illustrate the effect of the power structure of the supply chain and demand uncertainty. Özer et al. (2005) consider earlier commitment in a push system when the market is still unknown to the retailer and show that the entire supply chain can achieve Pareto optimization. Özer and Wei (2006) study an upstream firm with dominating power and show that advance purchase can enable the downstream firm to reveal its private forecast information. Netessine and Rudi (2006) combine the traditional (push) and drop-shipping (pull) channel into a dual-strategy (advance-purchase discount) supply chain. They find that a drop-shipping supply chain can result in higher profits. Taylor (2006) investigates the circumstances under which a manufacturer would prefer to sell early or late and assumes that the demand is retail price dependent. Selling early and selling late are similar to push and pull contracts, respectively. These circumstances involve whether information is symmetric and whether the retailer exerts sales effort. Bernstein et al. (2006) show that the pull-type VMI can coordinate the supply chain by considering two simple pricing schemes. Chen (2007) proposes a push-type purchasing mechanism where the buyer offers a quantity-payment contract and the supplier bids the up-front, lump-sum fee. In addition to the aforementioned literature on push, pull and advance-purchase contracts, there are many other papers that discuss wholesale price contracts. See the reviews by Cachon (2003) and Lariviere (1998) for a more detailed discussion.

Our work is also closely related to the research on the decentralized capacity de-

cisions in multiple-tier supply chains. Bernstein and DeCroix (2004) investigate a modular assembly system in which the final assembler outsources some of the assembly tasks to subassemblers, and the subassembler buys the components from suppliers. They then discuss the optimal capacity decision for this system and characterize the equilibrium price and capacity choices. Bernstein et al. (2007) consider the equilibrium price and capacity decisions in an assembly system with multiple-type products and different types of suppliers.

The study on delegation and control is also related with our work. Baron and Besanko (1992) consider the setting where the CM and supplier have private cost information. They show that delegation can not perform better than control because of loss-of-control cost. See Mookherjee (2006) for a comprehensive review on comparison between delegation and control under asymmetric cost information. The study on comparing delegation and control structures in multiple-tier supply chains begins in recent years. Guo et al. (2010) study the impact of information distortion induced by different outsourcing structures. They show that, with a long-term contract, delegation performs better than control even with information distortion. Kayaş et al. (2009) consider delegation and control in a three-tier supply chain under the Newsvendor setting. They compare the optimal menu contract with the price-only contract and find that either delegation or control may be preferable, depending on the degree of manufacturer's prior information on the suppliers' costs. Chen et al. (2010) consider a situation in which a manufacturer either decides how to allocate its capacity among multiple retailers or delegates this decision to its distributor.

2.3 Model Setting and Preliminaries

We use subscript o , m and s to label the OEM, the CM and the supplier, respectively. Customer demand for the end product is random and denoted by a random variable

X with a density function f and a cumulative distribution function (cdf) F . Define $\bar{F}(x) = 1 - F(x)$. Besides, we assume that the demand distribution has increasing generalized failure rate (IGFR) property. Many common distributions have this property, including uniform, normal, logistic, extreme value, chi-square, chi, exponential, Laplace, Weibull ($r \geq 1$), gamma ($\alpha \geq 1$), and beta ($\alpha \geq 1, \beta \geq 1$). And this assumption has been widely used in the operations management literature, see Lariviere and Porteus (2001), Cachon (2004), Dong and Zhu (2007) and the reference therein for further information. The market price for the end product is exogenously given and denoted by p . And one unit of the end product the CM produces requires one unit of the supplier component. Assume the CM and the supplier incur a cost of c_m and c_s for building one unit of their capacities, respectively. The production costs of the OEM, the CM and the supplier are normalized to zero. (The analysis can be extended to the case of positive production costs.) We also assume that the related fixed costs are sunk. To guarantee a positive profit margin, $p > c_m + c_s$ is assumed. The demand distribution and capacity installing costs are all common knowledge (see Plambeck and Taylor (2007) and Nagarajan and Bassok (2008) for the discussion on this assumption).

Consider that a long lead-time is required for production and there exist two ordering opportunities, i.e. an early order before production, and a late order just before or during the selling season. Denote the pre-selling period as period 1 and the selling season as period 2. Similar to Cachon (2004) and Dong and Zhu (2007), we assume the wholesale prices are set before orders and production take place. They are the result of industry competition or the outcome of negotiation between the supply chain parties. Then a downstream party can prebook in period 1, or it can place at-once orders in period 2. Specifically, for the control structure, we denote the wholesale price offered to player i in period t by w_{it} , $i = m, s$, $t = 1, 2$. For

the delegation structure, we assume the wholesale price offered to the supplier by the CM is still w_{st} , $t = 1, 2$, the same as that offered by the OEM under control. However, the wholesale price offered to the CM by the OEM in this case needs to cover both the CM's manufacturing cost and its component procurement cost. We denote the wholesale price paid to the CM under delegation as \tilde{w}_{mt} , $t = 1, 2$ ($\tilde{w}_{mt} \geq (c_m + w_{st})$, $t = 1, 2$). To avoid the trivial case, we focus on the wholesale price region $\{w_{m1}, w_{m2}, w_{s1}, w_{s2}\} \in [c_m, p] \times [c_m, p] \times [c_s, p] \times [c_s, p]$. We also assume that $p - w_{mt} - w_{st} > 0$ and $p - \tilde{w}_{mt} > 0$, $t = 1, 2$.

Denote the prebook order to party i as q_{i1} . Anticipating that a high level of demand may occur in period 2, this party may install the capacity more than the committed amount. Denote its additional installed capacity by q_{i2} which can be used to satisfy the at-once order. Let $D(q) = E[\min(X, q)]$ be the expected demand that can be satisfied by the production quantity q . Then, given q_{m1} , q_{m2} , q_{s1} and q_{s2} , the customer demand that can be satisfied by the supply chain is $D((q_{m1} + q_{m2}) \wedge (q_{s1} + q_{s2}))$, where $a \wedge b = \min(a, b)$. For both push and pull contract, we omit the subscript t as there exists only one ordering opportunity.

In the following sections, we are going to use superscript $j = C, D$ to represent the optimal solutions under control and delegation, respectively.

2.4 Push Contract

Under the push contract, there is no at-once order. The downstream supply chain party bears all the inventory risk and orders before the demand realization. So the upstream supply chain party just sets up/installs capacity for what is committed.

2.4.1 Push and control

Under push and control, the game sequence is defined as follows:

1. Given the unit wholesale prices w_{m1} and w_{s1} in period 1, the OEM announces its prebook quantity q to the CM and the supplier. (It is never in the best interest of the OEM to prebook different quantities to the CM and the supplier as the components of the CM and the supplier are compliments.)
2. The CM and the supplier then install their capacities according to the OEM's prebook order.

In period 2, demand is realized and all revenues and costs are incurred. As a result, the profit functions of the three parties are, respectively:

$$\Pi_o = pD(q) - (w_{m1} + w_{s1})q, \quad \Pi_m = (w_{m1} - c_m)q, \quad \text{and} \quad \Pi_s = (w_{s1} - c_s)q.$$

So the decision problem for the OEM is a Newsvendor-type problem, and the optimal ordering decision of the OEM can be summarized below.

Proposition 1. *Under push and control, the OEM's optimal prebook $q^C = \bar{F}^{-1}\left(\frac{w_{m1}+w_{s1}}{p}\right)$.*

Here, q^C is also the supply chain capacity (the minimum of the capacities of the CM and the supplier).

2.4.2 Push and delegation

Under push and delegation, the game sequence is thus as follows:

1. Given the unit wholesale price \tilde{w}_{m1} , the OEM announces its prebook quantity q to the CM. The CM then announces the OEM's prebook quantity q to the supplier. (It is never in the best interest of the CM to prebook a different quantity than q to the supplier because of complementarity between the CM's and the supplier's products.)

2. The CM and the supplier install their capacities according to their prebook order.

In period 2, demand is realized and all revenues and costs are incurred. Similarly, we can write the profit functions of the supply chain parties as

$$\Pi_o = pD(q) - \tilde{w}_{m1}q, \quad \Pi_m = (\tilde{w}_{m1} - w_{s1} - c_m)q, \quad \text{and} \quad \Pi_s = (w_{s1} - c_s)q.$$

Again, the OEM's optimization problem is a Newsvendor-type problem. Then we have the following proposition.

Proposition 2. *Under push and delegation, the optimal prebook quantity of the OEM and the CM is $q^D = \bar{F}^{-1}\left(\frac{\tilde{w}_{m1}}{p}\right)$.*

Note that q^D is also the supply chain capacity.

2.4.3 Comparison of control and delegation under push

Similar to Kayaş et al. (2009), here we focus on studying the preference of the OEM over control and delegation. Under the push contract, the difference between the OEM's profits under the two outsourcing structures can be written as

$$\Pi_o^D - \Pi_o^C = [pD(q^D) - \tilde{w}_{m1}q^D] - [pD(q^C) - \tilde{w}_{m1}q^C] + [(w_{m1} + w_{s1}) - \tilde{w}_{m1}]q^C. \quad (2.1)$$

Proposition 3. *Under the push contract, if $\tilde{w}_{m1} \leq (w_{m1} + w_{s1})$, $q^D \geq q^C$ and $\Pi_o^D \geq \Pi_o^C$; otherwise, $q^D < q^C$ and $\Pi_o^D < \Pi_o^C$.*

So if $\tilde{w}_{m1} < (w_{m1} + w_{s1})$, delegating the component procurement function to the CM is more beneficial to the OEM; otherwise, the OEM shall keep this function in-house. The reason is that the condition, $\tilde{w}_{m1} < (w_{m1} + w_{s1})$, both implies that the OEM can obtain a lower unit wholesale price and achieve cost saving by delegating

the procurement function to the CM, and implies that the OEM is willing to bear more inventory risk since $q^D \geq q^C$. This cost saving and higher system capacity lead to a higher expected profit for the OEM under delegation than that under control.

2.5 Pull Contract

Under the pull contract, the CM and the supplier have to invest in their capacities q_m and q_s in advance and there is no prebook from the OEM. Thus, both the CM and the supplier bear their own capacity risk.

2.5.1 Pull and control

Under pull and control, the game sequence is as follows:

1. In period 1, given the unit wholesale prices w_{m2} and w_{s2} in period 2, the CM and the supplier install their capacities q_m and q_s in anticipation of the OEM's at-once order.
2. In period 2, the market demand is observed. The OEM makes the at-once orders to the CM and the supplier to satisfy the observed demand.

We are going to solve this game by backward induction. First in period 2, the OEM makes the at-once order $x \wedge q_m \wedge q_s$, where x is the realized demand. $x \wedge q_m \wedge q_s$ actually represents the effective demand that the whole supply chain can satisfy by using the available capacities of the CM and the supplier.

Next, in period 1, anticipating the OEM's at-once order, the CM and the supplier decide how much capacities to build up to maximize their respective expected profits:

$$\Pi_m(q_m|q_s) = w_{m2}D(q_m \wedge q_s) - c_m q_m, \quad \text{and} \quad \Pi_s(q_s|q_m) = w_{s2}D(q_m \wedge q_s) - c_s q_s.$$

Here, the capacity game between the CM and the supplier is a simultaneous one. We first derive the best response function of the CM given the supplier's capacity decision q_s . Since the CM and the supplier's products are complements, it is never optimal for the CM to install a capacity $q_m > q_s$. We can show that given the supplier's capacity q_s , the best response function of the CM is to install

$$q_m^*(q_s) = \min(K_m^C, q_s),$$

where $K_m^C = \bar{F}^{-1}\left(\frac{c_m}{w_{m2}}\right)$ and is the CM's optimal Newsvendor capacity decision by assuming the supplier's capacity q_s is ample (much larger than q_m)¹. It represents the maximum amount of the capacity that the CM has incentives to build up under control. Similarly, the best response function of the supplier is

$$q_s^*(q_m) = \min(K_s^C, q_m),$$

where $K_s^C = \bar{F}^{-1}\left(\frac{c_s}{w_{s2}}\right)$ and also represents the maximum amount of the capacity that the supplier has incentives to build up under control. Solving these two best response functions simultaneously yields the equilibrium capacities of the CM and the supplier under pull and control as

$$q_m^C = q_s^C = K_m^C \wedge K_s^C.$$

Consequently, the supply chain capacity is also $K_m^C \wedge K_s^C$.

Proposition 4. *Under pull and control, the equilibrium capacities of the CM and the supplier are $q_m^C = q_s^C = K_m^C \wedge K_s^C$.*

¹Note that when the supplier's capacity is ample, the CM's expected profit function becomes $\Pi_m(q_m) = w_{m2}D(q_m) - c_m q_m$,

2.5.2 Pull and delegation

Under pull and delegation, the game sequence is defined as follows:

1. In period 1, given the unit wholesale prices \tilde{w}_{m2} and w_{s2} in period 2, the CM and the supplier install their capacities q_m and q_s in anticipation of the OEM's at-once order.
2. In period 2, the market demand is observed. The OEM makes at-once order to the CM and then the CM makes at-once order to the supplier.

Similarly we solve this game backwards. Again the OEM and the CM make the at-once order $x \wedge q_m \wedge q_s$ in period 2. And in period 1, the CM and the supplier make their respective capacity decisions by maximizing their expected profit functions:

$$\Pi_m(q_m|q_s) = (\tilde{w}_{m2} - w_{s2})D(q_m \wedge q_s) - c_m q_m, \quad \text{and} \quad \Pi_s(q_s|q_m) = w_{s2}D(q_m \wedge q_s) - c_s q_s.$$

Similar to K_m^C and K_s^C in section §5.1, define K_m^D and K_s^D as

$$K_m^D = \bar{F}^{-1} \left(\frac{c_m}{\tilde{w}_{m2} - w_{s2}} \right), \quad \text{and} \quad K_s^D = \bar{F}^{-1} \left(\frac{c_s}{w_{s2}} \right) = K_s^C.$$

Then K_m^D (K_s^D) is the optimal capacity the CM (supplier) is going to invest in under delegation assuming that the supplier (CM) has ample capacity. It represents the maximum amount of the capacity that the CM (supplier) has incentives to build up under delegation. Naturally, we observe that the supplier's capacity building incentives remain the same under the two outsourcing structures as it receives the same wholesale price no matter whether paid by the OEM or the CM. Analogously, the equilibrium capacities of the CM and the supplier under pull and delegation are

$$q_m^D = q_s^D = K_m^D \wedge K_s^D = K_m^D \wedge K_s^C.$$

And the corresponding supply chain capacity is $K_m^D \wedge K_s^D$.

Proposition 5. *Under pull and delegation, the equilibrium capacities of the CM and the supplier are $q_m^D = q_s^D = K_m^D \wedge K_s^D$.*

2.5.3 Comparison of control and delegation under pull

First we compare the supply chain system capacity under the two outsourcing structures and obtain the following corollary.

Corollary 1. *Under the pull contract, if $\tilde{w}_{m1} \leq (w_{m1} + w_{s1})$, $K_m^D \leq K_m^C$ and $(K_m^D \wedge K_s^D) \leq (K_m^C \wedge K_s^C)$; otherwise, $K_m^D > K_m^C$ and $(K_m^D \wedge K_s^D) > (K_m^C \wedge K_s^C)$.*

So compared with control structure, if the total unit wholesale price (covering both manufacturing and procurement cost) is lower under delegation structure, then the CM will build up less capacity and as a result, the supply chain capacity under delegation is also lower.

In order to compare the performance of the OEM under control and delegation, we define the relative gain of the OEM by switching from control to delegation as

$$\gamma = \frac{\Pi_o^D - \Pi_o^C}{\Pi_o^C} = \frac{(p - \tilde{w}_{m2})D(K_m^D \wedge K_s^D)}{(p - w_{m2} - w_{s2})D(K_m^C \wedge K_s^C)} - 1.$$

We have the following lemma on γ .

Lemma 1. *γ is quasi-concave in \tilde{w}_{m2} .*

By the quasi-concavity of γ function, it must cross 0 at most twice. Note that when $\tilde{w}_{m2} = w_{m2} + w_{s2}$, $\Pi_o^D = \Pi_o^C$. So γ crosses 0 at $\tilde{w}_{m2} = w_{m2} + w_{s2}$. Denote the other possible point that γ crosses 0 as $\underline{\tilde{w}_{m2}}$. Then we have the following proposition.

Proposition 6. *If $\tilde{w}_{m2} \in [\underline{\tilde{w}_{m2}} \wedge (w_{m2} + w_{s2}), \max(\underline{\tilde{w}_{m2}}, w_{m2} + w_{s2})]$, then $\gamma \geq 0$; otherwise, $\gamma < 0$.*

Proposition 6 shows that compared with the total wholesale price the OEM pays under control, $w_{m2} + w_{s2}$, when the wholesale price paid to the CM under delegation is moderate, falling in a medium range, then delegation is more beneficial to the OEM, but if the wholesale price paid to the CM under delegation is either too high or too low, then control is more beneficial to the OEM. The possible driving force behind this is the tradeoff between the cost saving of the unit wholesale price and the potential loss of the high demand. Under delegation, when \tilde{w}_{m2} is too high, then the OEM has a small profit margin and when the realized demand is small, it may hurt the OEM's profits. Similarly, when \tilde{w}_{m2} is too low, the CM is not willing to build up a large capacity and as a result, the system capacity is small, and the OEM will lose the sales when the realized demand is high. That may explain why the OEM prefers control over delegation when \tilde{w}_{m2} is either too high or too low.

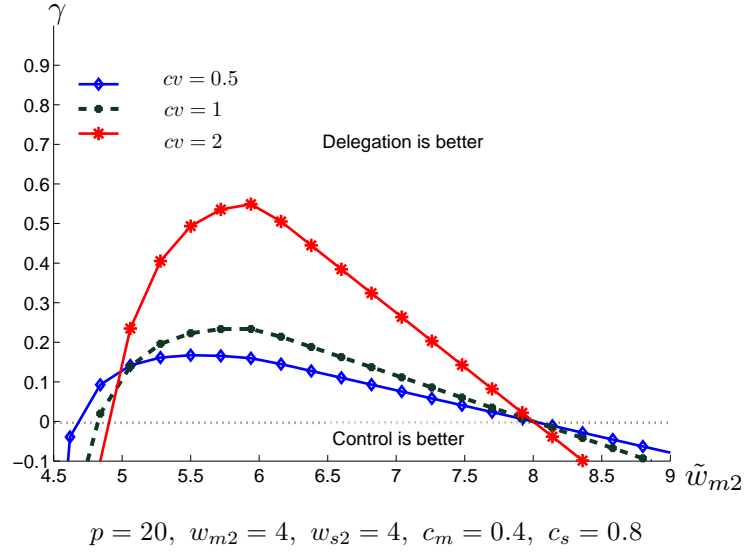


Figure 2.2: Impact of \tilde{w}_{m2} and CV on γ

Assume the customer demand follows a truncated normal distribution with a mean μ and a standard deviation σ . Then the coefficient of variation (CV) is $CV = \sigma/\mu$.

Let $p = 20$, $w_{m2} = 4$, $w_{s2} = 4$, $c_m = 0.4$ and $c_s = 0.8$, by varying \tilde{w}_{m2} and CV, we numerically examine how the customer demand and the wholesale price paid to the CM under delegation affect γ , a measurement of the OEM's preference over the two outsourcing structures under pull contract, see Figure 2.2. We observe from Figure 2.2 that delegation is more likely to be preferred by the OEM if the customer demand has small CV. That is, it is better for the OEM to control the procurement function instead of delegating to the CM when facing high demand uncertainty. Figure 2.2 also confirms our Proposition 6 that delegation is preferred by the OEM when \tilde{w}_{m2} is in a moderate range.

2.6 TWP Contract

Under the TWP contract, there exist two ordering opportunities for the OEM: in periods 1 and 2. Thus, besides the committed capacities for the prebook placed in period 1, the CM and the supplier may build up extra capacities to satisfy the potential at-once orders in period 2.

2.6.1 TWP and control

The sequence of events under TWP and control is as follows.

1. In period 1, given the unit wholesale price pairs (w_{m1}, w_{s1}) and (w_{m2}, w_{s2}) in periods 1 and 2, the OEM decides the prebook q_{m1} and q_{s1} , its quantity commitment to the CM and the supplier, respectively.
2. The CM and the supplier then simultaneously decide how much extra capacities to install, q_{m2} and q_{s2} .
3. In period 2, demand is observed. The OEM may make at-once orders based on the available capacities and satisfies as much demand as possible.

Under this scenario, the game between the OEM and the CM/supplier follows a Stackelberg setting, whereas the capacity game between the CM and the supplier is simultaneous. We also solve such a game backwards.

First, given the committed prebook q_{m1} and q_{s1} by the OEM, the CM and the supplier decide on the additional capacities that will maximize their expected profits.

$$\mathbf{CM} : \text{Max}_{q_{m2}} \quad \Pi_m^C = w_{m1}q_{m1} + w_{m2}[D((q_{m1} + q_{m2}) \wedge (q_{s1} + q_{s2})) - D(q_{m1})] - c_m(q_{m1} + q_{m2}), \quad (2.2)$$

$$\mathbf{Supplier} : \text{Max}_{q_{s2}} \quad \Pi_s^C = w_{s1}q_{s1} + w_{s2}[D((q_{m1} + q_{m2}) \wedge (q_{s1} + q_{s2})) - D(q_{s1})] - c_s(q_{s1} + q_{s2}) \quad (2.3)$$

It can be shown that the objective function in (2.2) is concave in q_{m2} and, given the supplier's additional capacity q_{s2} , the best response function of the CM is

$$q_{m2}^C(q_{s2}) = \min(K_m^C, q_{s1} + q_{s2}) - q_{m1},$$

where K_m^C is defined in §5.1. Similarly, the objective function in (2.3) is concave in q_{s2} and given the CM's additional capacity q_{m2} , the best response function of the supplier is

$$q_{s2}^C(q_{m2}) = \min(K_s^C, q_{m1} + q_{m2}) - q_{s1},$$

where K_s^C is also defined in §5.1. Then, the equilibrium extra capacities that the CM and the supplier build up are

$$q_{m2}^C = (K_m^C \wedge K_s^C - q_{m1})^+, \quad \text{and} \quad q_{s2}^C = (K_m^C \wedge K_s^C - q_{s1})^+, \quad (2.4)$$

where $x^+ = \max(x, 0)$. From the above expression, we find that, when the OEM's advanced quantity commitment is more than $K_m^C \wedge K_s^C$, the capacity that the CM and the supplier have incentives to build up under pull contract, then the CM and the supplier will produce just that amount and there is no capacity available for the at-once order. But when the OEM's prebook amount is small, the CM and the supplier will set up their total capacity up to $K_m^C \wedge K_s^C$. Thus the supply chain system

capacity is $\max(K_m^C \wedge K_s^C, q_{m1} \wedge q_{s1})$.

Anticipating the CM's and the supplier's capacity decisions, the OEM will decide on its prebook quantities to maximize its expected profit.

$$\begin{aligned}
\text{OEM: } \max_{q_{m1}, q_{s1}} \Pi_o^C &= pD((q_{m1} + q_{m2}^C) \wedge (q_{s1} + q_{s2}^C)) \\
&\quad - w_{m1}q_{m1} - w_{m2}[D((q_{m1} + q_{m2}^C) \wedge (q_{s1} + q_{s2}^C)) - D(q_{m1})] \\
&\quad - w_{s1}q_{s1} - w_{s2}[D((q_{m1} + q_{m2}^C) \wedge (q_{s1} + q_{s2}^C)) - D(q_{s1})] \quad (2.5)
\end{aligned}$$

Define $\Omega = (q_{m1}, q_{s1}) \in [0, \infty) \times [0, \infty)$, and the subsets $\Omega_1 = [0, K_m^C \wedge K_s^C) \times (\cdot)$, $\Omega_2 = [K_m^C \wedge K_s^C, \max(K_m^C, K_s^C)) \times (\cdot)$ and $\Omega_3 = [\max(K_m^C, K_s^C), \infty) \times (\cdot) \in \Omega - \Omega_1 - \Omega_2$.

Proposition 7. *The OEM's expected profit under control and TWP is locally concave on the above three sets, respectively, but not globally concave in (q_{m1}, q_{s1}) . And the optimal prebook (q_{m1}^C, q_{s1}^C) must be located in one of these sets and derived by comparing all the local optima.*

- The local optimum on $[0, K_m^C \wedge K_s^C) \times (\cdot)$ is $q_{m1}^C = \bar{F}^{-1}\left(\frac{w_{m1}}{w_{m2}}\right) \wedge K_m^C \wedge K_s^C$, and $q_{s1}^C = \bar{F}^{-1}\left(\frac{w_{s1}}{w_{s2}}\right) \wedge K_m^C \wedge K_s^C$, where the OEM prebooks and also makes at-once orders after demand realization (Partial commitment strategy).
- The local optimum on $[K_m^C \wedge K_s^C, \max(K_m^C, K_s^C)) \times (\cdot)$ depends on the outcome of $K_m^C \wedge K_s^C$.

(a) if $K_m^C \wedge K_s^C = K_m^C$, the OEM prebooks to the CM no less than what it prebooks to the supplier (Push the CM strategy) where

$$q_{s1}^C = \bar{F}^{-1}\left(\frac{w_{s1}}{w_{s2}}\right), \quad q_{m1}^C = \max\left(\bar{F}^{-1}\left(\frac{w_{m1}}{p - w_{s2}}\right) \wedge K_s^C, K_m^C\right), \quad \text{and } q_{m1}^C > q_{s1}^C,$$

$$\text{or } q_{m1}^C = q_{s1}^C = \max\left(K_m^C, \bar{F}^{-1}\left(\frac{w_{m1} + w_{s1}}{p}\right) \wedge K_s^C\right).$$

(b) if $K_m^C \wedge K_s^C = K_s^C$, the OEM prebooks to the supplier no less than what it prebooks to the CM (Push the supplier strategy) where

$$q_{m1}^C = \bar{F}^{-1}\left(\frac{w_{m1}}{w_{m2}}\right), \quad q_{s1}^C = \max\left(K_s^C, \bar{F}^{-1}\left(\frac{w_{s1}}{p - w_{m2}}\right) \wedge K_m^C\right), \quad \text{and } q_{m1}^C < q_{s1}^C,$$

$$\text{or } q_{m1}^C = q_{s1}^C = \max\left(K_s^C, \bar{F}^{-1}\left(\frac{w_{m1} + w_{s1}}{p}\right) \wedge K_m^C\right).$$

- The local optima on $[\max(K_m^C, K_s^C), \infty) \times (\cdot)$ is

$$q_{m1}^C = q_{s1}^C = \max\left(\bar{F}^{-1}\left(\frac{w_{m1} + w_{s1}}{p}\right), K_m^C, K_s^C\right),$$

where the OEM pushes the CM and the supplier to produce more than their maximum capacity building incentives (Push strategy).

Proposition 7 implies that under control, TWP contract provides more flexibility on capacity/inventory risk sharing. Depending on the outcome of the optimal prebook, the OEM may partially commit to the CM and the supplier and share the capacity/inventory risk if the outcome belongs to the set Ω_1 ; the OEM may push only one supply chain party (the CM or the supplier) with low capacity building incentives if the outcome belongs to the set Ω_2 ; and the OEM may push both the CM and the supplier to produce more than what they are willing to if the outcome belongs to the set Ω_3 , and there is no extra capacity available for the at-once order (equivalent to push contract).

It is worthy highlighting that under all the above prebook strategies, only when the second period wholesale price is no less than that in the first period, i.e., if $w_{m1} \geq w_{m2}$ / $w_{s1} \geq w_{s2}$, the local optimum $q_{m1}^C = \bar{F}^{-1}\left(\frac{w_{m1}}{w_{m2}}\right) = 0$ / $q_{s1}^C = \bar{F}^{-1}\left(\frac{w_{s1}}{w_{s2}}\right) = 0$. Thus the OEM will adopt pull strategy and prebook nothing to the CM/supplier.

2.6.2 TWP and delegation

The sequence of events under TWP and delegation is as follows.

1. In period 1, given the unit wholesale price pairs (\tilde{w}_{m1}, w_{s1}) and (\tilde{w}_{m2}, w_{s2}) in periods 1 and 2, the OEM decides the prebook quantity to be committed to the CM, q_{m1} . Then the CM decides the prebook quantity committed to the supplier, q_{s1} .
2. Next, the CM and the supplier decide how much extra capacities they want to build up, q_{m2} and q_{s2} , respectively.
3. In period 2, demand is observed. The OEM and the CM may make at-once orders to satisfy as much demand as possible.

Note that when the CM is delegated the procurement function, to satisfy the OEM's prebook and taking the complementarity between the CM's and the supplier's products into consideration, the CM's prebook q_{s1} should be no less than q_{m1} , i.e., $q_{s1} \geq q_{m1}$. This also means that the total capacity the CM installs, $q_{m1} + q_{m2}$ is no less than q_{s1} .

Similar to that under TWP and control, we can show that given the OEM's and the CM's prebook q_{m1} and q_{s1} , under TWP and delegation, the equilibrium extra capacities that the CM and the supplier are going to install are

$$q_{m2}^D = (\max(q_{s1}, K_m^D \wedge K_s^D) - q_{m1})^+, \quad \text{and} \quad q_{s2}^D = (K_m^D \wedge K_s^D - q_{s1})^+, \quad (2.6)$$

where K_m^D and K_s^D are defined in §5.2. Thus the system capacity is $\max(q_{s1}, K_m^D \wedge K_s^D)$.

Anticipating the equilibrium (q_{m2}^D, q_{s2}^D) , the CM decides prebook q_{s1} to maximize its expected profit:

$$\begin{aligned} \text{CM: } \max_{q_{s1} \geq q_{m1}} \Pi_m^D = & \tilde{w}_{m1}q_{m1} + \tilde{w}_{m2}[D((q_{m1} + q_{m2}^D) \wedge (q_{s1} + q_{s2}^D)) - D(q_{m1})] - c_m(q_{m1} + q_{m2}^D) \\ & - w_{s1}q_{s1} - w_{s2}[D((q_{m1} + q_{m2}^D) \wedge (q_{s1} + q_{s2}^D)) - D(q_{s1})]. \end{aligned} \quad (2.7)$$

Denote the optimal prebook as q_{s1}^D . Then anticipating the CM's and the supplier's capacity and ordering decisions, the OEM decides its prebook amount by solving the following problem.

$$\max_{q_{m1} \geq 0} \Pi_o^D = pD((q_{m1} + q_{m2}^D) \wedge (q_{s1}^D + q_{s2}^D)) - \tilde{w}_{m1}q_{m1} - \tilde{w}_{m2}[D((q_{m1} + q_{m2}^D) \wedge (q_{s1}^D + q_{s2}^D)) - D(q_{m1})].$$

The following propositions summarize the OEM's and the CM's prebook decisions, which depend on the relative size of K_m^D and K_s^D .

Proposition 8. *Under TWP and delegation, suppose $K_m^D \leq K_s^D$. Then the OEM's and the CM's optimal prebooks take one of the following:*

- (a). $q_{m1}^D = \bar{F}^{-1}\left(\frac{\tilde{w}_{m1}}{\tilde{w}_{m2}}\right) \wedge K_m^D$ and $q_{s1}^D = \max\left\{q_{m1}^D, K_m^D \wedge \bar{F}^{-1}\left(\frac{w_{s1}}{w_{s2}}\right)\right\}$, or
- (b). $q_{s1}^D = q_{m1}^D = \max\left(\bar{F}^{-1}\left(\frac{\tilde{w}_{m1}}{p}\right), K_m^D\right)$.

When $K_m^D \leq K_s^D$, the CM has less capacity building incentives than the supplier. From Proposition 8, we know there exist two prebooking equilibria. In the first prebook equilibrium (a), the downstream party, the OEM (CM) shares the inventory risk with the upstream party, the CM (supplier) by prebooking no more than K_m^D , the amount that the CM and the supplier have incentives to build up, and there exists the second ordering opportunity in period 2. This is *partial commitment* strategy. And in the second prebook equilibrium (b), the OEM bears all the inventory risk and pushes the CM to produce more than K_m^D , which is the maximum capacity the

CM is willing to produce, and consequently, the CM prebooks to the supplier what it receives from the OEM. There is no capacity available for period 2, so this is a *push* strategy. Whether the OEM will choose partial commitment or push strategy will be derived by comparing its expected profits under the two strategies.

Notice that in the first equilibrium of Proposition 8, if $\tilde{w}_{m1} \geq \tilde{w}_{m2}$, that is, the OEM actually obtains a lower wholesale price in period 2, then the OEM will prebook nothing and adopt pull strategy since $q_{m1}^D = \bar{F}^{-1}\left(\frac{\tilde{w}_{m1}}{\tilde{w}_{m2}}\right) = 0$. As to the CM, we can further show that when $\tilde{w}_{m1} \geq \tilde{w}_{m2}$, the CM will also adopt the pull strategy only if $w_{s1} \geq w_{s2}$. Otherwise, the CM will partially commit to the supplier.

Similarly, we can derive the equilibrium prebooks for the case of $K_m^D > K_s^D$.

Proposition 9. *Under delegation and TWP, suppose $K_m^D > K_s^D$. Then the OEM and the CM's equilibrium prebooks take one of the following:*

- (1). $q_{m1}^D = \bar{F}^{-1}\left(\frac{\tilde{w}_{m1}}{\tilde{w}_{m2}}\right) \wedge K_s^D$ and $q_{s1}^D = \max\left(q_{m1}^D, \bar{F}^{-1}\left(\frac{w_{s1}}{w_{s2}}\right) \wedge K_s^D\right)$;
- (2). $q_{m1}^D = \bar{F}^{-1}\left(\frac{\tilde{w}_{m1}}{\tilde{w}_{m2}}\right) \wedge K_s^D$ and $q_{s1}^D = \max\left(K_s^D, \bar{F}^{-1}\left(\frac{c_m + w_{s1}}{\tilde{w}_{m2}}\right) \wedge K_m^D\right)$;
- (3). $q_{m1}^D = q_{s1}^D = \max\left(K_s^D, \bar{F}^{-1}\left(\frac{\tilde{w}_{m1}}{p}\right) \wedge K_m^D\right)$;
- (4). $q_{m1}^D = \max\left(K_s^D, \bar{F}^{-1}\left(\frac{\tilde{w}_{m1}}{\tilde{w}_{m2}}\right) \wedge K_m^D\right)$, and $q_{s1}^D = \max\left(q_{m1}^D, \bar{F}^{-1}\left(\frac{c_m + w_{s1}}{\tilde{w}_{m2}}\right) \wedge K_m^D\right)$;
- (5). $q_{m1}^D = q_{s1}^D = \max\left(\bar{F}^{-1}\left(\frac{\tilde{w}_{m1}}{p}\right), K_m^D\right)$.

Proposition 9 shows that when $K_m^D > K_s^D$, that is, the CM has higher capacity building incentives than the supplier, there exist more prebooking equilibria than that in Proposition 8. That means, when the CM has higher capacity building incentives than the supplier, TWP under delegation offers more flexibility to allocate

the inventory/capacity risk among the three supply chain parties. In the first equilibrium, both the OEM and the CM share the inventory/capacity risk with their upstream party by prebooking no more than K_s^D , the capacity both the CM and the supplier are willing to install, which is again a *partial commitment* strategy. In the second equilibrium, the OEM still partially commits to the CM by prebooking less than K_s^D , but the CM is now pushing the supplier to produce more than K_s^D , the capacity that the supplier is willing to install. This is the so-called *OEM partial commit but CM push supplier* strategy. In the third and the fourth equilibrium, the OEM and the CM both prebook more than K_s^D , which are named *both push supplier* strategy. In the last equilibrium, both the OEM and the CM prebook more than K_m^D , the maximal capacity that the CM is willing to install, which is for sure a *push* strategy.

Again under the first two prebook equilibria of Proposition 9, only when $\tilde{w}_{m1} \geq \tilde{w}_{m2}$ will the OEM adopt pull strategy and we can further show that the CM will adopt pull strategy, too, only if $\tilde{w}_{m1} \geq \tilde{w}_{m2}$ and $w_{s1} \geq w_{s2}$.

2.6.3 Comparison of control and delegation under TWP

Admittedly, it is difficult to compare the profits of the OEM under the two outsourcing structures for the TWP contract. To draw some analytical conclusions, we consider two benchmark cases. In the first case, the pricing structures under delegation and control are the same. The second one considers an even stronger condition on price and cost parameters.

Same pricing structures

Consider a benchmark case where $\tilde{w}_{mt} = w_{mt} + w_{st}, t = 1, 2$. In this case, there is no price difference for the OEM between the two outsourcing structures. Then we can

derive the following proposition.

Proposition 10. *Assume $\tilde{w}_{mt} = w_{mt} + w_{st}, t = 1, 2$, then $K_m^C = K_m^D$ and $K_s^C = K_s^D$.*

- (1) *If $K_m^C \leq K_s^C$, $\Pi_o^C \geq \Pi_o^D$ for any given prebook strategy adopted by the OEM.*
- (2) *If $K_m^C > K_s^C$, $\Pi_o^C \geq \Pi_o^D$ if the OEM adopts either partial commitment or push strategy.*

Proposition 10 implies that when the supplier has incentives to build up a higher capacity than the CM ($K_m^C \leq K_s^C$), then delegating the procurement function to the CM actually makes the OEM worse off. One reason is that now the CM has no incentives to prebook to the supplier more than what it receives. Proposition 10 also implies that if $K_m > K_s$, delegation may be preferred by the OEM over control. The potential reason is that now the CM has incentives to build up a higher capacity than that of the supplier, and when delegated the procurement function, the CM may prebook to the supplier more than what it receives from the OEM, such as in the *OEM partial commits but CM pushes supplier* strategy, which helps to increase the system capacity and benefits the OEM when the realized demand is high.

We further conduct a numerical experiment to study the OEM's preference over the two outsourcing structures under the TWP contract by varying market price and wholesale price parameters and the end product's demand distribution. The combinations of parameters are listed in Table 2.1. In all scenarios, the customer demand has a truncated normal distribution.

The numerical results of the OEM's preference are depicted in Figure 2.3. We already have analytical results for the case $K_m \leq K_s$. Hence, we only need consider the region of $K_m > K_s$. We observe that control is preferred by the OEM when K_s is relatively small or large. Only when K_s is in a moderate range will delegation be preferable. The explanation for this observation is as follows. On the one hand, a

Table 2.1: Summary of Parameters

| | |
|-------------------------------|--|
| Selling price: | $p = 40, 60, 80$ |
| Capacity Parameters: | $K_m = 6 - 14$, step length=0.5 $K_s = 6 - 14$, step length=0.5 |
| Wholesale prices in period 1: | $w_{m1} = \theta_m p$, $(\theta_m = 0.1, 0.2, 0.3, 0.4)$ $w_{s1} = \theta_s p$, $(\theta_s = 0.1, 0.2, 0.3, 0.4)$ $\tilde{w}_{m1} = w_{m1} + w_{s1}$ |
| Cost: | $c_m = \delta_m w_{m1}$, $(\delta_m = 0.1, 0.3, 0.5, 0.7)$ $c_s = \delta_s w_{s1}$, $(\delta_s = 0.1, 0.3, 0.5, 0.7)$ |
| Wholesale prices in period 2: | $w_{m2} = c_m / F(K_m)$ $w_{s2} = c_s / \bar{F}(K_s)$ $\tilde{w}_{m2} = w_{m2} + w_{s2}$ |
| Mean of demand: | $\mu = 10$ |
| Standard deviation of demand: | $\sigma = (5, 10, 12)$ |

small Newsvendor quantity K_s implies a low second period wholesale price w_{s2} . Under such situation, if the OEM procures the components directly from the supplier, the OEM can obtain a high profit margin, thus the OEM prefers control. On the other hand, a large K_s means that the supplier itself has motivation to set up a large capacity, thus there is less need for the OEM to delegate the CM to push the supplier to produce more. Thus the OEM will choose control instead. Second, Figure 2.3 also shows that as the CV of the demand distribution increases, control is more likely to be preferred, which is consistent to our observation under pull contract, see Figure 2.2. That is, the OEM would like to control the component procurement function when the market has high uncertainty.

Same pricing and power structures

Here we further assume that $(w_{m2} - c_m)/w_{m2} = (w_{s2} - c_s)/w_{s2}$. Note that $(w_{m2} - c_m)/w_{m2}$ ($(w_{s2} - c_s)/w_{s2}$) is regarded as the well-known ‘‘Lerner index’’ (Lerner, 1934). Lerner (1934) shows that Lerner index reflects a firm’s market power, that is, a firm with a higher Lerner index has a greater power. Thus the CM and the supplier now

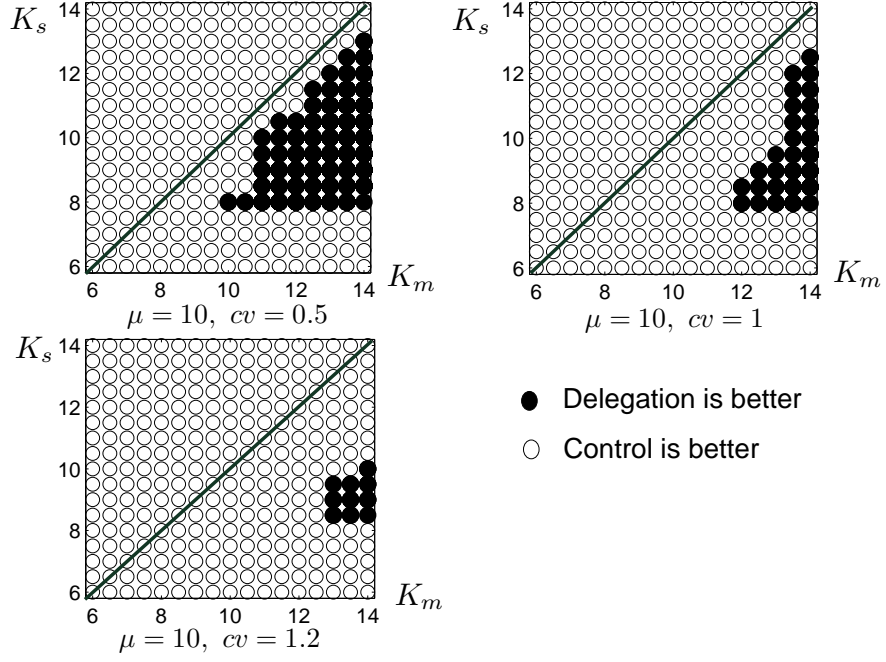


Figure 2.3: Control vs. Delegation under TWP when $\tilde{w}_{mt} = w_{mt} + w_{st}, t = 1, 2$

have the same market power over the OEM in period 2. We then have the following proposition.

Proposition 11. *Suppose $\tilde{w}_{mt} = w_{mt} + w_{st}, t = 1, 2$ and $(w_{m2} - c_m)/w_{m2} = (w_{s2} - c_s)/w_{s2}$. Then under both partial commitment and push strategies,*

1. $\Pi_o^C \geq \Pi_o^D, \Pi_m^C \leq \Pi_m^D$, and $\Pi_s^C = \Pi_s^D$.
2. $\Pi_o^C + \Pi_o^C + \Pi_s^C = \Pi_o^D + \Pi_m^D + \Pi_s^D$.
3. *If $\frac{w_{m1} + w_{s1}}{p} \geq (\frac{c_m}{w_{m2}} = \frac{c_s}{w_{s2}})$, then the OEM will choose partial commitment strategy under both control and delegation outsourcing structures.*

So when the CM and the supplier have the same market power over the OEM, and there is no price structure difference for the OEM between control and delegation, Proposition 11 shows that the whole supply chain as well as the supplier are indifferent between the two outsourcing structures. But control is more beneficial to the

OEM while delegation is more beneficial to the CM. So the choice of the outsourcing structures affects only the allocation of profits between the OEM and the CM. We observe that the condition in the third part of Proposition 11 is more likely to hold when the market price is low, and the wholesale prices are high. Thus the OEM has no incentives to prebook much and will choose partial commitment.

General pricing structure

For a general pricing structure, we have the following lemma on γ .

Lemma 2. $\gamma = (\Pi_o^D - \Pi_o^C)/\Pi_o^C$ is decreasing in \tilde{w}_{m1} .

So fixing other factors, the relative gain of the OEM by switching from delegation to control is decreasing in the OEM's first period unit procurement cost under delegation. If this cost is very small, the OEM will adopt delegation, see Figure 2.4.

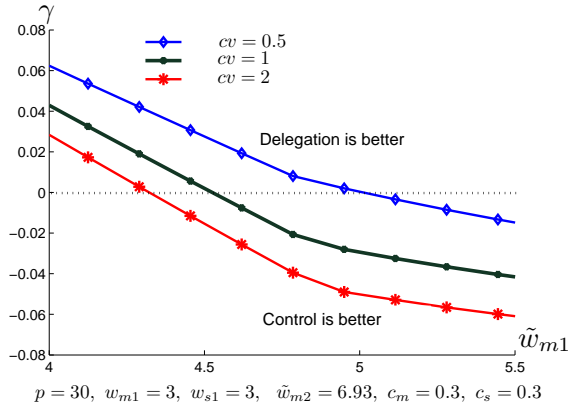


Figure 2.4: Impact of \tilde{w}_{m1} and CV on γ

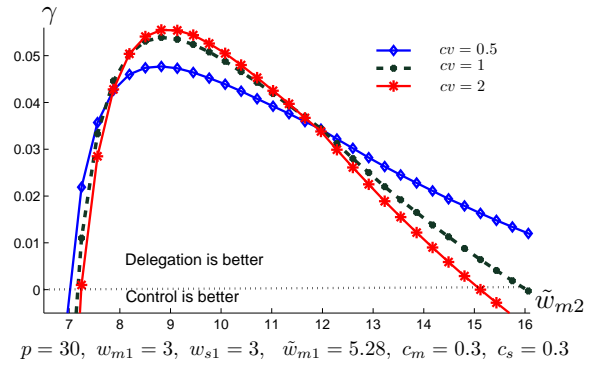


Figure 2.5: Impact of \tilde{w}_{m2} and CV on γ

We also conduct a numerical experiment by varying \tilde{w}_{m1} , \tilde{w}_{m2} and CV. Both Figures 2.4 and 2.5 again show that for the general scenarios of the TWP contract, delegation is more likely to be preferred by the OEM if CV is small, that is, if the demand has low uncertainty.

2.7 Comparison of Push, Pull and TWP

In this section, we compare the supply chain's performance across the three contracts.

Table 2.2: Supply Chain Capacity under Three Contracts

| | Control | Delegation |
|---------------|--|--|
| Push Contract | $F^{-1}\left(\frac{w_{m1}+w_{s1}}{p}\right)$ | $F^{-1}\left(\frac{\tilde{w}_{m1}}{p}\right)$ |
| Pull Contract | $K_m^C \wedge K_s^C$ | $K_m^D \wedge K_s^D$ |
| TWP Contract | $\max(K_m^C \wedge K_s^C, q_{m1}^C \wedge q_{s1}^C)$ | $\max(K_m^D \wedge K_s^D, q_{m1}^D \wedge q_{s1}^D)$ |

First we list the supply chain capacity under the various combinations of three contracts and two outsourcing structures in Table 3.3. It shows that the system capacity is higher under the TWP contract than under the pull contract for both outsourcing structures. This is reasonable: Under TWP, the OEM and the CM may prebook to their upstream party more than what the upstream party is willing to install by itself. As to the system capacities under pull and push contracts, we have the following corollary.

Corollary 2. $\bar{F}^{-1}((w_{m1}+w_{s1})/p) \geq (K_m^C \wedge K_s^C)$ if $(w_{m1}+w_{s1})/p \leq \max(c_m/w_{m2}, c_s/w_{s2})$; otherwise, $\bar{F}^{-1}((w_{m1}+w_{s1})/p) < (K_m^C \wedge K_s^C)$. $\bar{F}^{-1}(\tilde{w}_{m1}/p) \geq (K_m^D \wedge K_s^D)$ if $\tilde{w}_{m1}/p \leq \max(c_m/(\tilde{w}_{m2}-w_{s2}), c_s/w_{s2})$; otherwise, $\bar{F}^{-1}(\tilde{w}_{m1}/p) < (K_m^D \wedge K_s^D)$.

So for both outsourcing structures, whether the supply chain system capacity under the push contract is higher or lower than that under the pull contract depends solely on the relative magnitude of the market price, the wholesale prices in two periods and the capacity installation costs. It is independent of demand distribution.

Next we investigate the OEM's preference over the pull and push contracts under the two outsourcing structures by comparing the profits of the OEM.

Under control structure, we have

$$\Pi_o^C(pull) - \Pi_o^C(push) = (p - w_{m2} - w_{s2})D(K_m^C \wedge K_s^C) - [pD(q^C) - (w_{m1} + w_{s1})q^C].$$

Lemma 3. $\Pi_o^C(pull) - \Pi_o^C(push)$ is quasi-concave in w_{m2} and w_{s2} , and increasing in w_{m1} and w_{s1} .

Therefore, under control structure, if the at-once wholesale prices w_{m2} and w_{s2} are in a moderate range and/or the prebook wholesale prices w_{m1} and w_{s1} are high, then it is more likely that the OEM prefers pull contract over push contract. The reason is that the wholesale prices affect not only the OEM's profit margin and ordering decisions but also the CM's and the supplier's capacity building incentives. Those decisions then jointly affect the supply chain capacity and thus the amount of demand that can be satisfied. If the wholesale prices in periods 1/2 are high, the OEM can only obtain small profit margin. Thus the OEM will not prebook much under push contract. And if the wholesale prices in period 2 are low, then the CM and the supplier have small profit margin and thus would not install much capacity in advance under pull contract. Therefore, under those cases, the system capacity will be low, and the OEM is unable to satisfy all the demands if the realized demand is high, which hurts the OEM's performance.

Similarly, under delegation structure, we have

$$\Pi_o^D(pull) - \Pi_o^D(push) = (p - \tilde{w}_{m2})D(K_m^D \wedge K_s^D) - [pD(q^D) - \tilde{w}_{m1}q^D].$$

And we obtain the similar results as those under control structure.

Lemma 4. $\Pi_o^D(pull) - \Pi_o^D(push)$ is quasi-concave in \tilde{w}_{m2} and increasing in \tilde{w}_{m1}

So under delegation structure, the OEM will prefer the pull contract over the push contract if the at-once wholesale price \tilde{w}_{m2} is in a moderate range and/or the prebook wholesale price \tilde{w}_{m1} is high. And the reason behind is similar to that under Lemma 3.

2.8 Concluding Remarks

Global outsourcing to the low-cost countries and regions have lengthened the distance among the supply chain parties and raised many new issues. In this chapter, we considered the issue of inventory/capacity risk allocation in a multi-tier supply chain composed of an OEM, a CM and a supplier by allowing the OEM to choose between different outsourcing structures. Specifically, we studied three inventory/capacity risk allocation mechanisms, push, pull and TWP contracts, under two vertical outsourcing structures, control and delegation. For each combination of the risk allocation contracts and outsourcing structures, we derived the corresponding optimal equilibrium ordering quantity and capacity decisions.

As to the preference of the outsourcing structures, we showed that under the push contract, the OEM prefers delegation to control as long as it can achieve a cost-saving advantage of the total procurement price by delegating the component procurement function to the CM. For the pull contract, we showed that the OEM may prefer control over delegation when the wholesale price it pays to the CM under delegation is either too high or too low. Only when the wholesale price under delegation is in a moderate range and the demand for the final product is stable can delegation be more preferable. As to the TWP contract, we found that the capacity building incentives of the CM and the supplier have a strong impact on the performance of the outsourcing structures. If the CM has incentives to build a larger capacity than that of the supplier, it may be willing to bear more inventory risk and thus the OEM can benefit from delegation. Otherwise, control will be preferred by the OEM. We also found that control is more beneficial to the OEM if the market has high uncertainty and the pull/TWP contract is adopted.

As to the preference over the contract, we showed that the OEM will prefer pull over push if the prebook wholesale prices are high or the at-once wholesale prices are

in a moderate range.

Compared with a two-tier supply chain setting, this multi-tier supply chain setting allowed us to study the combination of the outsourcing structures and risk allocation contracts. In the current version, we assumed that the wholesale prices are exogenously given and there is no cost and demand information asymmetry. It would be interesting to explore other situations with endogenous wholesale prices, cost and demand information asymmetry and the potential competition from the CM, which are left for future research.

Chapter 3

Negotiation and Procurement Strategies in a Multi-tier Supply Chain

3.1 Introduction

In today's global economy, outsourcing production activities to the third-party contract manufacturers (CMs) has become a prominent practice in many companies. For example, the original equipment manufacturers (OEMs) such as IBM Corp., Hewlett-Packard Co. (HP) and Dell Computers (Dell), which traditionally produced in-house, now often outsource their production to CMs located in China and Taiwan (Smith 2008).

Along with production outsourcing to the third party CMs, the OEMs also need to consider another important issue, that is, component procurement. Should the OEM authorize the CMs to purchase the required materials on its behalf or do it by itself? When shall an order be placed, before demand realization and after it? Answers to the two questions affect the procurement price and supply risk (or inventory availability), which are two critical factors influencing the OEM's outsourcing decision (Amaral et al. 2006). The OEM and the CM may demonstrate different bargaining powers over the supplier, which affects the outcome of the component procurement price. And different outsourcing structures and ordering timings affect the inventory risk allocation among supply chain parties, which affects the CM's and supplier's capacity setting-up and results in different levels of supply risk. Under delegation, it is the CM who takes the ownership of the component inventory whereas it is the OEM under control structure. And ordering before demand realization shifts

the inventory/capacity risk downwards along the supply chain while ordering after demand realization shifts it upwards.

In this chapter, we aim to study the impacts on price negotiation and supply risk (inventory availability) of different procurement strategies. For the sake of simplicity, we consider a serial three-tier supply chain consisting of an OEM, a CM and a supplier, and assume that the OEM outsources all manufacturing functions to the CM.

We consider two outsourcing structures, control and delegation. In the former case, the OEM retains the component procurement function in-house; in the latter case, the CM is responsible for both manufacturing and component procurement. We also consider two types of contracts on ordering timing, push and pull.

1. *Push*: The quantity-order decision take place before demand realization. There is no at-once order after demand realization.
2. *Pull*: The quantity-order decision occur after demand realization. The CM and the supplier need to invest in specific capacities or commit resources in advance.

In total, we consider the following four procurement strategies according to the combination of the above outsourcing structures and the timing of order arrangements: Control+push (\mathcal{CS}), control+pull (\mathcal{CL}), delegation+push (\mathcal{DS}) and delegation+pull (\mathcal{DL}).

We found cases for all procurement strategies from some representative OEMs. We list them in Table 4.1, in which the horizontal dimension is the outsourcing structure and the vertical dimension is the timing of order. In the electronics industry, Sony-Ericsson, Palm Inc. and Cisco adopted the pull contract (Cederholm and Smajic 2009, ACP 2010 and Souza 2003) and delegated the procurement of materials to the CMs such as Flextronics (Huckman and Pisano 2004). However, Apple procured

flash memory directly with its supplier Samsung through forward contract (Krazit 2008a and Patel 2009) and placed its production order to the CMs such as Foxconn before demand realization (Krazit 2008b), whereas Sun Microsystems and Nokia direct source the material supply and adopted either the just-in-time or build-to-order pull system (Minahan 2007, Davis and Spekman 2003, Nokia 2010 and Reinhardt 2006). Moreover, the same OEM may control the procurement function of certain components while outsourcing the procurement of others to CMs, and use pull contract for products and push contract for others. For example, Dell and HP maintain the strategic sourcing of key components, but delegates the procurement of commodity components (Smock 2004 and Liu 2007). And both pull (build-to-order) and push (made-to-stock) system are used in HP (Nagali et al. 2008 and Kleinau 2005). We can find similar three-tier structures in the automobile industry if we consider the tier-1 suppliers as CMs and tier-2 suppliers as the suppliers. American automobile manufacturers are famous for made-to-stock push system, including Ford, General Motors (GM) and Chrysler (Taylor and Taylor 2008). Originally those companies controlled the component procurement function but now there exists an increasing trend on delegating this function to selected tier-1 suppliers. In contrast, Japanese automobile manufacturers, such as Toyota and Honda, are famous for the Just-in-Time pull system and delegation outsourcing structure (Sturgeon and Florida 2000, Kayış et al. 2009).

Table 3.1: Adoption of Outsourcing Strategies: Some Industry Examples

| | Control | Delegation |
|------|---|--|
| Push | Ford, GM, Chrysler (previous) HP (key components), Apple | Ford, GM, Chrysler (recently) HP (commodity components) |
| Pull | HP and Dell (key components) Sun Microsystems, Nokia | HP and Dell (commodity components) Toyota, Palm, Sony-Ericsson, Cisco |

To obtain sharper insights on which procurement strategy the OEM shall adopt and under what conditions, we take a comprehensive modeling approach on price negotiation and capacity decisions. To model the wholesale-price negotiation among the OEM, the CM and the supplier, we consider the cooperative *generalized Nash bargaining* (GNB) game. As to the capacity decisions of the CM and the supplier, we model them as a newsvendor type problem, where the CM and the supplier need to invest in specific capacities before demand realization, such as special equipment, raw materials purchasing and worker training. Moreover, when the CM (supplier) makes a capacity decision, it also has to take the supplier's (CM's) capacity decision into consideration, as the whole supply chain's capacity is jointly determined by the two parties. For each of the four scenarios: \mathcal{CS} , \mathcal{CL} , \mathcal{DS} and \mathcal{DL} , we derive the negotiated wholesale prices and equilibrium capacity decisions. The two criteria for evaluating the procurement strategies may not be aligned because a more favorite purchasing price for the OEM could mean a smaller profit margin for the supplier, which can reduce its incentives in setting up its capacity and thus harm the supply of the components. Hence, we also calculate the expected profits for supply chain parties as a more accurate criteria of evaluating the procurement strategies. We then compare the results first along the horizontal dimension (control versus delegation) to investigate whether the OEM should delegate the component procurement function to the CM, and then along the time dimension (push versus pull) to explore whether the OEM should make an advance quantity commitment to its CM/supplier.

Our conclusions are multi-folded. We list our recommendation of control or delegation structure for the given risk allocation contract in Table 3.2. Industry cases in Table 4.1 imply that there may not exist a simple answer that one procurement strategy uniformly dominates the other. However, our analytical results show that this hunch does not hold when a push contract is adopted, in which we show that

delegation always dominates control for the OEM. In particular, we show that for the push contract, the OEM's ordering decision, or the supply chain's capacity, is always optimal from the viewpoint of the whole supply chain under either control or delegation. However, delegation reduces the total procurement price (the sum of wholesale prices paid for the CM's service and the supplier's component) for the OEM. Surprisingly, this conclusion is independent of the CM's bargaining power over the supplier. That is, even when the CM is not as powerful as the OEM in bargaining with the supplier, it is still beneficial for the OEM to delegate the procurement function to it. This may explain the increasing trend for the American automobile manufacturers to switch from direct procurement to authorizing the selected tier-1 suppliers to purchase the components. Note that this conclusion is obtained in our serial supply chain setting where the OEM bears all inventory risks under push contract. Hence, supply risk is not a consideration here. If the CM is responsible for multiple OEMs, an OEM may still prefer taking a direct control over procurement of scarce components to avoid the supply risk arising from a situation where the CM uses those components for other OEMs' products. This might explain the case for Apple to control the procurement of flash memory.

Table 3.2: Control vs. Delegation under Pull/Push Contract

| | Control | Delegation |
|------|-------------------------|-------------------------|
| Push | Not recommended | Recommend |
| Pull | Recommend conditionally | Recommend conditionally |

However, for the pull contract, both control and delegation have their advantages. We show that delegation still results in a lower total procurement price for the OEM, even though the CM is not powerful. However, delegation does not necessarily generate a higher expected profit for the OEM as a lower total procurement price

generated by delegation could harm the CM's and supplier's capacity-building incentives, which may eventually hurt the OEM. We find that when the CM's bargaining power over the supplier is *larger* than a threshold, the supplier will build a *smaller* capacity under delegation than under control. This is reasonable: A strong CM tends to rip off too much rent from the supplier, which reduces the supplier's incentives in setting up a large capacity. Therefore, if the capacity is the key consideration for the OEM, such a hunch that the OEM shall delegate procurement to a powerful CM is false. Instead, the OEM shall take a direct control over procurement to assure the supply of those key components. This might explain the practice for HP and Dell to control the procurement of key components while delegate the procurement of commodity components as inventory availability plays a critical role for the key component while it is not the case for the commodity components. In another case, Palm, the OEM of popular handheld computers, usually outsources its component procurement function to its CM, Flextronics (Huckman and Pisano 2004), but as a result of suffering from a shortage of LCD panels and flash memory, two critical components used to construct the devices, it began purchasing those components by itself (Spooner 2000).

Finally we compare push and pull contracts. We show that the negotiated wholesale prices under the pull contract are higher than the corresponding ones under the push contract, that is, the advance order shall enjoy a price discount. Furthermore, the supply chain capacity under the pull contract is smaller than the one under the push contract. Therefore, although the OEM does not bear any inventory/capacity risk under the pull contract, it has to pay higher wholesale prices for the at-once orders and face a smaller supply chain capacity. This reflects the tradeoff between choosing the pull and push contracts. We further find that the push contract can better coordinate the whole supply chain than the pull contract. Therefore, when dif-

ferent supply chain parties have very *unbalanced* capacity installing incentives, which could be caused by different production costs or extreme bargaining powers, the push contract is more preferred by the OEM. It is also more likely to be preferred when the customer demand has larger uncertainty. This is intuitive: When the demand is more stable, the CM and the supplier bear less capacity risks under the pull contract and thus have incentives to build the adequate capacities. As a result, there is less need for the push contract.

The rest of the chapter is organized as follows. Section 2 reviews the related literature. Section 3 discusses the model setting and notations. In sections 4 and 5, we study the performance of the supply chain under the push and pull contracts, respectively. In each contract, we consider both control and delegation structures and derive the GNB-induced wholesale prices, the OEM/CM's ordering decision as well as the CM's and the supplier's capacity installing decisions. Section 6 compares the performance of the pull and push contracts. Some concluding remarks are provided in Section 7. All of the proofs are moved to the appendix.

3.2 Literature Review

Our work is related with those studies on delegation and control in economics literature. Baron and Besanko (1992) consider a setting with one manufacturer and two suppliers where the suppliers' cost information is private. They show that delegation cannot perform better than control because of loss-of-control cost. Other work on comparison between delegation and control along this line can be found in the survey paper by Mookherjee (2006).

The study on comparing delegation and control structures in multiple-tier supply chains begins in recent years. Kayış et al. (2009) assume the production costs of the CM and the supplier are hidden information. Then they consider both menu contracts

and price-only contracts, and find that either control or delegation can be preferable for the OEM. Chen et al. (2010) design menu contracts to study the price masking issue under consignment and turnkey structures. Guo et al. (2010a) study the impact of information distortion induced by different outsourcing structures. They show that, with a long-term contract, delegation performs better than control even with information distortion. Guo et al. (2010b) compare the delegation and control under a two-wholesale-price contract, assuming exogenously-given preorder and at-once wholesale prices. Different from Guo et al. (2010b), here we focus on the special cases of the two-wholesale-price contract, push and pull, and study endogenized wholesale prices which are obtained through negotiation processes. Chen et al. (2010) consider a three-tier supply chain with retailers, distributors and suppliers. They show that under a two-stage menu contract, the distributors' more accurate information can help retailers to obtain the production quantities they need. Different from foregoing work which focus on information asymmetry, we mainly focus on the study of price negotiation and inventory/capacity decisions under different risk-allocation contracts.

Our work is also related to the studies of advance quantity commitments among the supply chain parties. Ferguson (2003) and Ferguson et al. (2005) study the manufacturer's quantity commitment timing decision, i.e., before or after demand realization. In their Stackelberg game, they consider situations where both the manufacturer and the supplier may set the wholesale price. Cachon (2004) and Dong and Zhu (2007) investigate the pull, push and advance-purchase contracts in a two-tier supply chain with exogenous wholesale prices. Taylor and Plambeck (2007a) study the wholesale price and capacity investment issues under price-only and price-and-quantity contracts between a supplier and the buyer. Erhun et al. (2008) study a capacitated two-tier supply chain and assume that the wholesale price is set by

the supplier and the procurement quantity by the buyer. Then they compare the supplier's and the buyer's performances under three schemes: no commitment, early commitment and two periods with early commitment. Li and Scheller-Wolf (2010) consider a supply chain composed of a buyer and multi-suppliers with private cost information. The buyer first offers a push or pull contract, and then selects the supplier through a wholesale price auction. They numerically find that the push contract is preferred by the buyer if the suppliers' number is large and the demand level is high while the pull contract is preferred if demand has high uncertainty and the supplier's cost is large. These studies focus on a two-tier supply chain in which the wholesale prices are either exogenously given (e.g., Cachon 2004, Dong and Zhu 2007) or optimized in a take-it-or-leave-it contract offered by the supplier or the buyer (e.g., Ferguson 2003, Ferguson et al. 2005). Here, we study a three-tier supply chain which provides one more layer of flexibility to the OEM by allowing the OEM not only deciding how to share the inventory/capacity risk with the upstream parties but also choosing the way how it outsources. Besides, we model wholesale price negotiation via the cooperative GNB scheme and consider different bargaining timing.

The study on (generalized) Nash bargaining and price negotiation is also related. The Nash bargaining (NB) scheme was initiated by Nash (1950) and later extended by Roth (1979) into the GNB scheme. The difference between the NB and GNB schemes is that the former assumes that the players have equal bargaining powers while the latter assumes that the players have unequal bargaining powers. Compared with the NB scheme, the GNB scheme is more robust (Roth 1979) and realistic. The experimental literature provides strong support for the GNB scheme (Roth 1995). Both NB and GNB concepts have been broadly applied to the analysis of supply chain-related problems; see the review by Nagarajan and Sosic (2008) and the references therein for further information. Below we review some related operations

management papers who study the price negotiation issue. Iyer and Villas-Boas (2003) examine how the bargaining relationship among supply chain parties affects channel coordination. Plambeck and Taylor (2005) consider two OEMs who focus on innovation and may sell their factories to the CMs. In particular, they study the impact of the bargaining powers on the supply chain parties' innovation and capacity investment decisions. Plambeck and Taylor (2007a) assume the firms can renegotiate the supply contracts after demand realization and study how that can improve capacity allocation efficiency among n buyers. Plambeck and Taylor (2007b) consider a quantity flexibility contract and show that the potential for renegotiation can either strengthen or weaken the firms' incentives in capacity investment, product development and marketing, and hence profits. Nagarajan and Bassok (2008) explore a sequential negotiation model where an assembler bargains on the wholesale prices and procurement quantities with the coalitions formed by n suppliers between themselves. By assuming a manufacturer and a supplier can achieve Nash bargaining outcomes, İşlegen and Plambeck (2009) study the timing and level of capacity investment. Feng and Lu (2009) characterize the OEMs' design outsourcing decision via GNB and linear Hotelling model.

We note that Kostamis and Duenyas (2009) study both quantity commitment and bargaining issues in a two-tier supply chain. The main difference between their work and ours is that here, we study a multi-tier supply chain and focus on comparing the performance of different vertical outsourcing structures.

3.3 Model Setting and Preliminary

3.3.1 Model Setting

Consider a supply chain comprising an OEM, a CM and a supplier. For simplicity, they are labeled o , m and s , respectively. We assume that each unit of the end

product produced by the CM requires one unit of a supplier component. For firm i , the unit capacity cost is c_i , $i = m, s$. Let p be the market price for the end product. Assume that the end product has a positive profit margin, i.e., $p > c_m + c_s$. Define w_i as the wholesale price for one unit of firm i 's component/product, $i = m, s$. Note that under delegation, the OEM pays the CM a lumpsum wholesale price for the whole product, not just for the CM's service. We denote such a lumpsum price as \tilde{w}_m .

Demand for the final product is random and is represented by random variable X . Assume that X has a continuous distribution with a cumulative density function (cdf) $F(\cdot)$ and a probability density function (pdf) $f(\cdot)$. Assume that $f(x) > 0$ for all $x \geq 0$, and $f(x) = 0$ otherwise. Let $\bar{F}_j(\cdot) = 1 - F_j(\cdot)$. The expected demand that can be satisfied with production quantity q can be expressed as

$$\mu(q) = E[\min(X, q)].$$

In addition, the distribution has an increasing generalized failure rate (IGFR) property, which is a fairly weak requirement that many common distributions satisfy (see Lariviere 2006).

The timeline is divided into two periods, 1 and 2, where 1 denotes the pre-selling period and 2 the selling period. We assume demand for the final product, its market price, and the capacity installation costs of the CM and the supplier to be common knowledge. For example, in the bio-pharmaceutical and semi-conductor manufacturing sectors, cost and demand information are usually common knowledge (Plambeck and Taylor 2007b).

3.3.2 Generalized Nash Bargaining Game

The GNB scheme provides a unique bargaining solution that can be obtained by solving the following optimization problem.

$$\text{Max}_{\pi_i \geq d_i, \pi_j \geq d_j} \Omega_{ij} = (\pi_i - d_i)^\alpha (\pi_j - d_j)^{1-\alpha}, i \neq j,$$

where Ω_{ij} is the *Nash product*, π_i and d_i correspond to supply chain player i 's profit and reserved profit (also called status quo point) if the players fail to reach an agreement, respectively, and parameters α and $1 - \alpha$, $\alpha \in [0, 1]$ denote player i and j 's bargaining powers. Note that the case $\alpha = 1/2$ corresponds to the equal bargaining powers, that is, the NB scheme, and the extreme values $\alpha = 0$ or $\alpha = 1$ reduce the two-player bargaining setting to the centralized one player setting, under which the total profit pie Ω_{ij} will be allocated to one player.

We assume that the supply chain parties are rational and risk neutral; their bargaining powers are exogenously given. The players' bargaining powers can be estimated from some transactional data. For example, Chen et al. (2008) propose a specific estimation approach to use the American automobile consumers' brand choice information and the seller-buyer reservation prices to evaluate their relative bargaining powers. Denote α and $1 - \alpha$ as the relative bargaining powers of the OEM and the CM, β and $1 - \beta$ as those of the OEM and the supplier, and γ and $1 - \gamma$ as those of the CM and the supplier, where $\alpha, \beta, \gamma \in [0, 1]$. We also assume that the supply chain parties will gain no profit if no agreement is reached. Thus, $d_o = d_m = d_s = 0$.

Under both push and pull contracts, the negotiation of wholesale prices happen along with the ordering quantity decisions. Recall that under the push contract, the ordering quantity decisions are made before demand realization, while under the pull contract, the quantity ordering decisions are made after the demand realization.

Consequently, wholesale price negotiation occurs before demand realization under the push contract and after it under the pull contract.

The same as Kostamis and Duenyas (2009), we assume that the supply chain parties bargain over the second-period trade gain under the pull contract, as the CM and the supplier have already sunk their costs. In other words, the negotiation problem here is how to divide the marginal profit, $p - c_m - c_s$ of the supply chain among the three parties. Therefore, under the pull contract, these parties establish the wholesale prices by bargaining for at-once orders (which are beyond the OEM's prebook amount). Let Π_{i2} represent firm i 's trade gain generated from the at-once orders, and Π_i its total expected profit.

3.3.3 Centralized supply chain

We provide a benchmark case based on the results for a centralized supply chain. The objective for such a supply chain is to maximize the entire supply chain's expected profit:

$$p\mu(q) - (c_m + c_s)q.$$

Clearly, this is a newsvendor model with the optimum

$$q^* = \bar{F}^{-1}\left(\frac{c_m + c_s}{p}\right),$$

and the corresponding maximal profit is $\Pi = p\mu(q^*) - (c_m + c_s)q^*$.

Below we will apply the GNB scheme to study the performance of the OEM, the CM and the supplier under push and pull contracts. And let subscript C and D represent the optimal outcomes under control and delegation, respectively.

3.4 Outsourcing Structures with Push Contract

Under a push contract, the OEM prebooks before the demand realization and there is no at-once order. Consequently, the OEM bears all the inventory risks.

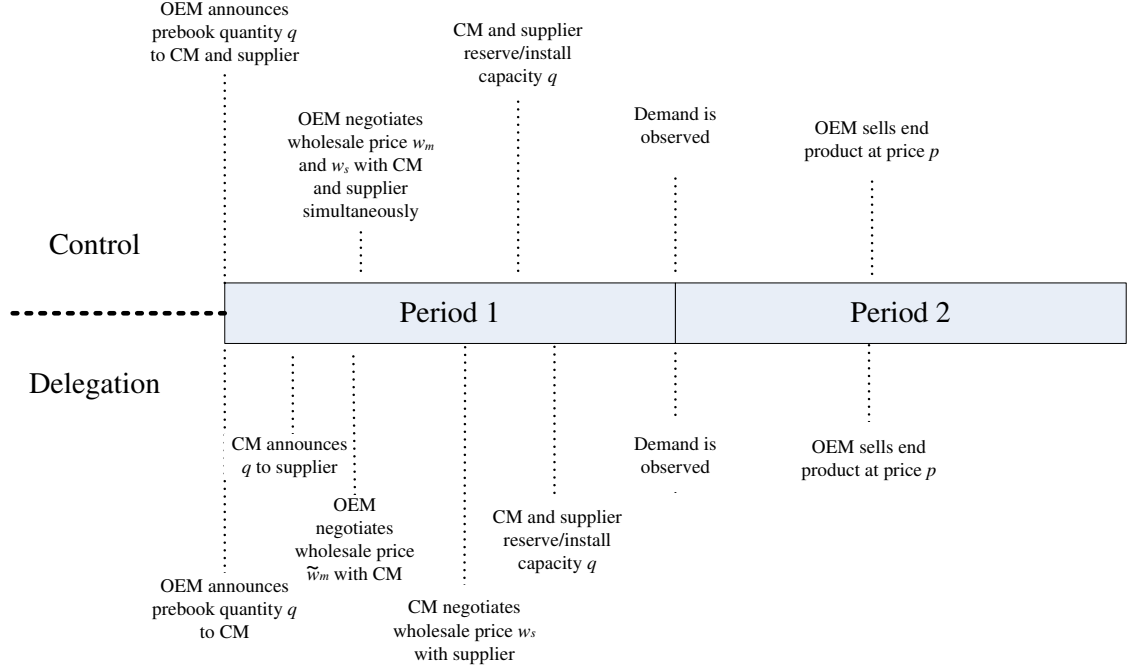


Figure 3.1: Timeline of Decisions and Events under Push Contract: Control vs Delegation

3.4.1 Control with push contract (\mathcal{CS})

Under \mathcal{CS} , the game sequence in period 1 is as follows (see Figure 3.1).

1. The OEM announces its prebook quantity q and makes a commitment to the CM and the supplier. (It is never in the OEM's best interest to prebook different quantities with the CM and the supplier, as their components are complements of each other.)
2. The OEM negotiates wholesale prices w_m and w_s with the CM and the supplier, respectively, via GNB.

3. The CM and the supplier install their capacities according to the OEM's pre-book.

In period 2, the market demand is observed, and all revenues and costs are incurred.

We solve this game backwards. First given the OEM's prebook quantity q , we solve the GNB game between the OEM and the CM and the one between the OEM and the supplier. The profit functions of the three parties are, respectively:

$$\Pi_o = p\mu(q) - (w_m + w_s)q, \quad \Pi_m = (w_m - c_m)q, \quad \text{and} \quad \Pi_s = (w_s - c_s)q.$$

The negotiated wholesale prices can be obtained through maximizing the *Nash Products* defined as follows:

$$\begin{aligned} \text{Max}_{w_m} \quad \Omega_{om} &= [\Pi_o(w_m)]^\alpha [\Pi_m(w_m)]^{1-\alpha} = [p\mu(q) - (w_m + w_s)q]^\alpha [(w_m - c_m)q]^{1-\alpha}, \\ \text{Max}_{w_s} \quad \Omega_{os} &= [\Pi_o(w_s)]^\beta [\Pi_s(w_s)]^{1-\beta} = [p\mu(q) - (w_m + w_s)q]^\beta [(w_s - c_s)q]^{1-\beta}. \end{aligned}$$

After substituting those negotiated prices into the the OEM's profit function Π_o , we can obtain the OEM's optimal ordering decision by solving the maximization problem.

The results are summarized in Proposition 12.

Proposition 12. *Under CS,*

$$(1) \text{ the OEM's optimal prebook quantity } q^{CS} = q^* = \bar{F}^{-1} \left(\frac{c_m + c_s}{p} \right).$$

(2) the GNB-derived wholesale prices are

$$\begin{aligned} w_m^{CS} &= \frac{(1-\alpha)\beta}{\alpha + \beta - \alpha\beta} \frac{p\mu(q^*)}{q^*} + \frac{\alpha c_m - \beta(1-\alpha)c_s}{\alpha + \beta - \alpha\beta}, \\ w_s^{CS} &= \frac{(1-\beta)\alpha}{\alpha + \beta - \alpha\beta} \frac{p\mu(q^*)}{q^*} + \frac{\beta c_s - \alpha(1-\beta)c_m}{\alpha + \beta - \alpha\beta}, \end{aligned}$$

for the CM and the supplier, respectively. w_m^{CS} decreases in α and w_s^{CS} decreases in β .

(3) the entire supply chain reaches centralized profit Π , and the supply chain parties divide the total supply chain profit as follows.

$$\Pi_o^{CS} = \frac{\alpha\beta}{\alpha + \beta - \alpha\beta}\Pi, \quad \Pi_m^{CS} = \frac{(1-\alpha)\beta}{\alpha + \beta - \alpha\beta}\Pi, \quad \text{and} \quad \Pi_s^{CS} = \frac{(1-\beta)\alpha}{\alpha + \beta - \alpha\beta}\Pi. \quad (3.1)$$

Π_o^{CS} is increasing in α and β . Π_m^{CS} is decreasing in α and Π_s^{CS} is decreasing in β .

We can verify that $w_m^{CS} \geq c_m$ and $w_s^{CS} \geq c_s$. Hence, both the CM and the supplier will take the contract.

Conclusion (1) shows that the OEM's order quantity coincides with the newsvendor quantity for the whole supply chain. Thus, a push contract can eliminate *double marginalization* and coordinate the entire supply chain to achieve the centralized performance under the control structure. It is natural to wonder why the OEM's pre-order decision coincides with the centralized capacity decision under CS . The reasons are as follows. The GNB scheme allows the supply chain parties to divide 'a pie' (the system's profit) according to their relative negotiation powers, and each party's profit is increasing in its own bargaining power. When price negotiation occurs before demand realization, the pie becomes *the expected profit for the whole supply chain*. Hence, the OEM's decision on maximizing its own share of the pie is equivalent to maximizing the expected profit for the whole supply chain.

As shown in Conclusion (2), the optimal wholesale price w_m^{CS} / w_s^{CS} decreases in the OEM's bargaining power α/β . Thus, the OEM can negotiate a lower wholesale price when its bargaining power is greater. Conclusion (3) shows the allocation of the total profit among the three parties, which is solely determined by their negotiation

powers, and the players' share is increasing in their respective bargaining powers.

3.4.2 Delegation with push contract (\mathcal{DS})

Under \mathcal{DS} , the game sequence in period 1 is as follows (see Figure 3.1).

1. The OEM announces its prebook quantity q and commits to the CM. The CM then announces the OEM's prebook quantity q to the supplier and commits to it. (It is never in the CM's best interest to prebook a different quantity than q with the supplier because of the complementarity between the CM's and the supplier's products.)
2. The OEM negotiates wholesale price \tilde{w}_m with the CM, and the CM negotiates wholesale price w_s with the supplier, sequentially.
3. The CM and the supplier install their capacities according to their prebook order.

In period 2, market demand is observed, and all revenues and costs are incurred.

We will first derive the negotiated wholesale prices in Step 2. Given prebook quantity q , the profit functions of the supply chain parties under delegation are

$$\Pi_o = p\mu(q) - \tilde{w}_m q, \quad \Pi_m = (\tilde{w}_m - w_s - c_m)q, \quad \text{and} \quad \Pi_s = (w_s - c_s)q.$$

In the GNB process, the OEM negotiates with the CM, and the CM then negotiates with the supplier. It is a sequential game, and we will solve it backwards. Given prebook quantity q and the CM's bargaining power over the supplier, γ , the CM and the supplier negotiate wholesale price w_s to maximize their *Nash Product*:

$$\text{Max}_{w_s} \quad \Omega_{ms} = [\Pi_m(w_s)]^\gamma [\Pi_s(w_s)]^{1-\gamma} = (\tilde{w}_m - w_s - c_m)^\gamma (w_s - c_s)^{1-\gamma} q.$$

Solving the above optimization problem generates wholesale price $w_s^{DS}(\tilde{w}_m)$. Anticipating this negotiated price, the OEM and the CM negotiate wholesale price \tilde{w}_m to maximize their *Nash Product*:

$$\max_{\tilde{w}_m} \Omega_{om} = [\Pi_o(\tilde{w}_m)]^\alpha [\Pi_m(\tilde{w}_m)]^{1-\alpha} = [p\mu(q) - \tilde{w}_m q]^\alpha [(\tilde{w}_m - w_s^{DS}(\tilde{w}_m) - c_m)q]^{1-\alpha}.$$

Solving this maximization problem generates price \tilde{w}_m^{DS} .

After obtaining the negotiated price \tilde{w}_m^{DS} , we can plug it into Π_o to derive the OEM's optimal ordering decision. The analytical results are summarized in Proposition 13.

Proposition 13. *Under DS,*

(1) *the OEM/CM's optimal prebook quantity $q^{DS} = q^* = \bar{F}^{-1}\left(\frac{c_m+c_s}{p}\right)$.*

(2) *the negotiated wholesale prices are*

$$\tilde{w}_m^{DS} = \alpha(c_m+c_s) + (1-\alpha)p\frac{\mu(q^*)}{q^*}, \text{ and } w_s^{DS} = [\gamma + (1-\gamma)\alpha]c_s + (1-\gamma)(1-\alpha)\left(p\frac{\mu(q^*)}{q^*} - c_m\right).$$

\tilde{w}_m^{DS} is decreasing in α and w_s^{DS} is decreasing in γ .

(3) *the supply chain parties' profits are respectively*

$$\Pi_o^{DS} = \alpha\Pi, \quad \Pi_m^{DS} = \gamma(1-\alpha)\Pi, \quad \text{and} \quad \Pi_s^{DS} = (1-\gamma)(1-\alpha)\Pi. \quad (3.2)$$

(4) *Π_o^{DS} is increasing in α ; Π_m^{DS} is decreasing in α and increasing in γ ; and Π_s^{DS} is decreasing in γ .*

It can be verified that $\tilde{w}_m^{DS} \geq (c_m + c_s)$, and $w_s^{DS} \geq c_s$. Hence, both the CM and the supplier will take the contract.

Interestingly, Conclusion (1) of Proposition 13 shows that the ordering quantity still coincides with the newsvendor quantity for the whole supply chain. Thus a push

contract under delegation also coordinates the whole supply chain. From conclusion (2), we have that the optimal wholesale price $\tilde{w}_m^{DS}/w_s^{DS}$ is decreasing in α/γ , the bargaining power of the OEM/CM. Again, the party with the higher negotiation power can negotiate a smaller wholesale price. What's more, Conclusion (4) shows that the players' profits are also increasing in their respective bargaining powers.

3.4.3 Comparison of outsourcing structures with push contract

In the previous analysis, we find that the optimal ordering quantity is the same under both control and delegation structure when the push contract is adopted. Both structures achieve the centralized performance and the OEM bears the same inventory risk.

From Propositions 1 and 2, we can obtain the following comparison result on the equilibrium wholesale prices.

Corollary 3. *Under the push contract, $(w_m^{CS} + w_s^{CS}) \geq \tilde{w}_m^{DS}$. And $w_s^{CS} \geq w_s^{DS}$ if $\beta \in \left[0, 1 / \left(1 + \frac{(1-\gamma)(1-\alpha)}{\alpha(\alpha+\gamma-\alpha\gamma)}\right)\right]$; otherwise, $w_s^{CS} < w_s^{DS}$.*

Corollary 3 shows that the negotiated contract manufacturing wholesale price under delegation (i.e., \tilde{w}_m^{DS}) is always (weakly) lower than $w_m^{CS} + w_s^{CS}$, the total wholesale price the OEM needs to pay under control. It implies that under the GNB scheme and the push contract, through delegating the procurement function to the CM, the OEM actually achieves cost saving in unit price, no matter whether the bargaining power of the CM with respect to the supplier is large or small.

According to Schelling (1960), restricting the flexibility of a player's action can sometimes make a player's threat credible and therefore improve its commitment power. Here, in our context, under control, the OEM needs to bargain over two

wholesale prices, one with the CM and the other with the supplier. However, under delegation, the OEM restricts its flexibility by only bargaining with the CM. The subsequent negotiation between the CM and the supplier just decides how to divide the whatever wholesale price negotiated by the CM with the OEM. This kind of restriction actually improves the OEM's bargaining power and allows it to achieve a lower total procurement price. We take a close look at the procurement price that the OEM has to pay per unit of the product under the two structures:

$$\left(1 - \alpha \frac{\beta}{\alpha + \beta - \alpha\beta}\right) \frac{p\mu(q^*)}{q^*} + \alpha \frac{\beta}{\alpha + \beta - \alpha\beta} (c_m + c_s), \text{ under control;}$$

$$\text{and } (1 - \alpha) \frac{p\mu(q^*)}{q^*} + \alpha(c_m + c_s), \text{ under delegation.}$$

They are in the same form except that α parameter under delegation is deflated by a fraction $\frac{\beta}{\alpha + \beta - \alpha\beta} (\leq 1)$ under control. That is, the bargaining power of the OEM is α under delegation, but it reduces to $\alpha \times \frac{\beta}{\alpha + \beta - \alpha\beta}$ when the OEM negotiates with the integrated party of the CM and the supplier under control. We may deem this fraction $\frac{\beta}{\alpha + \beta - \alpha\beta} (\leq 1)$ as an indicator of the loss-of-bargaining-power.

Corollary 3 also shows a threshold value of β , larger than which the OEM can negotiate a lower wholesale price with the supplier than that negotiated by the CM under delegation.

Comparing the OEM, the CM and the supplier's optimal profits in (3.1) and (3.2) leads to the following corollary.

Corollary 4. *Under the push contract, $\Pi_o^{CS} \leq \Pi_o^{DS}$. $\Pi_m^{CS} \leq \Pi_m^{DS}$ if $\gamma \in [\gamma_m, 1]$; otherwise, $\Pi_m^{CS} > \Pi_m^{DS}$, where $\gamma_m = \frac{\beta}{\alpha + \beta - \alpha\beta}$. And $\Pi_s^{CS} \leq \Pi_s^{DS}$ if $\gamma \in [0, \max(0, \gamma_s)]$; otherwise, $\Pi_s^{CS} > \Pi_s^{DS}$, where $\gamma_s = \frac{(1-\alpha)\beta + \alpha^2(\beta-1)}{(1-\alpha)(\alpha + \beta - \alpha\beta)}$.*

Corollary 4 shows that the OEM obtains a weakly higher profit under delegation

than under control, no matter how bargaining powers are allocated among the three players. Moreover, the CM and the supplier may have higher/lower profit under control over delegation.

3.5 Outsourcing Structures with Pull Contract

Under a pull contract, the OEM makes at-once orders after demand realization, i.e., after random demand X is observed; The CM and the supplier have to invest in their capacities q_m and q_s long time before demand realization and thus bear all their capacity risk. As a result, the demand that the whole supply chain can satisfy is $x \wedge q_m \wedge q_s$, where $a \wedge b = \min(a, b)$ and x is the realized demand.

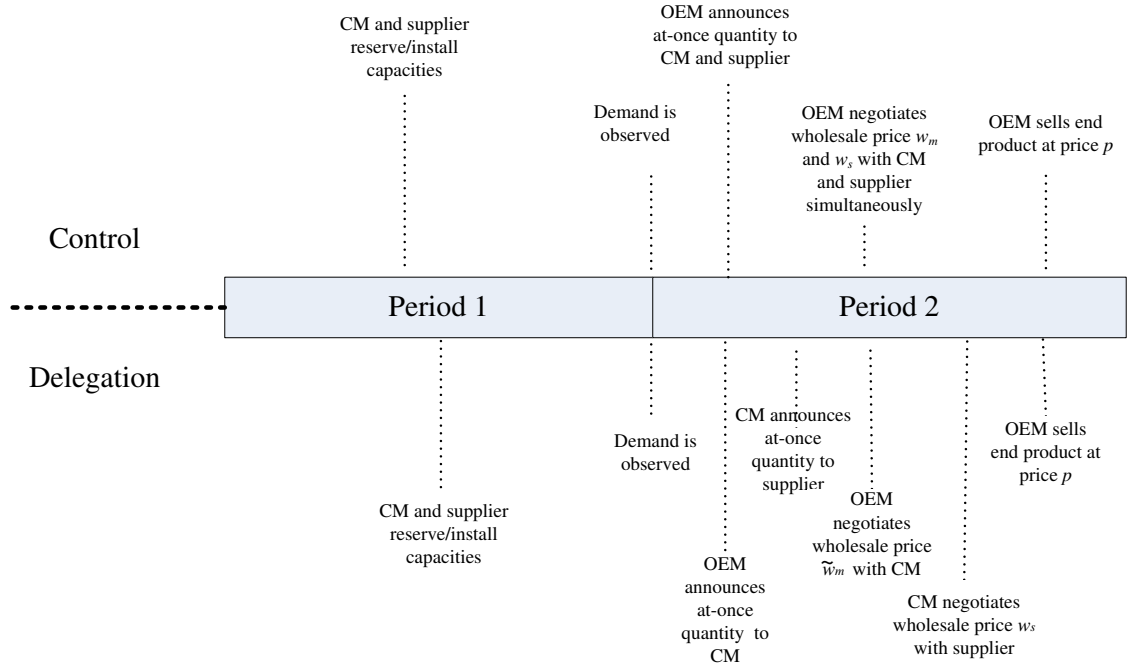


Figure 3.2: Timeline of Decisions and Events under Pull Contract: Control vs Delegation

3.5.1 Control with pull contract (\mathcal{CL})

Under \mathcal{CL} , the game sequence is as follows (see Figure 3.2).

1. In period 1, the CM and supplier install their capacities q_m and q_s in anticipation of the OEM's at-once order.
2. In period 2, market demand is observed. The OEM places the at-once order to satisfy the observed demand and negotiates the wholesale prices w_m and w_s with the CM and supplier, respectively.

We again solve the game backwards.

In period 2, given the at-once order $x \wedge q_m \wedge q_s$, the trade gains of the three parties generated from those at-once orders are, respectively,

$$\Pi_{o2} = (p - w_m - w_s)(x \wedge q_m \wedge q_s), \quad \Pi_{m2} = (w_m - c_m)(x \wedge q_m \wedge q_s), \quad \Pi_{s2} = (w_s - c_s)(x \wedge q_m \wedge q_s).$$

By maximizing the Nash product between the OEM and the CM and the one between the OEM and the supplier, we obtain the negotiated second-period wholesale prices.

Proposition 14. *The equilibrium wholesale prices under \mathcal{CL} via GNB are*

$$w_m^{CL} = \frac{(1 - \alpha)\beta}{\alpha + \beta - \alpha\beta} (p - c_s) + \frac{\alpha}{\alpha + \beta - \alpha\beta} c_m,$$

$$w_s^{CL} = \frac{(1 - \beta)\alpha}{\alpha + \beta - \alpha\beta} (p - c_m) + \frac{\beta}{\alpha + \beta - \alpha\beta} c_s.$$

Notice that $w_m^{CL} \geq c_m$ and $w_s^{CL} \geq c_s$ since $p > c_m + c_s$. Therefore, both the CM and the supplier can obtain a positive marginal profit for the sold quantity.

In period 1, the CM and the supplier make decisions on production quantity/capacity to install to maximize their respective expected profits:

$$\Pi_m(q_m | q_s) = w_m^{CL} \mu(q_m \wedge q_s) - c_m q_m, \quad \text{and} \quad \Pi_s(q_s | q_m) = w_s^{CL} \mu(q_m \wedge q_s) - c_s q_s.$$

This is a simultaneous game. The equilibrium capacity decision is summarized in the following proposition. Define

$$Q_m^{CL} = \bar{F}^{-1} \left(\frac{c_m}{w_m^{CL}} \right) = \bar{F}^{-1} \left[\frac{(\alpha + \beta - \alpha\beta)c_m}{(1 - \alpha)\beta(p - c_s) + \alpha c_m} \right].$$

Then Q_m^{CL} measures the CM's standard newsvendor decision when the supplier's production quantity q_s is ample (much larger than q_m)¹. It represents the maximum amount of the capacity that the CM has incentives to build under \mathcal{CL} . Similarly, define

$$Q_s^{CL} = \bar{F}^{-1} \left(\frac{c_s}{w_s^{CL}} \right) = \bar{F}^{-1} \left[\frac{(\alpha + \beta - \alpha\beta)c_s}{(1 - \beta)\alpha(p - c_m) + \beta c_s} \right].$$

Proposition 15. *The equilibrium capacities of the CM and the supplier under \mathcal{CL} are $q_m^{CL} = q_s^{CL} = Q_m^{CL} \wedge Q_s^{CL}$.*

3.5.2 Delegation with pull contract (\mathcal{DL})

Under \mathcal{DL} , the game sequence is as follows (see Figure 3.2).

1. In period 1, the CM and the supplier install their capacities q_m and q_s in anticipation of the OEM's at-once order.
2. In period 2, market demand is observed and at-once orders are placed to satisfy the realized demand subject to the capacity constraint. The OEM negotiates the wholesale price \tilde{w}_m with the CM, and the CM negotiates the wholesale price w_s with the supplier, sequentially.

¹Note that when the supplier's capacity is infinite, the CM's expected profit function becomes $\Pi_m(q_m) = w_m^{CL}\mu(q_m) - c_m q_m$,

Under delegation, the trade gains that the three parties generate from the at-once orders in period 2 are, respectively,

$$\Pi_{o2} = (p - \tilde{w}_m)(x \wedge q_m \wedge q_s), \quad \Pi_{m2} = (\tilde{w}_m - w_s - c_m)(x \wedge q_m \wedge q_s), \quad \Pi_{s2} = (w_s - c_s)(x \wedge q_m \wedge q_s).$$

Given the at-once order $x \wedge q_m \wedge q_s$, the OEM negotiates with the CM over its wholesale price, and then the CM negotiates with the supplier over its wholesale price. We solve such a sequential bargaining game backwards which generates the following result.

Proposition 16. *The equilibrium wholesale prices under \mathcal{DL} via GNB are*

$$\tilde{w}_m^{DL} = \alpha(c_m + c_s) + (1 - \alpha)p; \quad w_s^{DL} = (\alpha + \gamma - \alpha\gamma)c_s + (1 - \gamma)(1 - \alpha)(p - c_m).$$

Clearly, $\tilde{w}_m^{DL} \geq (c_m + c_s)$, and $w_s^{DL} \geq c_s$ since $p > c_m + c_s$.

Next, substituting \tilde{w}_m^{DL} and w_s^{DL} into the CM and the supplier's total expected profit functions yields

$$\Pi_m(q_m|q_s) = (\tilde{w}_m^{DL} - w_s^{DL})\mu(q_m \wedge q_s) - c_m q_m, \quad \Pi_s(q_s|q_m) = w_s^{DL}\mu(q_m \wedge q_s) - c_s q_s.$$

Similar to Q_m^{CL} and Q_s^{CL} , define Q_m^{DL} and Q_s^{DL} as follows:

$$\begin{aligned} Q_m^{DL} &= \bar{F}^{-1} \left(\frac{c_m}{\tilde{w}_m^{DL} - w_s^{DL}} \right) = \bar{F}^{-1} \left[\frac{c_m}{\gamma(1 - \alpha)(p - c_s) + (1 - \gamma + \alpha\gamma)c_m} \right], \\ Q_s^{DL} &= \bar{F}^{-1} \left(\frac{c_s}{w_s^{DL}} \right) = \bar{F}^{-1} \left[\frac{c_s}{(1 - \gamma)(1 - \alpha)(p - c_m) + (\alpha + \gamma - \alpha\gamma)c_s} \right]. \end{aligned}$$

Q_m^{DL} (Q_s^{DL}) can be understood as the optimal production quantity the CM (supplier) is going to invest in assuming the supplier (CM) has ample capacity under \mathcal{DL} . It represents the maximum amount of the capacity that the CM (supplier) has incentives to build under \mathcal{DL} .

Proposition 17. *The equilibrium capacities of the CM and the supplier under \mathcal{DL}*

are $q_m^{DL} = q_s^{DL} = Q_m^{DL} \wedge Q_s^{DL}$.

3.5.3 Comparison of outsourcing structures with pull contract

Under the pull contract, social optimization cannot be achieved, and the CM and the supplier build the same amount of capacity in equilibrium, i.e., $Q_m^{CL} \wedge Q_s^{CL}$ under control, and $Q_m^{DL} \wedge Q_s^{DL}$ under delegation.

Proposition 18. *For the CM, its capacity under two outsourcing structures satisfies $Q_m^{CL} \leq Q_m^{DL}$ if $\alpha \in [\frac{\beta(1-\gamma)}{\gamma(1-\beta)}, 1]$; otherwise, $Q_m^{CL} > Q_m^{DL}$. For the supplier, its capacity under two outsourcing structures satisfies $Q_s^{CL} \leq Q_s^{DL}$ if $\gamma \in [0, \frac{\beta-\alpha(\alpha+\beta-\alpha\beta)}{(1-\alpha)(\alpha+\beta-\alpha\beta)}]$; otherwise, $Q_s^{CL} > Q_s^{DL}$.*

Proposition 18 shows that the outsourcing structure and the bargaining power distribution of the supply chain parties jointly affect the capacity building incentives of the CM and the supplier when facing the uncertain market demand. The comparison result on the supplier's capacities under two outsourcing structures is very interesting. One may believe that the procurement function shall be delegated to a powerful CM. While it might be true that this can achieve a lower purchasing price for the component, we show the other side of this practice: When the CM is more powerful (γ is larger), the supplier builds less capacity under delegation than under control. This can be explained by the reduced profit margin for the supplier. Hence, the OEM might consider the direct control over the procurement of key components, in the aim of boosting up the supplier's capacity-building incentives and assuring the smoothness of production.

Next we compare the optimal wholesale prices. Interestingly we obtain the same results as those in Corollary 3 under the push contract.

Corollary 5. *Under the pull contract, $(w_m^{CL} + w_s^{CL}) \geq \tilde{w}_m^{DL}$. And $w_s^{CL} \geq w_s^{DL}$ if $\beta \in \left[0, 1 / \left(1 + \frac{(1-\gamma)(1-\alpha)}{\alpha(\alpha+\gamma-\alpha\gamma)}\right)\right]$; otherwise, $w_s^{CL} < w_s^{DL}$.*

Again Corollary 5 implies that similar to the push contract, under the pull contract, the OEM can also achieve the total cost saving per unit of product by delegating the component procurement function to the CM. However, it does not imply that the OEM's expected profit is also larger under \mathcal{DL} since the whole supply chain's capacity could be smaller under \mathcal{DL} than the one under \mathcal{CL} . The following corollary provides a sufficient condition for the OEM to obtain a larger expected profit under \mathcal{CL} .

Corollary 6. *Under the pull contract, if $\mu(Q_m^{DL} \wedge Q_s^{DL}) \leq \frac{\beta}{\beta+\alpha-\alpha\beta}\mu(Q_m^{CL} \wedge Q_s^{CL})$, $\Pi_o^{DL} \leq \Pi_o^{CL}$.*

The inequality in Corollary 6 defines a complex relationship among the bargaining powers, cost parameters and demand structure. It shows that under the pull contract, control is more likely to be beneficial to the OEM if the system capacity under delegation $Q_m^{DL} \wedge Q_s^{DL}$ is lower than those under control, $Q_m^{CL} \wedge Q_s^{CL}$, and if the OEM's bargaining power over the CM (i.e., α) is small and that over the supplier (i.e., β) is large. The potential reasons are the follows. First, if the OEM's bargaining power over the supplier is larger than some threshold value, the OEM actually can negotiate a lower wholesale price for the components under control than that negotiated by the CM under delegation (Corollary 5). Second, if the whole supply chain system capacity is low, when the realized demand is high, the OEM may lose the potential customer. These two driving forces may make control more preferable to the OEM.

3.6 Comparison of Push and Pull Contracts

We now compare the two contracts from the viewpoint of the whole supply chain and the OEM.

3.6.1 Wholesale prices and supply chain capacity

In this subsection, we will compare the negotiated wholesale prices and supply chain capacity under push and pull contracts. First we summarize the *supply chain capacity* -the minimum of the CM and the supplier's capacities- in Table 3.3. As shown in §4, the push contract coordinates the whole supply chain under both control and delegation. And from §5.1 and §5.2, we know that the supply chain capacity is $Q_m^{CL} \wedge Q_s^{CL}$ under \mathcal{CL} and $Q_m^{DL} \wedge Q_s^{DL}$ under \mathcal{DL} . This difference is caused by the bargaining timing. When price negotiation happens after the demand realization, the parties bargain over 'a pie', which is the realized revenue, and ignore other parties' sunk capacity costs; anticipating this result, the CM and the supplier's capacity installing decisions in the initial period may be sub-optimal, from the viewpoint of the whole supply chain.

Table 3.3: Supply Chain Capacity under Push and Pull Contracts

| | Control | Delegation |
|---------------|--|--|
| Push Contract | $\bar{F}^{-1}\left(\frac{c_m+c_s}{p}\right)$ | $\bar{F}^{-1}\left(\frac{c_m+c_s}{p}\right)$ |
| Pull Contract | $Q_m^{CL} \wedge Q_s^{CL}$ | $Q_m^{DL} \wedge Q_s^{DL}$ |

The following proposition shows that the supply chain capacity under pull contract is not larger than the one under the push contract.

Proposition 19. $Q_m^{CL} \wedge Q_s^{CL} \leq \bar{F}^{-1}\left(\frac{c_m+c_s}{p}\right)$, and $Q_m^{DL} \wedge Q_s^{DL} \leq \bar{F}^{-1}\left(\frac{c_m+c_s}{p}\right)$.

Second, we list the GNB-derived equilibrium wholesale prices under push and pull contracts in Table 3.4. Tables 3.4 shows that for both control and delegation, the

negotiated wholesale prices are in the same form except that p in the expression of negotiated wholesale price under pull is replaced with $p \frac{\mu(q^*)}{q^*}$ under push. Note that it always holds that $\frac{\mu(q^*)}{q^*} < 1$ since $\mu(q^*) = E[\min(X, q^*)] < q^*$. Hence, we have the following proposition.

Proposition 20. *The negotiated wholesale prices under the pull contract are higher than those corresponding wholesale prices under the push contract.*

This is pretty interesting: the endogenous pre-book wholesale price obtained via GNB is always lower than the endogenous at-once order wholesale price. That is, the OEM (or the OEM and the CM) is (are) able to negotiate lower wholesale prices if it (they) is (are) willing to bear the inventory risk and make quantity commitment. Otherwise, when demand is realized and orders are placed on spot, the CM and the supplier bear the capacity risk and are more likely to request higher wholesale prices. This is consistent with the industry practice. For example, O'Neill Inc. offered an advance-purchase discount to retailers (Cachon 2004).

In particular, the difference term $\frac{\mu(q^*)}{q^*}$ accounts for the demand uncertainty in it. Consider a random demand variable X with cdf F which belongs to a location-scale family of distributions; that is, $X = a + b\xi$ ($a \geq 0, b > 0$), where ξ is a random variable with a cdf G , a mean μ and a standard deviation σ . Clearly, the mean and standard deviation of X are $a + b\mu$ and $b\sigma$, respectively. Hence, b measures the market X 's *relative risk*. It can be shown that $\frac{\mu(q^*)}{q^*}$ is decreasing in b and therefore the following proposition holds.

Proposition 21. *When demand belongs to a location-scale family of distributions, $\frac{\mu(q^*)}{q^*}$ is decreasing in the demand variance.*

Therefore, the larger the demand uncertainty, the lower the negotiated prebook wholesale price under the push contract when demand belongs to a location-scale

family.

Note that Propositions 19-21 are independent of the cost parameters, bargaining powers and the vertical outsourcing structures. Therefore, they are very general conclusions.

Table 3.4: Negotiated Wholesale Prices under Push and Pull Contracts

| | Control | Delegation |
|----------|--|--|
| Push | $w_m^{CS} = \frac{(1-\alpha)\beta}{\alpha+\beta-\alpha\beta} \frac{p\mu(q^*)}{q^*} + \frac{\alpha c_m - \beta(1-\alpha)c_s}{\alpha+\beta-\alpha\beta}$ | $\tilde{w}_m^{DS} = \alpha(c_m + c_s) + (1-\alpha) \frac{p\mu(q^*)}{q^*}$ |
| Contract | $w_s^{CS} = \frac{(1-\beta)\alpha}{\alpha+\beta-\alpha\beta} \frac{p\mu(q^*)}{q^*} + \frac{\beta c_s - \alpha(1-\beta)c_m}{\alpha+\beta-\alpha\beta}$ | $w_s^{DS} = (\gamma + \alpha - \alpha\gamma)c_s + (1-\gamma)(1-\alpha) \left(\frac{p\mu(q^*)}{q^*} - c_m \right)$ |
| Pull | $w_m^{CL} = \frac{(1-\alpha)\beta}{\alpha+\beta-\alpha\beta} p + \frac{\alpha c_m - \beta(1-\alpha)c_s}{\alpha+\beta-\alpha\beta}$ | $\tilde{w}_m^{DL} = \alpha(c_m + c_s) + (1-\alpha)p$ |
| Contract | $w_s^{CL} = \frac{(1-\beta)\alpha}{\alpha+\beta-\alpha\beta} p + \frac{\beta c_s - \alpha(1-\beta)c_m}{\alpha+\beta-\alpha\beta}$ | $w_s^{DL} = (\alpha + \gamma - \alpha\gamma)c_s + (1-\gamma)(1-\alpha)(p - c_m)$ |

3.6.2 The OEM's choice on timing of orders

As shown in Propositions 19 and 20, although the OEM bears no inventory risk under the pull contract, it has to pay higher wholesale prices for its at-once orders and face a smaller supply chain capacity. Hence, both push and pull contracts have pros and cons for the OEM. In this subsection, we would like to explore the situations under which one contract is better than the other for the OEM.

We define the difference between the OEM's profits under pull and push contracts as follows:

$$\Pi^C = \Pi_o^{CL} - \Pi_o^{CS}, \quad \Pi^D = \Pi_o^{DL} - \Pi_o^{DS}.$$

Lemma 5. Π^C is increasing in w_m^{CS} and w_s^{CS} and is unimodal in w_m^{CL} and w_s^{CL} . Π^D is increasing in \tilde{w}_m^{DS} and unimodal in \tilde{w}_m^{DL} .

From the above lemma, we obtain some qualitative results on the OEM's preference over the contract type. Lemma 5 shows that under control structure, if (1) the negotiated pre-book wholesale prices w_m^{CS} and w_s^{CS} are high or (2) the negotiated

at-once wholesale prices w_m^{CL} and w_s^{CL} are in a moderate range, $\Pi^C > 0$ and the pull contract is preferred by the OEM. Otherwise, the OEM shall prefer the push contract. The first part of the conclusion is intuitive: Although the OEM needs to bear all inventory risk, it shall choose push as long as the wholesale prices in period 1 are sufficiently low. But the second part of the conclusion is quite counter-intuitive: Why shall the OEM not choose pull if the at-once order wholesale prices are very low? The potential reason is that the at-once wholesale prices in period 2 not only influence the OEM's profit margins but also influence the CM and the supplier's capacity building incentives. Too high at-once wholesale prices of course hurt the OEM and reduces the benefit of pull. And too low at-once wholesale prices hurt the CM and the supplier and consequently reduce their capacity building incentives, leading to low supply chain capacity. This eventually also hurts the OEM. Similarly, under delegation structure, if \tilde{w}_m^{DS} is large or \tilde{w}_m^{DL} is in a moderate range, pull contract is preferred by the OEM.

Understanding the above relationship, we further consider the impact of market demand, cost parameters and parties' bargaining powers on the choice of contract type.

Define the *relative gain of pull over push* under control and delegation structures respectively as follows:

$$g^C = \frac{\Pi_o^{CL} - \Pi_o^{CS}}{\Pi_o^{CS}}, \quad \text{and} \quad g^D = \frac{\Pi_o^{DL} - \Pi_o^{DS}}{\Pi_o^{DS}}.$$

So only when g^C (g^D) is positive, it is worthwhile for the OEM to adopt pull contract and place orders after observing demand information, otherwise, the demand information actually hurts the OEM's performance and the OEM should adopt push contract instead and place order before demand realization.

Let μ and σ represent the mean and standard deviation of the demand for the

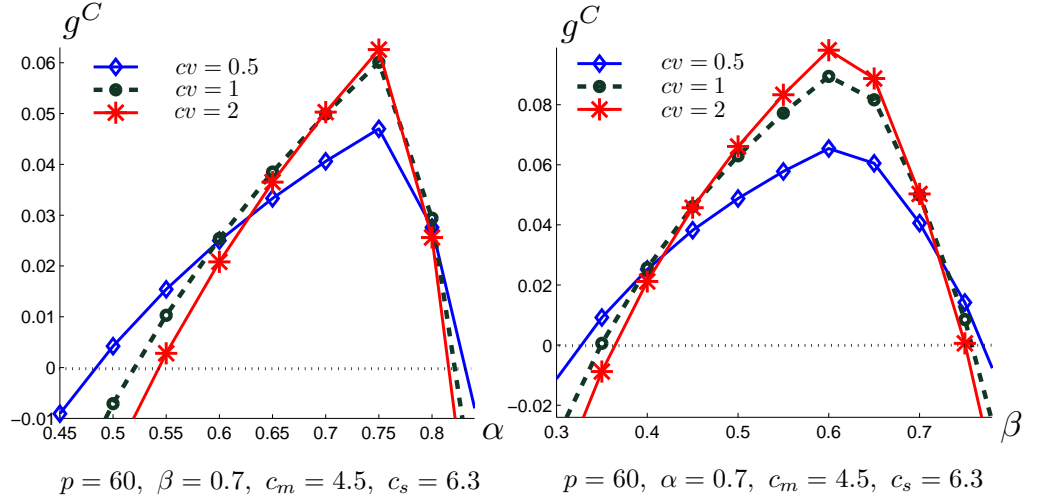
end product. Without loss of generalization, the demand for the end product is assumed to have a normal distribution truncated at zero to avoid negative demand realizations. (Specifically, starting with a normal distribution with cdf $G_j(\cdot)$, the demand has a distribution with cdf $F_j(x) = 0$ for $x < 0$ and $F_j(x) = (G_j(x) - G_j(0))/(1 - G_j(0))$ for $x \geq 0$.) Assuming the other parameters, i.e., p , $c_s(c_m)$, α , β , γ are constant, we then numerically examine the sign of $g^C(g^D)$ as a function of $c_m(c_s)$, the CM(supplier)'s capacity installing cost, the bargaining power parameters, and the coefficient of variation CV (σ/μ).

Impact of bargaining powers

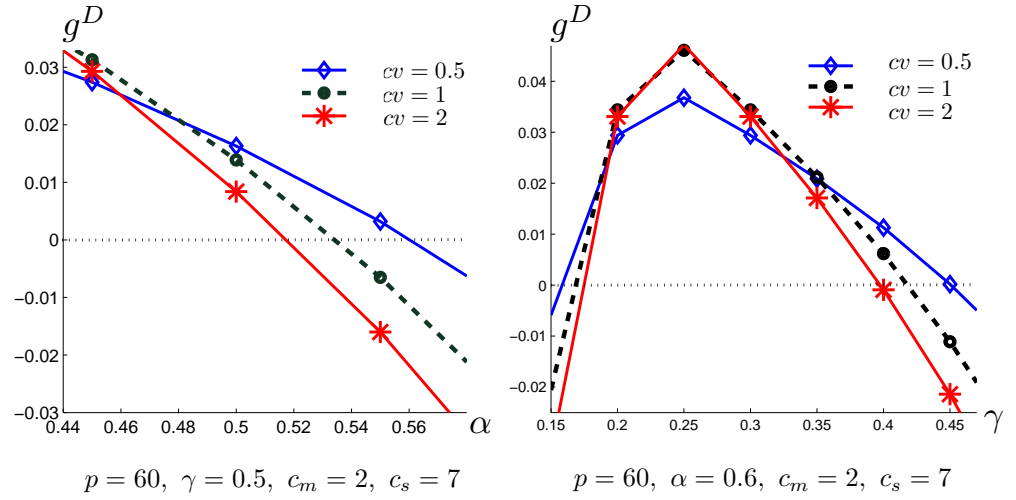
The impact of bargaining powers is illustrated in Figures 3.3. We observe that under delegation, pull contract is preferred when α , the bargaining power of the OEM over CM, is small. Therefore, under delegation, the incentives for the OEM to bear inventory risk is increasing with its negotiation power over the CM. It is interesting that in all other cases, pull contract is preferable when negotiation power parameters are in a moderate range, neither too large nor too small. To explain this observation, recall that the capacity for the whole supply chain party is jointly decided by the CM and the supplier under pull contract. And moderate negotiation powers imply that negotiation parties have similar bargaining powers over each other. This allows the profit to be fairly shared among supply chain parties to achieve *balanced* capacity set-ups. On the other hand, allocation of profit in an extreme way will result in one party's low incentives in capacity set-up, which will eventually hurt everyone.

Impact of capacity costs

For other factors such as the capacity installing costs c_m and c_s , we find similar patterns across different settings and thus show the representative results in Figures



(a) Impact of the OEM's Bargaining Powers under Control



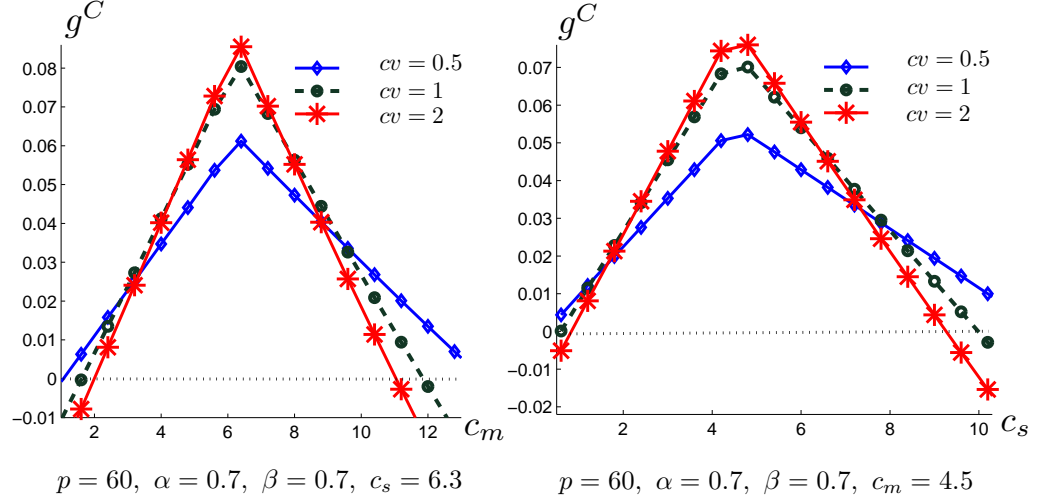
(b) Impact of the OEM's and the CM's Bargaining Powers under Delegation

Figure 3.3: Impact of Bargaining Powers

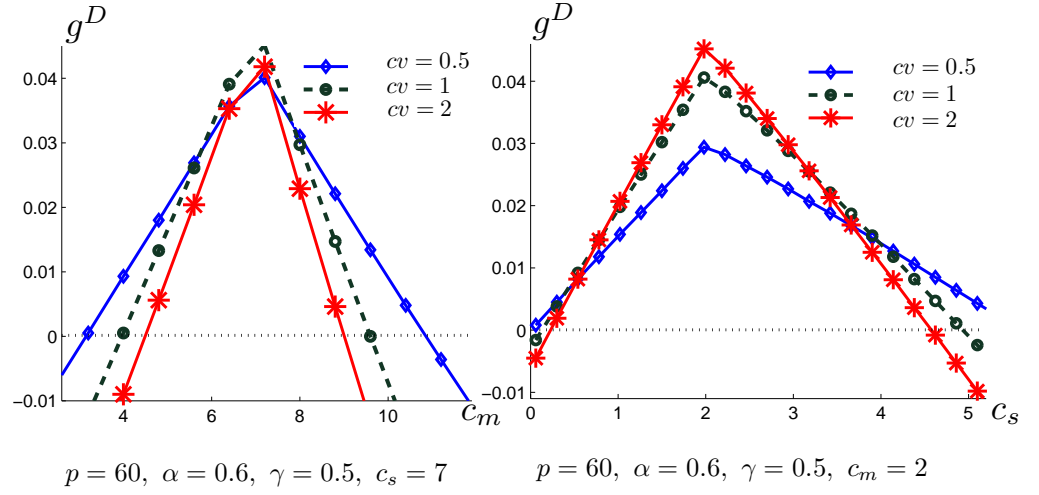
3.4. We observe that either pull or push contract can be preferred by the OEM, and the effect of $c_m(c_s)$ is not monotone. $g^C(g^D)$ can be firstly increasing in $c_m(c_s)$ and then decreasing. In particular, it shows that push contract is preferable when the capacity costs c_m and c_s are very large or either of them is very small. It is intuitive that when c_m and c_s are very large, the OEM would like to choose the push contract to motivate the capacity decisions of the CM and the supplier. However, it is quite interesting that when one of them is very small, the OEM would also like to choose push contract. We use a numerical example to illustrate this result. Consider the setting with $p = 40$, $\alpha = 0.7$, $\beta = 0.6$, $c_s = 12.8$ and $c_m = 1$. We have $Q_m^{CL} = 6.9331$, $Q_s^{CL} = 2.8204$, and $q^* = 4.8438$. And the OEM's profit under pull contract is 28.4317 and the one under push contract is 29.6714. Clearly, in this example, the CM has incentives to set up a large capacity due to its low capacity cost; however, the supplier does not have such a capacity due to a large capacity cost. In the push setting, the capacity decision is the same as a centralized one which is decided by the sum of c_m and c_s . Hence, when the CM and the supplier have very *unbalanced* capacity costs, push contract can coordinate each other and achieve a larger supply chain capacity.

Impact of demand variance

From the above figures, we observe that the range of $g^C > 0$ and $g^D > 0$ is usually decreasing in CV . That means pull contract is more likely to be preferred by the OEM when CV is smaller. This is reasonable: When demand is less risky, both the CM and the supplier have incentives to set-up adequate capacities and hence pull contract is more beneficial.



(a) Impact of the CM's and the Supplier's Capacity Installing Costs under Control



(b) Impact of the CM's and the Supplier's Capacity Installing Costs under Delegation

Figure 3.4: Impact of Capacity Installing Costs

3.7 Concluding Remarks

In this chapter, we studied price negotiation, quantity ordering and capacity installation decisions in a multi-tier supply chain consisting of an OEM, a CM and a supplier by considering two risk-allocation contracts – push and pull, and two vertical outsourcing structures – control and delegation.

We showed that under push contract, the GNB over wholesale price before demand realization can always coordinate the whole supply chain to achieve the centralized performance, no matter which outsourcing structure is adopted. Furthermore, we showed that under such contract, it is more beneficial for the OEM to delegate the procurement function to the CM instead of keeping such function in-house.

As to pull contract, we found that the GNB is no longer able to coordinate the whole supply chain, but delegation can always lead to a cost saving in the total unit procurement price paid by the OEM. But the OEM can be better off under control than under delegation if the following two scenarios occur: lower component wholesale prices negotiated by the OEM than by the CM and higher capacity levels built up by the CM and the supplier under control than those under delegation.

Comparing push and pull contracts showed that the negotiated pre-book wholesale prices are always lower than the corresponding negotiated at-once wholesale prices. Also, the supply chain capacity under the pull contract is smaller than the one under the push contract. Hence, the OEM has to pay higher wholesale prices and face smaller supply chain capacity for not bearing inventory risks. We numerically found that push contract is preferable when the CM and the supplier's capacity installing incentives are very unbalanced and the market demand has high uncertainty.

Admittedly, outsourcing activities are very complex and comparison of different outsourcing structures involves many other issues, such as loss of quality control, intellectual property (IP) leakage and potential competition from the CM. It would

be an interesting future research topic to bring in those issues into the modeling consideration.

Chapter 4

The Advantage of Quantity Leadership When Outsourcing Production to a Competitive Contract Manufacturer

4.1 Introduction

Outsourcing the manufacturing function to contract manufacturers (CMs) is a common practice for many original equipment manufacturers (OEMs) today. For example, in the personal computer industry, companies such as Apple Inc. and Hewlett-Packard Co. have outsourced all their assembly functions to Foxconn, Flextronics and other CMs in Taiwan and mainland China (Smith 2008). Due to the intense competition among CMs, the services they provide now go beyond the pure manufacturing function. In the electronics industry, for example, there is an increasing trend for classic CMs (which have no design capabilities) to become original design manufacturers (ODMs) that can offer value-added services in addition to product manufacturing, such as a product design service, to their brand-carrying customers. Foxconn and Flextronics have built large R&D centers to offer product design services to OEMs (Baljko 2006). This is a welcome development for OEMs, as it can help them to shorten lead times for new product development and facilitate greater product variety.

However, allowing the CMs to handle increasing business functions ranging from innovation and design to production and even logistics can be a double-edged sword, as these companies are becoming increasingly capable of producing and selling their own self-branded products. Business cases have been presented to illustrate the

interesting situation of a CM acting as both the *upstream partner* and *downstream competitor* of an OEM. For example, BenQ, Motorola's CM, produced its first own-brand cellular phone in 2005 (Hilmola et al. 2005); Asustek, a Taiwan-based CM for Apple, Dell, Sony and Toshiba, designs, produces and sells its own Asus brand of notebook computer (Shilov 2007); and Acer Inc., originally a CM for IBM and Apple, became the third largest computer manufacturer in the world (by sales) in 2007 (Nystedt 2007).

If a CM performs a single role, whether upstream partner or downstream competitor, then the relationship between it and the OEM is relatively simple. In the former case, the OEM decides the production quantity as a monopoly, and the CM is responsible only for manufacturing; in the latter case, according to the traditional oligopoly theory, the party that first decides the production quantity is able to capture a larger share of the market and obtain a higher profit, thereby exhibiting first-mover advantage (see, e.g., Vives 2001). However, a competitive CM is not only an OEM's competitor, but also its business partner. A competitive CM's revenue is generated both from producing and selling its own self-branded products and from contract manufacturing. The answer to the outcome of the Cournot competition between an OEM and its competitive CM and the incentives of the two in choosing quantity leadership/followership remain unclear, which provides the motivation for this study.

In practice, it is common for an OEM to act as a Stackelberg leader in contracting with a competitive CM. However, there are some cases in which the latter assumes the leadership role. For example, at Computex 2007 in Taipei, Asustek first announced its production of a low-cost sub-notebook based on Intel's Classmate PC reference design. At the same time, it also reported a sales target of 200,000 units by the end of 2007 and between three and five million by 2009 (Laptops 2007, Vilches 2007). One year later, one of its OEMs, Dell, entered the same market with a target production

and sales quantity of more than 3.6 million (Dannen 2008).

In this chapter, we assume that there exist an OEM and a competitive CM in the end market. The OEM outsources part of its production to this competitive CM and the remainder to other non-competitive CMs. We assume that all CMs, whether competitive or non-competitive, are capable of both design and manufacture.¹ We assume that there is no intellectual property (IP) conflict between the products of the OEM and the CM. We also assume that the products offered by the competitive CM and the OEM are imperfectly substitutable. That is, the OEM's products can be fully substituted for those of the CM, but the reverse does not hold true. We consider three basic Cournot (quantity) competition games between these two parties: a "simultaneous"-move game, a sequential-move Stackelberg game with the OEM as the leader, and a sequential-move Stackelberg game with the competitive CM as the leader. To explore the endogenous quantity leadership issue, we consider the extended two-stage game in Hamilton and Slutsky (1990). In the first stage, the two players simultaneously choose a leadership or followership role; in the second stage, they play a simultaneous game if both players choose leadership or followership in the first stage, and a sequential game otherwise.

For the sake of providing a full picture of the outcomes of the three games, we first consider a scenario in which the wholesale price and the proportion outsourced from the OEM to its competitive CM are *exogenously* given. We show that both first- and second-mover advantage may exist for the OEM and its competitive CM. We find that the advantage of quantity leadership depends on multiple factors, such as the

¹With regard to the electronics industry, the CMs investigated in this chapter are considered as ODMs. Note that although ODMs are capable of design and manufacture, they do not necessarily constitute OEM competitors. In this industry, some ODMs have launched successfully self-branded businesses, whereas others such as BenQ (Wang 2006) tried but failed to do so. Others, such as Foxconn and Flextronics, are enjoying large accumulative profits from contract manufacturing and have therefore decided to stick to non-consumer-market-entry behavior. (Note that Foxconn and Flextronics do produce self-branded components but up to now, have not produced self-branded end products for the consumer market.)

market size, the wholesale price, the product substitution rates and the percentage of production that the OEM outsources to this competitive CM. Particularly, when the wholesale price or the proportion of the production outsourced to the CM is lower than a threshold value, both parties prefer Stackelberg leadership and, consequently, play a “simultaneous”-move game in the consumer market. We also find that as the degree of homogeneity between the products of the OEM and its competitive CM increases, it becomes more difficult to keep the CM as the follower and likelier that a “simultaneous”-move game appears.

We then consider a scenario in which both the wholesale price and the proportion outsourced from the OEM to its competitive CM are *endogenized*. Specifically, we consider the three basic games in a scenario in which the OEM determines the proportion of production that it outsources to the competitive CM whereas the wholesale price is endogenously determined by the competitive CM.

Interestingly, we find that the OEM outsources *entirely* from the competitive CM as long as its wholesale price is no more than that of non-competitive CMs. We further show that when the competitive CM sets the wholesale price, it always sets a wholesale price that is low enough to allow both parties to *coexist* in the market.

This finding implies that a rational competitive CM will not readily give up its contract manufacturing business and a rational OEM will be *cautious* about employing the outsourcing quantity as a weapon against its competitive CM. A win-win solution for both may be to allow coexistence in the market. Otherwise, the loss of orders from OEMs may actually spur CMs to develop and sell their own-brand products, thereby turning them into aggressive competitors. It was reported that many CMs in Taiwan and the Pearl River Delta region of China were forced to build their own brands to compensate for lost orders from OEMs following the global financial crisis that began in September 2008 (Liu 2009). On the other hand, there

are many examples of OEMs and competitive CMs coexisting in harmony. Some competitive CMs even put great effort into retaining a long-term relationship with their OEMs, such as by dividing themselves into two companies with one responsible for their self-branded business and the other for their contract manufacturing business (Chung 2004). Other CMs, for example, Arima, Clevo, Elite, TPV Technology and Twinhead, choose to maintain their self-branded and ODM businesses in the same organization; in the case of any conflict between their self-branded business and their contract manufacturing service, they will place priority on the latter and satisfy outsourced orders first by reducing the output of their own branded products (Yang 2006, Wang 2008). As a result, many OEMs choose to retain a long-term relationship with competitive CMs rather than terminate their business, especially when the CMs have accumulated special expertise, such as trained workers and good production control systems and policies.

We finally consider the situation under which the wholesale price is negotiated between the CM and the OEM via generalized Nash bargaining scheme. Paradoxically, we find that a weak CM behaves aggressively in the end-product market and consequently, a “simultaneous”-move game is played between itself and the OEM whereas a powerful CM is rather cooperative and thus, a sequential-move game is played. The reason behind this phenomenon is that a larger bargaining power allows the CM to obtain a larger revenue from contract manufacturing, which weakens the CM’s incentives on selling its own-brand products.

The remainder of this chapter is organized as follows. Section 2 reviews the related literature. Section 3 presents the notations and assumptions for our models. Section 4 analyzes how the outsourcing decision of an OEM affects the production quantity and leadership preference of both its competitive CM and itself in asymmetric Cournot competition. Sensitivity analysis of the substitutability parameter is also conducted

in this section. Section 5 extends the discussion to a setting with endogenized quantity and wholesale price. Section 6 studies the endogenous wholesale prices via generalized Nash bargaining scheme. Section 7 concludes the chapter. All of the proofs are relegated to the online Appendix A.

4.2 Literature Review

The issue of subcontracting to a rival/potential entrant has been discussed in the economics literature. Spiegel (1993) shows that if the transfer payment can be shared via Nash bargaining, then outsourcing production to a potential rival can always make both the incumbent and the potential rival better off, meaning the latter has fewer incentives to build its self-branded business. However, the study of outsourcing to a competitive CM is relatively new to the operations management literature. Arruñada and Vázquez (2006) provide a number of business cases of competition between an OEM and a competitive CM. Horng and Chen (2007) empirically examine why some Taiwanese CMs have shifted towards own brand management. Arya et al. (2007) investigate a Cournot competition model between a retailer and its supplier. In an encroachment setting, they assume that the supplier has the right to set the wholesale price and that the retailer maximizes its profit by choosing the retail quantity. In a non-encroachment setting, they assume the wholesale price to be exogenously given. By comparing encroachment and non-encroachment settings, they demonstrate that supplier encroachment can achieve Pareto improvement by inducing lower wholesale prices and increasing downstream competition. Ozkan and Wu (2009a) explore the market entry timing problem from the perspective of a competitive CM by adopting a product life-cycle model. Ozkan and Wu (2009b) further consider the capacity allocation issue of a competitive CM. Lim and Tan (2010) investigate the make, buy or make-and-buy decisions of an OEM by taking into consideration the interaction

between the OEM and its supplier (a CM in our context) over two periods. They show that the OEM's high brand equity can prevent the potential market entry of their CMs. Chen et al. (2010) examine the OEM's component sourcing decision when it faces a competitive CM, i.e., whether it should buy and resell the components or delegate the procurement function to the competitive CM. In contrast to their work, we investigate how the OEM's outsourcing decisions affect the preferences of its competitive CM and itself concerning Stackelberg leadership/followership. We also consider the decisions on wholesale price and outsourcing proportion.

Our work is closely related to the study of firms' outsourcing decisions. A survey of the operational issues related to outsourcing can be found in Elmaghraby (2000). Cachon and Harker (2002) consider two competitive firms facing economies of scale. McGovern and Quelch (2005) summarize the reasons to engage in outsourcing, and discuss what to outsource and the responsibility of marketing managers. Ülkü et al. (2007) investigate whether the OEM/CM should bear the inventory/capacity risk. Arya et al. (2008a) are concerned with a firm's make-or-buy decision in which the firm can either produce inputs internally or outsource to a monopoly supplier. Gray et al. (2009a) explore the impact of cost-reduction ability and the OEM's outsourcing decision in a two-period game setting. Gray et al. (2009b) further test the OEM's outsourcing propensity by jointly considering cost and quality issues. Kaya and Özer (2009) discuss the quality risks of outsourcing. Feng and Lu (2009) characterize OEMs' design-related outsourcing decisions. In the marketing field, Stremersch et al. (2003), Leiblein and Miller (2003), Hoetker (2005) and Parmigiani (2007) empirically investigate the OEM's make-or-buy decision from the transaction cost perspective.

Our work is also related to studies on multi-channel distribution and dual sales. Chiang et al. (2003) consider a setting in which the manufacturer can open a direct channel to compete with its retailers, and then investigate the impact of that channel

on supply chain performance. They show that it can benefit the manufacturer even when no direct sales occur. Tsay and Agrawal (2004b) study the channel conflict issue between existing reseller partners and direct sales, and find that the addition of a direct channel is not necessarily detrimental to the reseller. Chen et al. (2008) assume consumer demand to be endogenously affected by the service level (delivery lead time and product availability) and investigate the best time for the manufacturer to establish a direct channel or a retail channel if it is already selling through one of these channels. Arya et al. (2008b) consider a dual distribution channel in which the manufacturer sells the product to a retailer and also competes with the retailer in the retail market. More work in this stream can be found in the survey carried out by Tsay and Agrawal (2004a).

We note that Wang et al. (2009) adopt the endogenized timing game to investigate the production strategy choices of two competing firms. Each firm individually decides whether to be efficient (begin production before demand realization) or responsive (begin production after demand realization.) They identify the conditions under which being efficient/ responsive is a Nash equilibrium (NE).

4.3 Notations and Assumptions

We consider an OEM (labeled o) that outsources the entire manufacture of its products to CMs. There exists one competitive CM (labeled c) that, on the one hand, manufactures the OEM's products and, on the other hand, produces and sells its own-brand products to the consumer market. Moreover, these two products are substitutable for each other. Let $\theta, \theta \in [0, 1]$, represent the proportion of production that the OEM outsources to the competitive CM. The OEM then purchases the remaining $(1 - \theta)$ proportion from other non-competitive CMs. For simplicity, we assume that the CM incurs the same production cost in producing the OEM's products and its

own. Let w represent the wholesale price that the OEM pays to all of the CMs for each unit of product they produce. We first consider w to be exogenously given and greater than each CM's unit production cost. Later, in §4.5 and §4.6, we extend our analysis to the cases in which the wholesale price is an endogenized decision variable either determined by the competitive CM or negotiated by the OEM and the competitive CM.

We assume that the OEM and the competitive CM engage in a quantity-setting Cournot competition in the consumer market. Thus, the market prices for their products are jointly determined by their respective production quantities, i.e., via inverse demand functions. For tractability, we adopt the commonly-used inverse demand function for the differentiated product of firm i ²:

$$p_i(q_i, q_j) = m - q_i - b_i q_j, \quad i, j = o, c; \quad i \neq j, \quad (4.1)$$

where p_i is firm i 's market price, q_i is its production quantity, and b_i is a parameter that measures the cross-effect of the change in firm i 's product demand that is caused by a change in that of firm j . Let $0 \leq b_i \leq 1$, and note that the limiting values $b_i = 0$ and $b_i = 1$ correspond to the cases of independent products and perfect substitutes, respectively. We interpret b_i as the substitution rate of firm j 's product over that of firm i , $i, j = o, c; \quad i \neq j$. As the OEM's products are usually regarded as superior to the CM's (Arruñada and Vázquez 2006), we assume that the former are perfect substitutes for the latter while the reverse does not hold; that is, $b_c = 1$. We also assume $b_o = b \leq 1$. To omit cases in which no production occurs, we assume that m , the upper bound on market size, is sufficiently large relative to the wholesale price w . For simplicity, we normalize the CM's marginal production cost to zero³. Then,

²Linear (inverse) demand functions are widely used in the economics, marketing and operations fields to investigate product competition; see Bernstein and Federgruen (2004) and Farahat and Parakis (2008) and the references therein.

³As both the competitive and non-competitive CMs in our work are considered to be ODMs, the

the profit functions of the OEM and its competitive CM are, respectively,

$$\Pi_o = (m - q_o - bq_c)q_o - wq_o, \quad (4.2)$$

$$\Pi_c = (m - q_c - q_o)q_c + \theta wq_o, \quad (4.3)$$

which are concave and differentiable. Note that in these two functions, the first term is the profit that each firm gains from selling products in the consumer market, whereas the second term is the transferred outsourcing payments (this term is negative for the OEM and positive for the competitive CM).

There exist three basic games between the OEM and its competitive CM: a “simultaneous”-move game, the OEM-as-leader sequential game and the CM-as-leader sequential game. The outcome for the “simultaneous”-move game is a Nash equilibrium, while the outcomes for the other two sequential-move games are Stackelberg equilibriums. To explore the OEM’s and the competitive CM’s preference concerning Stackelberg leadership and how that preference affects the realization of the three aforementioned settings, we consider a two-stage extended game called the endogenous timing game (see Hamilton and Slutsky 1990, Damme and Hurkens 2004, and Amir and Stepanova 2006). In this extended game, there exists a pre-play stage of which the OEM and the competitive CM simultaneously choose either to move first and be the Stackelberg leader (denoted as L) or move second and be the Stackelberg follower (denoted as F) independently of each other. The players are then committed to this choice. We use $\alpha = (\alpha_o, \alpha_c)$ to denote the joint actions of the OEM and the competitive CM. Then, $\alpha \in \{(L, L), (L, F), (F, L), (F, F)\}$. Next, each player’s timing choice is announced, and the next stage is played accordingly: a simultaneous play if both players decide to move first/second ($\alpha = (L, L)/(F, F)$) and a sequential play under perfect information otherwise (with the order of moves announced

difference between their cost structures is slight and can be ignored.

by the players). We denote Π_i^S , $i = o, c$ as firm i 's profit when it is engaged in a “simultaneous”-move game, where S stands for *simultaneous*. The resulting production quantity is denoted as q_i^S . We also denote Π_i^L (Π_i^F), $i = o, c$ as firm i 's profit when it is the Stackelberg leader (follower). Let q_i^L (q_i^F) represent the corresponding production quantity.

The subgame perfect equilibrium of this extended game leads to a quantity decision timing sequence, and the resulting payoffs of each player are listed in Table 4.1. By comparing the equilibrium payoffs under simultaneous and Stackelberg settings, we derive the conditions under which the OEM and the competitive CM would prefer Stackelberg leadership. In the subsequent analysis, we use the term CM to refer to the competitive CM .

Table 4.1: Quantity and Leadership Decisions

| CM \ OEM | OEM | |
|----------|--------------------|--------------------|
| | Leader | Follower |
| Leader | Π_o^S, Π_c^S | Π_o^F, Π_c^L |
| Follower | Π_o^L, Π_c^F | Π_o^S, Π_c^S |

4.4 Exogenous Wholesale Price and Outsourcing Decisions

We begin with a case of the exogenous wholesale price and outsourcing decision parameters, and investigate the preferences of the OEM and its competitive CM concerning the quantity leadership.

4.4.1 Equilibrium of three basic games

The closed-form expressions for the equilibrium outcomes under the three basic games are summarized in the following proposition.

Proposition 22. *For the “simultaneous”-move game, if $m > \frac{2}{2-b}w$, then the equilibrium production quantities and profits are:*

$$(1) \quad q_o^S = \frac{(2-b)m-2w}{4-b}, \quad q_c^S = \frac{m+w}{4-b};$$

$$(2) \quad \Pi_o^S = \frac{[(2-b)m-2w]^2}{(4-b)^2}, \quad \Pi_c^S = \frac{(m+w)^2}{(4-b)^2} + \frac{[(2-b)m-2w]\theta w}{4-b}.$$

For the OEM-as-leader game, if $m > \frac{2}{2-b}w$, then the equilibrium production quantities and profits are:

$$(1) \quad q_o^L = \frac{(2-b)m-2w}{2(2-b)}, \quad q_c^F = \frac{(2-b)m+2w}{4(2-b)};$$

$$(2) \quad \Pi_o^L = \frac{[(2-b)m-2w]^2}{8(2-b)}, \quad \Pi_c^F = \frac{[(2-b)m+2w]^2}{16(2-b)^2} + \frac{[(2-b)m-2w]\theta w}{2(2-b)}.$$

For the CM-as-leader game, if $m > \frac{4-b^2\theta-b}{4-3b}w$, then the equilibrium production quantities and profits are:

$$(1) \quad q_o^F = \frac{(4-3b)m-(4-b^2\theta-b)w}{4(2-b)}, \quad q_c^L = \frac{m+(1-b\theta)w}{2(2-b)};$$

$$(2) \quad \Pi_o^F = \frac{[(4-3b)m-(4-b^2\theta-b)w]^2}{16(2-b)^2}, \quad \Pi_c^L = \frac{[m+(1+b\theta)w][m+(1-b\theta)w]}{8(2-b)} + \frac{[(4-3b)m-(4-b^2\theta-b)w]\theta w}{4(2-b)}.$$

Therefore, if the market size is too small relative to the wholesale price, such that $m \leq \frac{2}{2-b}w$, then both the “simultaneous”-move and OEM-as-leader games are reduced to a monopoly setting with only the CM producing its monopolistic quantity and the OEM expelled from the market. A similar situation results if $m \leq \frac{4-b^2\theta-b}{4-3b}w$ under the CM-as-leader game. The explanation lies in the difference between the profit margins of the OEM and CM. By looking at their objective functions, (4.2) and (4.3), we can see that the OEM has to pay the CM a wholesale price w that is larger than the latter’s production cost; that is, the OEM has to bear a larger cost than the CM. Condition $m \leq \frac{2}{2-b}w$ in the “simultaneous”-move and OEM-as-leader games indicates that the wholesale price is so high that the market price does not even

cover the OEM's cost (the wholesale price paid to the CM). Condition $m \leq \frac{4-b^2\theta-b}{4-3b}w$ in the CM-as-leader game has a similar implication.

Proposition 22 provides several conclusions about the impact of the wholesale price on the equilibrium outcome. We can see that for both simultaneous and sequential games, a higher transfer wholesale price paid to the CM always results in a smaller production quantity and a smaller profit for the OEM. However, the wholesale price's impact on the CM depends on the production proportion that the OEM outsources to it. A high wholesale price can hurt the CM, as it reduces the order quantity from the OEM.

Proposition 22 also provides interesting conclusions concerning the impact of θ . In both the "simultaneous"-move and OEM-as-leader games, the equilibrium production quantities of the OEM and CM are independent of θ . By looking at the best response function of the CM, $q_c(q_o) = \frac{m-q_o}{2}$, we can see that it is independent of θ . This is because the market price for the CM's own-brand product is affected by the OEM's production quantity decision, not by its manufacturing outsourcing decision. Anticipating such independence, the OEM's decision is also independent of θ . However, in the CM-as-leader game, θ does affect the CM's production quantity decision because it affects the tradeoff between the CM's two streams of revenue: that generated from contracted manufacturing and that from self-manufacturing. Counterintuitively, the OEM's profit is increasing in θ . Therefore, to maximize its own profit, the OEM should outsource all of its production ($\theta = 1$) to the competitive CM. One argument is that the CM's profits come from two sources: contract manufacture and sales in the consumer market. When the CM is the quantity leader, by outsourcing more product manufacturing to that CM, the OEM reduces the CM's incentives to produce its own branded products and thus faces less competition from the CM in the consumer market.

4.4.2 Equilibrium of the extended timing game

Based on Proposition 22, we derive the conditions under which moving first and being the Stackelberg leader is beneficial for the OEM /CM by comparing their sequential payoffs over those of simultaneous ones.

The equilibrium outcome of the extended endogenous timing game depends on certain conditions. If $m < \min \left\{ \frac{2}{2-b}, \frac{4-b^2\theta-b}{4-3b} \right\} w$, then the OEM is always expelled from the market, and the CM is always the monopolist. If $\frac{4-b^2\theta-b}{4-3b}w < m < \frac{2}{2-b}w$, then the OEM is out of the market in the “simultaneous”-move and OEM-as-leader games; if $\frac{2}{2-b}w < m < \frac{4-b^2\theta-b}{4-3b}w$, then it is out of the market in the CM-as-leader game. We omit these three reduced cases here.

When $m > \max \left\{ \frac{4-b^2\theta-b}{4-3b}, \frac{2}{2-b} \right\} w$, both the OEM and the CM exist in the market in all three basic games. To characterize the equilibrium, we define

$$w_{AL} = \frac{16 - 10b + b^2}{8\theta(2-b)(4-b) - 16 + 6b}m, \text{ and } w_{AF} = \frac{1}{(4-b)\theta - 1}m.$$

Proposition 23. *Assume that $m > \max \left\{ \frac{4-b^2\theta-b}{4-3b}, \frac{2}{2-b} \right\} w$ or $w \leq \min \left\{ \frac{2-b}{2}, \frac{4-3b}{4-b^2\theta-b} \right\} m$.*

Comparing the three basic games in an asymmetric Cournot setting shows that at the quantity timing decision stage, the game can have the following possible outcomes.

- (1) *L is a dominant strategy if $\theta \in [0, \frac{1}{2-b})$ or $\theta \in [\frac{1}{2-b}, 1]$, but $w < w_{AL}$.*
- (2) *If $\theta \in [\frac{1}{2-b}, 1]$, then (L, F) is the unique pure NE for $w \in [w_{AL}, w_{AF})$, and (L, F) and (F, L) are the two NE for $w \in [w_{AF}, \frac{2-b}{2}m]$. w_{AL} and w_{AF} are decreasing in θ , and $w_{AL} \leq w_{AF}$ for $\theta \in [\frac{1}{2-b}, 1]$.*
- (3) *F cannot be the dominant strategy because $\Pi_o^L \geq \Pi_o^S$ and $\Pi_c^L \geq \Pi_c^S$.*

The results in Proposition 23 show that the outsourcing relationship between

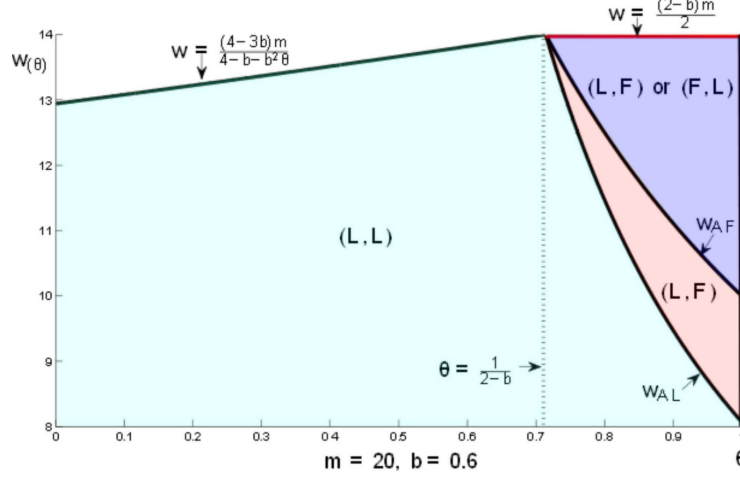


Figure 4.1: Impact of Wholesale Price on Quantity Timing Equilibrium

the OEM and the CM, the relative size of the wholesale price and the outsourcing proportion θ , all affect both parties' quantity leadership preference in the consumer market. Figure 4.1 illustrates the impact of the wholesale price on their Stackelberg leadership preference. More specifically, when θ , the proportion outsourced to the CM, is low ($< \frac{1}{2-b}$), no matter how high the wholesale price is, the CM will be aggressive in the consumer market and choose Stackelberg leadership. Even when θ is high, the CM will still choose Stackelberg leadership if the wholesale price offered by the OEM is low ($< w_{AL}$). Only when θ is large ($> \frac{1}{2-b}$) and the wholesale price is moderate ($w \in (w_{AL}, w_{AF})$) will the CM definitely take the follower position. Interestingly, when the outsourcing percentage θ is large ($> \frac{1}{2-b}$) and the wholesale price is high ($> w_{AF}$), (F, L) can also be the NE in the quantity timing game, and the OEM faces the possibility of losing its Stackelberg leadership. The reason is that when w is very high, the OEM's profit margin is too small. In such a scenario, the OEM's payoff as the follower is higher than that when it is in the "simultaneous"-move game. Knowing this to be the case, the CM is motivated to take the leadership position. What is more, w_{AL} is decreasing in θ , which implies that when the OEM

outsources a large proportion of its product manufacturing to the CM, the latter is willing to play the quantity followership role even if the wholesale price it is offered is not high.

Let $k = \frac{(2-b)m}{w}$, where $k > 2$. Define

$$\theta_{AL} = \frac{k(8-b) + 16 - 6b}{8(2-b)(4-b)}, \text{ and } \theta_{AF} = \frac{k + (2-b)}{(2-b)(4-b)}.$$

We now fix k and obtain the following corollary on the equilibrium strategy for different ranges of θ .

Corollary 7. Assume that $\frac{1}{2-b} \leq \theta \leq 1$.

- (1) L is a dominant strategy if $\theta \in [\frac{1}{2-b}, \theta_{AL})$.
- (2) (L, F) is a NE if $\theta \in [\theta_{AL}, \theta_{AF})$.
- (3) (L, F) and (F, L) are two NE if $\theta \in [\theta_{AF}, 1]$.
- (4) $\theta_{AF} > \theta_{AL}$; θ_{AL} , θ_{AF} and $\theta_{AF} - \theta_{AL}$ are all increasing in b .

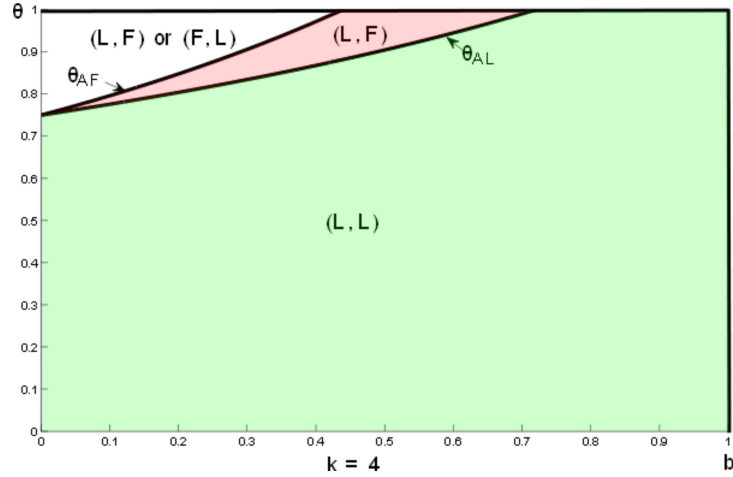


Figure 4.2: Impact of Outsourcing on Quantity Timing Equilibrium

Figure 4.2 illustrates how the OEM's outsourcing decision and the substitutability of the CM's product over that of the OEM affect the quantity timing equilibrium outcome. For any given substitution rate b , when the amount outsourced to the CM is relatively high, $\theta \in (\theta_{AL}, \theta_{AF})$, the CM will surely assume the Stackelberg followership position. Otherwise, it is motivated to take the leadership position. The figure also shows that when substitution rate b increases, both θ_{AL} and θ_{AF} are increasing. It therefore becomes more difficult to retain the CM as the follower as the degree of homogeneity between the two parties' products increases, and, consequently, it becomes easier for a "simultaneous"-move game to appear.

4.4.3 Impact of the CM product substitutability

Note that a larger b implies a higher degree of homogeneity between the OEM's and the CM's products. As the competitive CM enhances such abilities as learning, design, production and quality control, its product's substitutability b increases and may even reach 1. The following proposition summarizes the impact of b on the outcomes of the three basic games.

Proposition 24. *For the three basic games:*

(1) q_o^S , q_o^L and q_o^F are decreasing in b , and q_c^S , q_c^F and q_c^L are increasing in b .

(2) Π_o^S , Π_o^L and Π_o^F are decreasing in b .

(3) Π_c^S , Π_c^F and Π_c^L are increasing in b if $\theta \in [0, \frac{1}{2-b}]$. If $\theta \in (\frac{1}{2-b}, 1]$, then

(i) Π_c^S is decreasing in b for $m \in [\frac{2}{2-b}w, ((4-b)\theta - 1)w]$; otherwise, Π_c^S is increasing in b ;

(ii) Π_c^F is decreasing in b for $m \in [\frac{2}{2-b}w, \frac{4(2-b)\theta - 2}{2-b}w]$; otherwise, Π_c^F is increasing in b ; and

(iii) Π_c^L is decreasing in b for $m \in [\frac{4-b^2\theta-b}{4-3b}w, ((4-b)\theta-1)w]$; otherwise, Π_c^L is increasing in b .

Proposition 24 shows that in the three basic games, the OEM's equilibrium production quantities are higher if the CM's product has a lower degree of substitutability, whereas the situation is the reverse for the CM. In other words, if the OEM's/CM's products are favored over those of the CM/OEM, the OEM/CM will produce more. Moreover, the OEM always obtains a higher profit when the CM has a lower degree of product substitutability. Therefore, it is beneficial for OEMs to make large investments in R&D and product quality improvement. Interestingly, we find that if the market is not very large in size but the proportion outsourced to the competitive CM is high, the CM is also better off with a lower substitution rate b . Hence, a less-substitutable CM product is always preferred by the OEM and sometimes preferred by its competitive CM.

Moreover, when $b = 0$, that is, the competitive CM's products are not substitutes for those of the OEM, both parties are indifferent among the three basic games (according to Proposition 22); when $b = 1$, both the OEM and the competitive CM prefer leadership, and the "simultaneous"-move game is played (see Corollary 7).

4.5 Outsourcing with Endogenized Wholesale Price Determined by the CM

In the previous section, we assume that the wholesale price w and the outsourcing decision θ are exogenously given. Here, we consider a price-only contract in which the CM decides the wholesale price w and the OEM makes the optimal decision about θ . A similar assumption can be found in other operations management and marketing research studies, including those of Lariviere and Porteus (2001) and Cui et al. (2008). It is also consistent with current industry practices. Such CMs as Asustek, Quanta

and Foxconn usually offer price quotes to their OEMs, such as Apple, Dell and Sony. The OEMs then decide whether and what kind of contract to sign. For simplicity, we assume that the other non-competitive CMs charge a wholesale price p_0 and that $p_0 \geq w$; otherwise, the OEM would have no incentives to source from the competitive CM. The profit functions of the OEM and the competitive CM are, respectively,

$$\Pi_o = (m - q_o - bq_c)q_o - \theta wq_o - (1 - \theta)p_0q_o, \quad (4.4)$$

$$\Pi_c = (m - q_c - q_o)q_c + \theta wq_o. \quad (4.5)$$

It is possible that the competitive CM decides the wholesale price w first, followed by the OEM's outsourcing decision θ (named *Decision order 1*); alternatively, the OEM decides the outsourcing proportion first, followed by the CM's decision on w (named *Decision order 2*). Despite the difference in sequence, the main results are the same. Hence, we list only the decision order 1 results and relegate decision order 2 results to the online Appendix B. We use superscript $*$ to denote the optimal results when w and θ are endogenous.

4.5.1 “simultaneous”-move game

The game sequence in the “simultaneous”-move game is defined as follows and illustrated in Figure 4.3. The CM first decides the wholesale price w . The OEM then makes its outsourcing decision θ . Finally, the CM and the OEM decide their production quantities simultaneously. We solve the game backwards and obtain the following proposition.

Proposition 25. *For the “simultaneous”-move game:*

$$(1) \ w^{S*} = \min \{p_0, w^S\}, \text{ where } w^S = \frac{10-6b+b^2}{14-4b}m; \ \theta^* = 1.$$

$$(2) \ \text{If } p_0 > w^S, \text{ then } \Pi_o^{S*} = \frac{(1-b)^2}{(7-2b)^2}m^2, \ \Pi_c^{S*} = \frac{8-4b+b^2}{4(7-2b)}m^2; \text{ otherwise, } \Pi_o^{S*} =$$

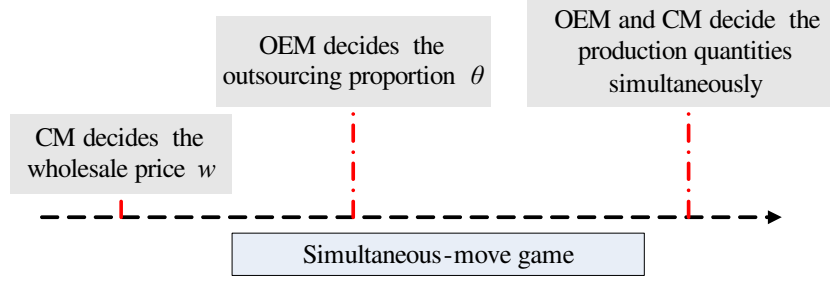


Figure 4.3: Game Sequence for “simultaneous”-move Game

$$\frac{[(2-b)m-2p_0]^2}{(4-b)^2}, \quad \Pi_c^{S*} = \frac{(m+p_0)^2}{(4-b)^2} + \frac{[(2-b)m-2p_0]p_0}{4-b}.$$

As Proposition 25 shows, the OEM will prefer to source its entire production from the competitive CM as long as $p_0 \geq w^{S*}$. Will the competitive CM then have the incentive to produce nothing for the OEM and thus expel it from the market? Note that a monopolist CM needs to charge a wholesale price of $w = \frac{2-b}{2}m$ and that its monopolist profit (denoted as Π_c^m) is $\Pi_c^m = \frac{m^2}{4}$. We then have the following corollary.

Corollary 8. $\Pi_c^{S*} \geq \Pi_c^m$ for $p_0 \geq \frac{6-b}{14-4b}m$.

The wholesale price offered by non-competitive CMs, p_0 , is often the result of a price war among them. Corollary 8 shows that when p_0 is higher than a threshold value, the CM has no incentive to charge a wholesale price sufficiently high to expel the OEM from the market. This result is rather surprising. A mixture model, that is selling its own products in the low-end market and carrying out contract manufacturing for the OEM in the high-end market, allows the CM to enjoy a higher profit than a pure model in which the CM acts as a monopolist and provides only low-end products in the consumer market. If the wholesale price war leads to $p_0 \leq \frac{6-b}{14-4b}m$, then the competitive CM cannot be a monopolist even if it wants to, as the OEM will source from other non-competitive CMs.

4.5.2 OEM-as-leader game

Recall that the leader here refers to the quantity leader, not the price leader. In the OEM-as-leader game, the game sequence is as follows. First, the CM decides its wholesale price; then the OEM jointly decides its production quantity and the fraction of production to source from the competitive CM; and last, the CM decides the production quantity for its own-brand products (see Figure 4.4). We again solve

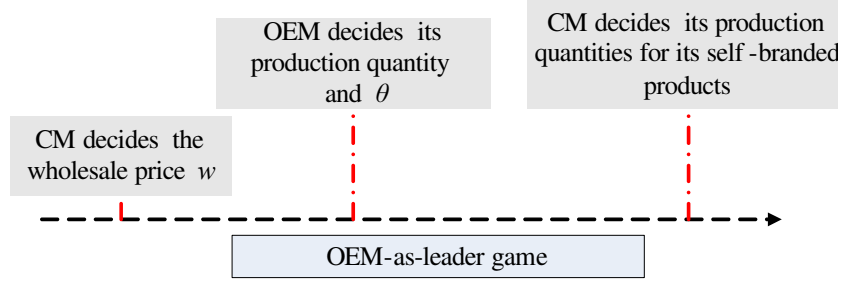


Figure 4.4: Game Sequence for OEM-as-leader Game

the game by backward induction, and obtain Proposition 26.

Proposition 26. *For the OEM-as-leader game:*

- (1) $w^{F*} = \min\{p_0, w^F\}$, where $w^F = \frac{(2-b)(5-2b)}{14-8b}m$; $\theta^* = 1$.
- (2) If $p_0 > w^F$, then $\Pi_o^{L*} = \frac{(2-b)(1-b)^2}{2(7-4b)^2}m^2$, $\Pi_c^{F*} = \frac{(2-b)(4-b)}{4(7-4b)}m^2$; otherwise, $\Pi_o^{L*} = \frac{[(2-b)m-2p_0]^2}{8(2-b)}$, $\Pi_c^{F*} = \frac{[(2-b)m+2p_0]^2}{16(2-b)^2} + \frac{[(2-b)m-2p_0]p_0}{2(2-b)}$.

Similarly, we compare the competitive CM's optimal profit with its monopolist profit, and obtain the following corollary.

Corollary 9. $\Pi_c^{F*} \geq \Pi_c^m$ for $p_0 \geq \frac{3(2-b)}{14-8b}m$.

Again, the competitive CM is better off by keeping the OEM in the consumer market. The analysis is similar to that in the “simultaneous”-move game.

4.5.3 CM-as-leader game

The game sequence for the CM-as-leader game is depicted in Figure 4.5. First, the CM decides its wholesale price and the production quantity for its own branded products. Second, the OEM decides its production quantity and the fraction to outsource from the competitive CM. We solve the game backwards, and obtain Proposition 27.

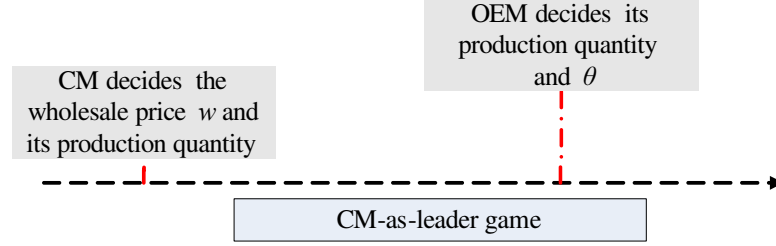


Figure 4.5: Game Sequence for CM-as-leader Game

Proposition 27. *For the CM-as-leader game:*

(1) $w^{L*} = \min\{p_0, w^L\}$ where $w^L = \frac{5-3b}{7-2b-b^2}m$, $\theta^* = 1$.

(2) If $p_0 > w^L$, then $\Pi_o^{F*} = \frac{(1-b)^2}{(7-2b-b^2)^2}m^2$, $\Pi_c^{L*} = \frac{(2-b)}{7-2b-b^2}m^2$; otherwise, $\Pi_o^{F*} =$

$$\frac{[(4-3b)m-(4-b-b^2)p_0]^2}{16(2-b)^2},$$

$$\Pi_c^{L*} = \frac{[m+(1+b)p_0][m+(1-b)p_0]}{8(2-b)} + \frac{[(4-3b)m-(4-b-b^2)p_0]p_0}{4(2-b)}.$$

Again we compare the competitive CM's optimal profit with its monopolist profit, and have the following corollary.

Corollary 10. $\Pi_c^{L*} \geq \Pi_c^m$ for $p_0 \geq \frac{(5-3b)-(1-b)\sqrt{2(2-b)}}{7-2b-b^2}m$.

Here the CM still prefers to charge a low wholesale price and earn some contract manufacturing revenue if p_0 is relatively high.

Based on the foregoing analyses, we have the following proposition.

Proposition 28. *For the three basic games:*

- (1) *The optimal wholesale price charged by the competitive CM is always the one that keeps both the OEM and itself in the consumer market.*
- (2) *If the competitive CM offers a wholesale price no higher than that of other non-competitive CMs ($w \leq p_0$), then the OEM will outsource its entire production to this CM (i.e., $\theta^* = 1$).*

Considering that it is very common for an OEM to target the high-end market while its CM targets the low-end market, Proposition 28 is very insightful for contract manufacturing practice. On the one hand, the OEM need not worry about being expelled from the consumer market by a competitive CM, as it is in the latter's best interest to keep the OEM in the market and earn revenue from selling its own-brand products and engaging in contract manufacturing. For example, Asustek believes that "the capability to create innovative technology (for its self-branded business) and maintain manufacturing strength is crucial for IT players as they try to out-flank their competitors in fast-changing times" (Chung 2004). On the other hand, the proposition states that the OEM should outsource all of its production to its CM competitor, which is counterintuitive. One possible explanation is that if the OEM chooses to outsource to other non-competitive CMs, the resulting lost profit will force the competitive CM to be more aggressive in producing and selling its own branded products which harms the OEM in the consumer market. Also the competitive CM has accumulated many special expertise, such as the trained workers, the advanced production technology and the quality control system. From the viewpoint of the transaction cost economics (Williamson 1985), these can be considered as transaction costs which hinder the switch to non-competitive CMs for the OEM. In the industrial practice, we observe that the competitive CM, Asustek snatched back an

Apple production order for the 14-inch wide screen iBook by charging a wholesale price lower than that of non-competitive CM, Quanta (Lin 2005).

4.5.4 Equilibrium of the extended timing game

To facilitate the derivation of the equilibrium of the extended timing game, we first state the following Lemma.

Lemma 6. $w_{AL} \leq w_{AF} \leq w^F \leq w^S \leq w^L$.

Consequently, the competitive CM's optimal wholesale prices in the three basic games have the following relationship: $w^{F*} \leq w^{S*} \leq w^{L*}$. In other words, the competitive CM charges the highest wholesale price in the CM-as-leader game and lowest in the OEM-as-leader games. Moreover, $w^F \leq w^{F*} \leq w^{S*} \leq w^{L*}$ if $p_0 \geq w^F$, whereas $w^{F*} = w^{S*} = w^{L*} = p_0 \leq w^F$ if $p_0 < w^F$. Recall that in all of the basic games, $\theta^* = 1$. Based on Proposition 23, we have the following proposition.

Proposition 29. *L is a dominant strategy if $p_0 < w_{AL}$; (L, F) is the unique pure NE if $p_0 \in [w_{AL}, w_{AF}]$; and (L, F) and (F, L) are the two NE if $p_0 > w_{AF}$.*

Proposition 29 shows that p_0 , the wholesale price of the non-competitive CMs, significantly influences the competitive CM's endogenized wholesale price decision, and thus the outcome of the quantity timing game; see Figure 4.6. If p_0 is very low, then the “simultaneous”-move game is preferable; if p_0 is moderate, then the OEM-as-leader game is preferable; and if p_0 is large, then the OEM-as-leader and CM-as-leader games are equally preferable.

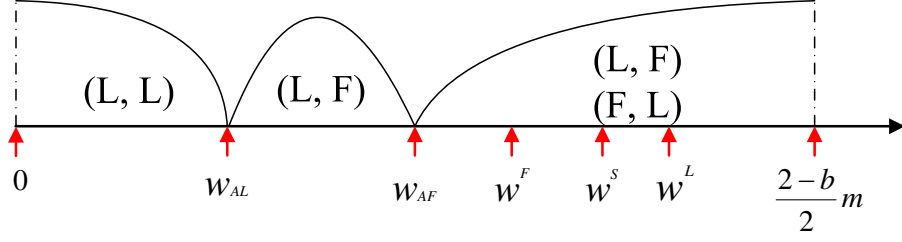


Figure 4.6: Impact of p_0 on Quantity Timing Equilibrium

4.6 Outsourcing with Endogenized Wholesale Price via Nash Bargaining

In §5, we assumed that the CM determines the outsourcing wholesale price. In practice, the wholesale price can also be conducted through negotiation (Feng and Lu 2009). In that case, both the OEM and the CM have their respective bargaining powers, which enable them to influence the outcome of the negotiated wholesale price. In this section, we consider such scenario and discuss the preference of the OEM/CM over the quantity leadership.

4.6.1 Generalized Nash bargaining scheme

One common methodology to study price negotiation is the generalized Nash bargaining (GNB) scheme, which was first proposed by Nash (1950) and later extended by Roth (1979). Recently some operations management scholars have adopted GNB scheme to study endogenized pricing issue, see Nagarajan and Bassok (2008), Nagarajan and Sosic (2008), Feng and Lu (2009), İşlegen and Plambeck (2009).

Specifically, in our work, the GNB scheme is defined to solve the following opti-

mization problem:

$$\begin{aligned} \text{Max}_w \quad & \Omega = (\Pi_c)^\alpha (\Pi_o)^{1-\alpha} \\ \text{s.t.} \quad & 0 \leq w \leq \min \left\{ p_0, \left(\frac{2-b}{2}m \text{ or } \frac{4-3b}{4-b-b^2}m \right) \right\}, \end{aligned} \quad (4.6)$$

$$\Pi_c \geq \Pi_c^r, \quad (4.7)$$

where Ω is the *Nash product* and Π_i is party i 's corresponding profit, $i = o, c$. α ($\alpha \in [0, 1]$) and $1 - \alpha$ correspond to the competitive CM's and the OEM's bargaining powers, respectively. The value $\alpha = 1/2$ stands for the equal bargaining power case, whereas the extreme values $\alpha = 0$ and $\alpha = 1$ reduce the two-player bargaining setting to one player setting. Both the OEM and the competitive CM are rational and risk neutral. Their bargaining powers are exogenously given. Condition(4.6) is the participation constraint for the OEM. First, w shall not be larger than p_0 , otherwise the OEM will have no incentives to source from this competitive CM. Second, we assume $w \leq \left(\frac{2-b}{2}m \text{ or } \frac{4-3b}{4-b-b^2}m \right)$ (it depends on which basic game to be played) so that both the OEM and the competitive CM can coexist in the market. Condition (4.7) is the participation constraint for the competitive CM, where Π_c^r is its reserved profit if not participating in the negotiation.

We denote the GNB-characterized wholesale price under three basic games as w^{Nj} , $j = S, F, L$, where superscript j stands for the CM's quantity leadership position in the basic game.

4.6.2 GNB-characterized wholesale price under three basic games

Here, the game sequence remains the same as that in the previous §4.5 except that in the first stage, instead of the CM deciding the wholesale price w , the competitive

CM and the OEM will negotiate the wholesale price w cooperatively. We also solve this game by backward induction. Moreover, as argued in §4.5, $\theta^* = 1$ as long as the GNB-characterized wholesale price $w^{Nj} \leq p_0$, $j = S, F, L$.

“simultaneous”-move game

For the “simultaneous”-move game, when $\theta^* = 1$, the CM’s and the OEM’s profit functions are respectively

$$\Pi_c^S(w) = \frac{(m+w)^2}{(4-b)^2} + \frac{[(2-b)m-2w]w}{4-b}, \quad \Pi_o^S(w) = \frac{[(2-b)m-2w]^2}{(4-b)^2}.$$

And the corresponding Nash product becomes

$$\text{Max}_w \quad \Omega^S = (\Pi_c^S(w))^\alpha (\Pi_o^S(w))^{1-\alpha} \quad (4.8)$$

$$s.t. \quad 0 \leq w \leq \min \left\{ p_0, \frac{2-b}{2}m \right\},$$

$$\Pi_c^S(w) \geq \Pi_c^{RS}, \quad (4.9)$$

where Π_c^{RS} is the reserved profit for the CM if not participating in the negotiation and giving up the contract manufacturing business. It can be shown that $\Pi_c^{RS} = (m+p_0)^2/(4-b)^2$.

Next, to characterize the GNB-induced wholesale price, we define

$$K^S = \frac{2(10-6b+b^2) + (1-b)(4-b)\alpha - (4-b)\sqrt{(1-b)^2\alpha^2 + 4(8-4b+b^2)(1-\alpha)}}{4(7-2b)}m;$$

$$\underline{w}^S = \frac{(10-6b+b^2)m - \sqrt{(10-6b+b^2)^2m^2 - 4(7-2b)(p_0^2 + 2p_0m)}}{2(7-2b)}.$$

Solving the above constrained optimization problem, we then have the following proposition on the negotiated wholesale price.

Proposition 30. *For the “simultaneous”-move game, the Nash product Ω^S is unimodal in w , and the GNB-characterized wholesale price is*

1. $w^{NS} = \min(p_0, \max(\underline{w}^S, K^S))$.
2. K^S is increasing in α and $K^S = w^S$ if $\alpha = 1$, where w^S is the CM determined wholesale price under the “simultaneous”-move game in §4.5.1.

In Proposition 30, K^S is the optimal solution of the unconstrained objective function (4.8). And \underline{w}^S is the wholesale price that leads to the CM’s participation constraint (4.9) binding. It provides a lower bound on the negotiated wholesale price. And p_0 , the wholesale price offered by the non-competitive CM, provides an upper bound for the negotiated wholesale price. Part 2 of Proposition 30 shows that the GNB-characterized wholesale price increases in the competitive CM’s bargaining power α while decreases in that of the OEM. Moreover, it shows that when the “simultaneous”-move game is played, the GNB-characterized wholesale price w^{NS} is less than the CM-determined wholesale price w^S in §4.5.1 (it becomes equal when $\alpha = 1$, provided that p_0 is high enough).

OEM-as-leader game

For the OEM-as-leader game, when $\theta^* = 1$, the CM’s and the OEM’s profit functions are respectively

$$\Pi_c^F(w) = \frac{[(2-b)m + 2w]^2}{16(2-b)^2} + \frac{[(2-b)m - 2w]w}{2(2-b)}; \quad \Pi_o^L(w) = \frac{[(2-b)m - 2w]^2}{8(2-b)}.$$

And the corresponding Nash product becomes

$$\text{Max}_w \quad \Omega^F = (\Pi_c^F(w))^\alpha (\Pi_o^L(w))^{1-\alpha} \quad (4.10)$$

$$s.t. \quad 0 \leq w \leq \min \left\{ p_0, \frac{2-b}{2}m \right\},$$

$$\Pi_c^F(w) \geq \Pi_c^{RF}, \quad (4.11)$$

where Π_c^{RF} is the CM's reserved profit if not participating in the negotiation. It can be shown that $\Pi_c^{RF} = \frac{[(2-b)m+2p_0]^2}{16(2-b)^2}$.

Similarly, define

$$K^F = \frac{(2-b)(5-2b) + (2-b)(1-b)\alpha - (2-b)\sqrt{(1-b)^2\alpha^2 + 4(2-b)(4-b)(1-\alpha)}}{2(7-4b)}m;$$

$$\underline{w}^F = \frac{(2-b)(5-2b)m - \sqrt{(2-b)^2(5-2b)^2m^2 - 4(7-4b)(p_0^2 + (2-b)p_0m)}}{2(7-4b)}.$$

Optimizing the above Nash product leads to the following proposition.

Proposition 31. *For the OEM-as-leader game, the Nash product Ω^F is unimodal in w , and the GNB-characterized wholesale price is*

1. $w^{NF} = \min(p_0, \max(\underline{w}^F, K^F))$.
2. K^F is increasing in α and $K^F = w^F$ if $\alpha = 1$, where $w^F = \frac{(2-b)(5-2b)}{2(7-4b)}m$ is the CM determined wholesale price under the OEM-as-leader game in §4.5.2.

In Proposition 31, K^F is the optimal solution of the unconstrained objective function (4.10). And \underline{w}^F is the wholesale price that leads to the CM's participation constraint (4.11) binding and it also provides a lower bound for the negotiated wholesale price. Similar to those under the “simultaneous”-move game in §4.6.2.1, Proposition 31 shows that the GNB-characterized wholesale price increases in the

competitive CM's bargaining power, α while decreases in that of the OEM, $1 - \alpha$. Moreover, Proposition 31 also shows that if $\alpha < 1$, the involvement of the OEM in the price negotiation leads to a lower wholesale price than that determined by the competitive CM itself.

CM-as-leader game

For the CM-as-leader game, when $\theta^* = 1$, the CM's and the OEM's profit functions are respectively

$$\begin{aligned}\Pi_c^L(w) &= \frac{[(m + (1 + b)w)][m + (1 - b)w]}{8(2 - b)} + \frac{[(4 - 3b)m - (4 - b - b^2)w]w}{4(2 - b)}; \\ \Pi_o^F(w) &= \frac{[(4 - 3b)m - (4 - b - b^2)w]^2}{16(2 - b)^2}.\end{aligned}$$

And the corresponding Nash product becomes

$$\text{Max}_w \quad \Omega^L = (\Pi_c^L(w))^\alpha (\Pi_o^F(w))^{1-\alpha} \quad (4.12)$$

$$s.t. \quad 0 \leq w \leq \min \left\{ p_0, \frac{4 - 3b}{4 - b - b^2} m \right\},$$

$$\Pi_c^L(w) \geq \Pi_c^{RL}, \quad (4.13)$$

where Π_c^{RL} is the CM's reserved profit if not participating in the negotiation. It can be shown that $\Pi_c^{RL} = \frac{(m+p_0)^2}{8(2-b)}$.

Define

$$\begin{aligned}K^L &= \frac{(5 - 3b)(4 - b - b^2) + 2(1 - b)(2 - b)\alpha - 2(2 - b)\sqrt{(1 - b)^2\alpha^2 + 2(16 - 8b - 7b^2 + 2b^3 + b^4)(1 - \alpha)}}{(4 - b - b^2)(7 - 2b - b^2)}m; \\ \underline{w}^L &= \frac{(5 - 3b)m - \sqrt{(5 - 3b)^2m^2 - (7 - 2b - b^2)(p_0^2 + 2p_0m)}}{7 - 2b - b^2}.\end{aligned}$$

Optimizing the above Nash product leads to the following proposition.

Proposition 32. *For the CM-as-leader game, the Nash product Ω^L is unimodal in w , and the GNB-characterized wholesale price is*

1. $w^{NL} = \min(p_0, \max(\underline{w}^L, K^L))$.
2. K^L is increasing in α and $K^L = w^L$ if $\alpha = 1$, where $w^L = \frac{5-3b}{7-2b-b^2}m$ is the CM determined wholesale price under the CM-as-leader game in §4.5.3.

In Proposition 32, K^L is the optimal solution of the unconstrained objective function (4.12) and it is increasing in α . And \underline{w}^L is the wholesale price that leads to the CM's participation constraint (4.13) binding and it provides a lower bound on the negotiated wholesale price. Moreover, the GNB-characterized wholesale price w^{NL} is also smaller than the CM-determined price w^L in §4.5.3 if $\alpha < 1$.

4.6.3 Equilibrium of the extended timing game

Analogous to the discussion in §4.5.4, the equilibrium outcome of the quantity timing game depends on the value of the negotiated wholesale prices under the three basic games — w^{NS} , w^{NF} and w^{NL} — and the wholesale price charged by the non-competitive CM, p_0 . Since w^{NS} , w^{NF} and w^{NL} are all increasing in α , we shall examine the impact of α and p_0 on the equilibrium of our quantity timing game.

$\alpha = 0$

We first consider the special case where $\alpha = 0$. The special case with $\alpha = 0$ is equivalent to the OEM-determine-wholesale-price setting. As the OEM's profit under the three basic games — $\Pi_o^S(w)$, $\Pi_o^L(w)$ and $\Pi_o^F(w)$ — are all *decreasing* in the wholesale price, the OEM will offer the CM a wholesale price as low as possible. According to Propositions 30, 31 and 32, there exists a lower bound on the wholesale price for the competitive CM to participate into the contract manufacturing business. We shall

assume that p_0 is higher than those lower bound of wholesale prices. Therefore, the OEM shall offer the CM the lower bound of the wholesale price. We thus have the following proposition.

Proposition 33. *If the OEM determines the wholesale price, the competitive CM always prefers leadership.*

According to Proposition 33, we only need to compare $\Pi_o^F(\underline{w}^L)$ and $\Pi_o^S(\underline{w}^S)$ to determine whether (L, L) or (F, L) is the equilibrium. When $b = 0$, it can be shown that $\Pi_o^F(\underline{w}^L) = \Pi_o^S(\underline{w}^S)$. For the case of $b > 0$, we conduct an extensive numerical study and find that it always holds that $\Pi_o^F(\underline{w}^L) < \Pi_o^S(\underline{w}^S)$; see Figure 4.7 for the illustration. Thus, the OEM also prefers leadership and (L, L) is the unique equilibrium for the extended timing game when the OEM determines the wholesale price.

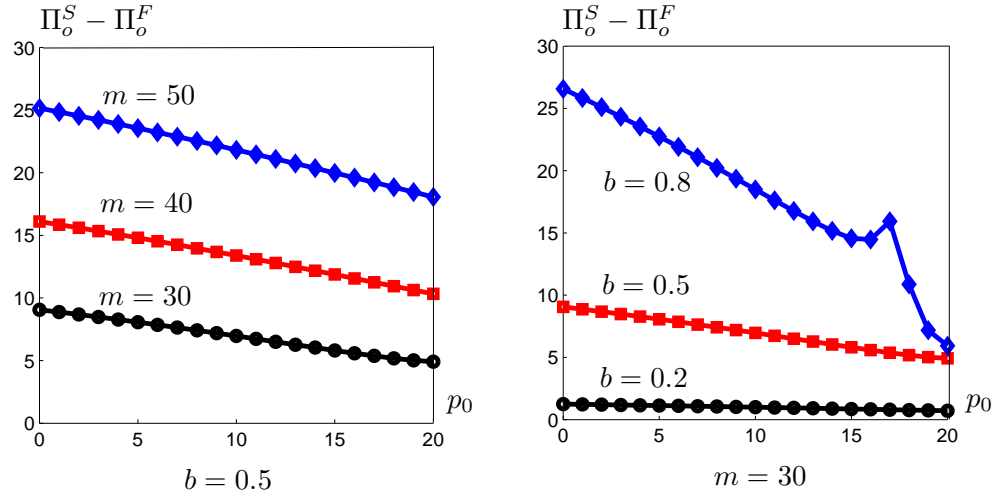


Figure 4.7: Comparison between Π_o^S and Π_o^F if $\alpha = 0$

This conclusion is quite paradoxical: A weak CM actually behaves aggressively

in the end-product market. Here is the explanation: The wholesale price determined by the OEM is very low and therefore, the revenue generated from contract manufacturing business becomes tiny, which spurs the competitive CM to become aggressive in the end-product consumer market.

$$\alpha > 0$$

In this subsection we consider the general case where the CM's negotiation power, $\alpha > 0$. An extensive numerical study is conducted in which we first fix α and vary p_0 , and then fix p_0 and vary α . See Table 4.2 for the list of parameters used in our numerical study.

Table 4.2: Parameters

| varying p_0 case | varying α case |
|----------------------------------|-------------------------------------|
| $\alpha = 0.2, 1$ | $p_0 = 1, 20$ |
| $m = 30, b = 0.5$ | $m = 30, b = 0.5$ |
| $p_0 = 0 : 20$ (steplength: 0.5) | $\alpha = 0 : 1$ (steplength: 0.05) |

Across various parameter settings, we observe several patterns and illustrate them in Figures 4.8 and 4.9. In each figure, the payoff differences among the three basic games for each player are depicted, which allows us to carry out the equilibrium analysis.

Figure 4.8 shows the impact of p_0 on the OEM's and the CM's quantity leadership preference. When α is small, such as $\alpha = 0.2$, (L, L) is the unique equilibrium for the extended timing game. Again, the limited revenue from the contract manufacturing forces the competitive CM to become aggressive in the end market. However, as α increases, we observe many different equilibria. In particular, when $\alpha = 1$, the equilibrium outcomes are exactly the same as those in Proposition 29, that is, when p_0 is small, (L, L) is the equilibrium; when p_0 is moderate, (L, F) is the equilibrium

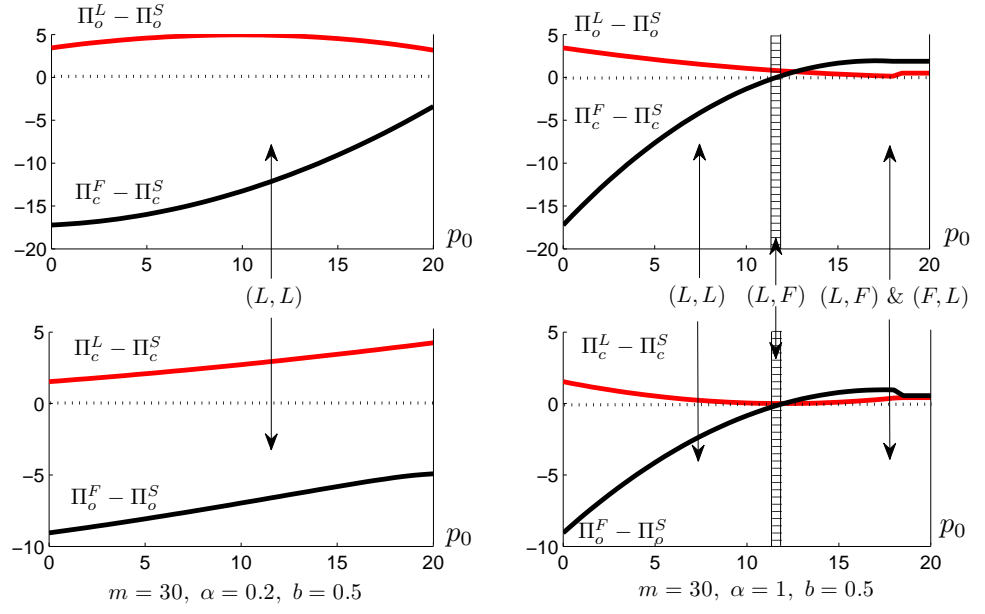


Figure 4.8: Impact of p_0 on the Equilibrium of the Quantity Timing Game

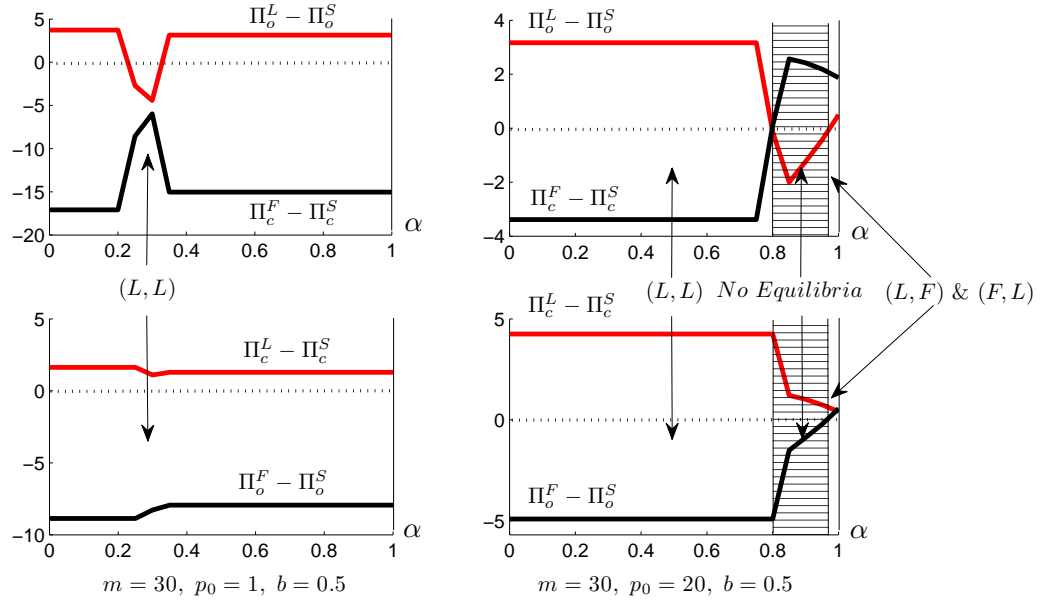


Figure 4.9: Impact of the CM's bargaining power α on the Equilibrium of the Quantity Timing Game

as demonstrated in the shaded area of Figure 4.8; when p_0 is large, two equilibria (L, F) and (F, L) coexist.

Figure 4.9 shows the results for a given p_0 . When $p_0 = 1$, (L, L) is always the equilibrium no matter how large α is. This again can be explained from the CM's revenue: Although the CM's bargaining power is large here, a low outside option for the OEM, p_0 , still allows the OEM to offer a low wholesale price to the CM, which forces the CM to be the market leader. When $p_0 = 20$, the equilibrium outcome depends on α . If α is less than 0.8, the equilibrium is (L, L). An interesting observation arises when α is larger than 0.8 but less than 0.95 (the shaded area in the figure). In this case, the OEM prefers a “simultaneous”-move game while the competitive CM prefers a sequential-move game, which implies that no pure-strategy equilibrium exists. To explain this phenomena, let us take a close look at the negotiated wholesale prices as shown in Table 4.3. The bolded numbers show that the wholesale price under the “simultaneous”-move game is the lowest for $0.8 \leq p_0 \leq 0.95$. This low wholesale price reduces the OEM's incentives to be the market leader.

Table 4.3: Impact of Bargaining Power on Negotiated Wholesale Prices

| p_0 | α | w^{NS} | w^{NF} | w^{NL} |
|-------|-------------|--------------|--------------|--------------|
| 20 | 0.75 | 10.26 | 10.00 | 10.83 |
| 20 | 0.80 | 10.26 | 10.40 | 10.83 |
| 20 | 0.85 | 11.31 | 11.70 | 11.49 |
| 20 | 0.90 | 12.90 | 13.20 | 13.10 |
| 20 | 0.95 | 14.89 | 15.06 | 15.10 |
| 20 | 1.00 | 18.13 | 18.00 | 18.26 |

We also observe that when both α and p_0 are large, the two equilibria (L, F) and (F, L) coexist. Complementary to the conclusion under $\alpha = 0$ in §4.6.3.1, our numerical studies here show that the OEM and the CM tend to “collaborate” in terms of adopting sequential move when the CM's bargaining power is large and the OEM has no favorable outside option (a high p_0).

4.7 Conclusion

In this chapter, we considered a CM that is both an upstream partner and a downstream competitor of the OEM and explored the advantages of quantity leadership in the consumer market by analyzing an asymmetric Cournot model. We showed that both parties can prefer either Stackelberg leadership or followership depending on the circumstances. Whether the OEM and the CM play a “simultaneous”-move, OEM-as-leader or CM-as-leader game depends on the market size, the wholesale price, the outsourcing percentage and the degree of substitutability between their products. Most importantly, we showed that a high proportion of products outsourced to a competitive CM at a moderate-range wholesale price can effectively reduce the CM’s incentives to become the Stackelberg leader. If this outsourcing proportion is small or the wholesale price is lower than a threshold value, then both the OEM and the CM will prefer Stackelberg leadership.

We also showed that the OEM’s production quantities and profits decrease when the degree of substitutability of the competitive CM’s product is higher, whereas the competitive CM’s production quantities increase when this is the case. Interestingly, we showed that if the proportion outsourced from the OEM to the competitive CM is high but the market size is small, then the latter’s profit actually decreases with greater product substitutability.

We then discussed the OEM’s optimal outsourcing decisions and the CM’s optimal wholesale pricing decisions in the three basic games by assuming the CM is the Stackelberg price leader in deciding the wholesale price and found that the CM will set a low wholesale price to allow the OEM and itself coexist in the market. Furthermore, the OEM will outsource all of its manufacturing to this competitive CM.

Last, we considered the scenario where the wholesale price is determined through Nash bargaining. We showed that the two parties tend to collaborate by adopting

sequential move when the CM's bargaining power is large and the non-competitive CM's wholesale price is high enough. Otherwise, the CM becomes aggressive in the end market and the "simultaneous"-move game is likely to be played.

Admittedly, outsourcing activities are very complex in practice. Deciding which functions to outsource and which type of CM to choose involves the consideration of multiple factors, such as IP leakage, potential competition from the CM, the product cost structure, tax issue, the lead time for new product development and inventory liabilities. The study presented here focuses on the issue of competition between the OEM and the CM. It would be interesting to consider a richer model with other factors included.

Chapter 5

Summary and Future Research

In this dissertation, we conducted detailed analysis in three essays on contract manufacturing. For the first essay, we focus on the outsourcing structure selection under three risk allocation contracts: Push, pull and TWP. We obtain the analytical conditions in which the OEM prefers delegation. There are several possible extensions for this topic. First, for simplicity, we have assumed the same wholesale prices to the supplier under both control and delegation outsourcing structures. However, in practice the supplier may charge different wholesale prices to the OEM (under control) and the CM (under delegation). Second, we have assumed that the CM and the supplier make their capacity decisions simultaneously. An interesting future question is to consider different decision sequences and to study whether the results will be changed.

For the second topic, we considered a GNB scheme and its impact on the quantity commitment, capacity decisions and the supply chain coordination. We also analyzed the OEM's selection on outsourcing structure and the timing of quantity ordering. Possible extensions include: (1) Multi-period game. The supply chain parties may sign a long-term contract in which the unsatisfied demand is met in the next period, and the price negotiation can be conducted in each period depending on the realized demand and market information. (2) Risk attitude issue. The supply chain parties may have different risk attitudes, which affect their capacity decisions. (3) Two-wholesale price contract. It is possible that the three supply chain parties are involved in a two-wholesale-price contract, and hence, the price negotiation can be conducted in two periods: One is before demand realization, and the other one is after demand

realization.

For the third topic, we studied the OEM and its competitive CM's preference over quantity leadership/followship. We derive the conditions under which the Stackelberg leadership or followership is more preferable for the two parties. One possible extension in this direction is to consider different demand information for different layers of supply chain parties and then consider the generalized Nash bargaining in this setting.

There exist some limitations for the dissertation. First, we have assumed newsvendor models in the first and second essays, which are single period models. In reality, many decisions are made via a multiple period decision-making process. The information of the demand, inventory and selling price can be updated. The wholesale prices can be renegotiated accordingly. Second, in each tier, we have assumed one single OEM, one single CM and one single supplier. We have not considered the case of multiple players in each tier. It would be interesting to consider the impact of the horizontal competition among the players in the same tier. Third, for essay 3, we have studied a deterministic model but have not consider the impact of demand uncertainty. In the future research, I would like to relax the current assumptions and investigate whether the findings we have obtained still hold or not.

Appendix A

Proofs of Chapter 1

Proof of Proposition 3: In equation (2.1), the first part $[pD(q^D) - \tilde{w}_{m1}q^D] - [pD(q^C) - \tilde{w}_{m1}q^C]$ is non-negative since $q^D = \bar{F}^{-1}\left(\frac{\tilde{w}_{m1}}{p}\right)$ is the optimal solution of the function $pD(q) - \tilde{w}_{m1}q$, but the sign of the second part, $[(w_{m1} + w_{s1}) - \tilde{w}_{m1}]q^C$ depends on whether \tilde{w}_{m1} is smaller than $w_{m1} + w_{s1}$. If $\tilde{w}_{m1} \leq (w_{m1} + w_{s1})$, the second part is also non-negative, so $\Pi_o^D \geq \Pi_o^C$.

If $\tilde{w}_{m1} > w_{m1} + w_{s1}$, $q^D < q^C$. Let's consider the following problem:

$$\frac{\Pi_o^C - \Pi_o^D}{q^C} = \underbrace{\tilde{w}_{m1} - (w_{m1} + w_{s1})}_{>0} - \underbrace{\frac{[pD(q^D) - \tilde{w}_{m1}q^D] - [pD(q^C) - \tilde{w}_{m1}q^C]}{q^C}}_{>0}.$$

Let $y = \tilde{w}_{m1} - (w_{m1} + w_{s1}) > 0$ and $z = \frac{[pD(q^D) - \tilde{w}_{m1}q^D] - [pD(q^C) - \tilde{w}_{m1}q^C]}{q^C}$. Then fixing $w_{m1} + w_{s1}$, both y and z are increasing in \tilde{w}_{m1} . Moreover, we have

$$\frac{\partial z}{\partial \tilde{w}_{m1}} = \frac{q^C - q^D}{q^C} = 1 - \frac{q^D}{q^C} < 1.$$

Therefore, the increasing speed of z is always slower than y . Note that $y = z = 0$ if $\tilde{w}_{m1} = w_{m1} + w_{s1}$. we thus have $y > z$ if $\tilde{w}_{m1} > w_{m1} + w_{s1}$. Therefore, $\Pi_o^C > \Pi_o^D$ if $\tilde{w}_{m1} > w_{m1} + w_{s1}$.

Proof of Lemma 1: Note that $D(K_m^D \wedge K_s^D) = E(K_m^D \wedge \min(K_s^C, X))$. $\min(K_s^C, X)$ is independent of \tilde{w}_{m2} while K_m^D increases in \tilde{w}_{m2} . Therefore, if \tilde{w}_{m2} is small enough, we have $E(K_m^D \wedge \min(K_s^C, X)) = K_m^D$. Consequently, Π_o^D is quasi-concave in \tilde{w}_{m2} (Lariviere and Porteus 2001). If \tilde{w}_{m2} is large enough, we have $E(K_m^D \wedge \min(K_s^C, X)) = E(K_s^C \wedge X)$, then Π_o^D decreases in \tilde{w}_{m2} . So γ is quasi-concave in \tilde{w}_{m2} .

Proof of Proposition 7: First assume $K_m^C \leq K_s^C$. Again taking into consideration the complementarity between the CM and the supplier's products, and their incentives to set up no more than $K_m^C \leq K_s^C$ units of capacities, there exist only three prebook options for the OEM: (1). $\max(q_{m1}, q_{s1}) \leq K_m^C$; (2). $\max(q_{s1}, K_m^C) \leq q_{m1} \leq K_s^C$; and (3). $K_s^C \leq q_{m1}$.

Under option 1, $\max(q_{m1}, q_{s1}) \leq K_m^C$. Thus, the OEM's profit function is

$$\Pi_o^C = pD(K_m^C) - w_{m1}q_{m1} - w_{m2}(D(K_m^C) - D(q_{m1})) - w_{s1}q_{s1} - w_{s2}(D(K_m^C) - D(q_{s1})).$$

It can be shown that the optimal prebook quantities are

$$q_{m1}^C = \bar{F}^{-1}\left(\frac{w_{m1}}{w_{m2}}\right) \wedge K_m^C, \quad \text{and} \quad q_{s1}^C = \bar{F}^{-1}\left(\frac{w_{s1}}{w_{s2}}\right) \wedge K_m^C$$

Under option 2, $(q_{m1} + q_{m2}^C) \wedge (q_{s1} + q_{s2}^C) = q_{m1}$. Then, the OEM pushes the CM, and the CM will produce only the prebook quantity. Thus, $q_{m2} = 0$. Therefore, if the OEM decides to prebook $q_{s1} < q_{m1}$, then

$$\Pi_o^C = pD(q_{m1}) - w_{m1}q_{m1} - w_{s1}q_{s1} - w_{s2}(D(q_{m1}) - D(q_{s1})).$$

Thus the optimal prebook quantities are :

$$q_{s1}^C = \bar{F}^{-1}\left(\frac{w_{s1}}{w_{s2}}\right), q_{m1}^C = \max\left(\bar{F}^{-1}\left(\frac{w_{m1}}{p - w_{s2}}\right) \wedge K_s^C, K_m^C\right), \quad \text{and} \quad q_{s1}^C < q_{m1}^C.$$

And if the OEM decides to prebook $q_{s1} = q_{m1}$, then we can show that

$$q_{m1}^C = q_{s1}^C = \max\left(K_m^C, \bar{F}^{-1}\left(\frac{w_{m1} + w_{s1}}{p}\right) \wedge K_s^C\right)$$

Lastly we consider $q_{m1} \geq K_s^C$. Then, naturally, the OEM pushes both the CM

and the supplier and $q_{m1} = q_{s1} = q$: $\Pi_o^C = pD(q) - (w_{m1} + w_{s1})q$. We can show that

$$q_{m1}^C = q_{s1}^C = \max \left(\bar{F}^{-1} \left(\frac{w_{m1} + w_{s1}}{p} \right), K_s^C \right)$$

If $K_m^C > K_s^C$, we can derive the similar results, thus we can prove Proposition 7.

Proof of Proposition 8: When $K_m^D \leq K_s^D$, if $q_{m1} < K_m^D$, then the CM has no incentives to prebook $q_{s1} > K_m^D$. and they will produce up to K_m^D . So

$$\Pi_m^D = \tilde{w}_{m1}q_{m1} + \tilde{w}_{m2}(D(K_m^D) - D(q_{m1})) - w_{s1}q_{s1} - w_{s2}(D(K_m^D) - D(q_{s1})) - c_m K_m^D.$$

Since $q_{s1} \geq q_{m1}$, the CM will prebook to the supplier

$$q_{s1}^D = \max \left\{ q_{m1}, K_m^D \wedge \bar{F}^{-1} \left(\frac{w_{s1}}{w_{s2}} \right) \right\}.$$

And the corresponding OEM's profit function is

$$\Pi_o^D = pD(K_m^D) - \tilde{w}_{m1}q_{m1} - \tilde{w}_{m2}(D(K_m^D) - D(q_{m1})).$$

It can be shown that the optimal prebook to the CM $q_{m1}^D = \bar{F}^{-1} \left(\frac{\tilde{w}_{m1}}{\tilde{w}_{m2}} \right) \wedge K_m^D$.

If $q_{m1} \geq K_m^D$, then the CM will prebook $q_{s1} = q_{m1}$. And $\Pi_o^D = pD(q) - \tilde{w}_{m1}q$. Then, $q_{s1}^D = q_{m1}^D = \max \left(\bar{F}^{-1} \left(\frac{\tilde{w}_{m1}}{p} \right), K_m^D \right)$.

Proof of Proposition 9: When $K_m^D > K_s^D$, If the prebook to the CM $q_{m1} < K_s^D$, then the CM needs to decide: Should it push the supplier and prebook $q_{s1} > K_s^D$, or not? If the CM decides not, then the supplier as well as the CM will produce up to K_s^D , and the CM's profit function is

$$\Pi_m^D = \tilde{w}_{m1}q_{m1} + \tilde{w}_{m2}(D(K_s^D) - D(q_{m1})) - w_{s1}q_{s1} - w_{s2}(D(K_s^D) - D(q_{s1})) - c_m K_s^D.$$

It can be shown that $q_{s1}^D = \max \left(q_{m1}, \bar{F}^{-1} \left(\frac{w_{s1}}{w_{s2}} \right) \wedge K_s^D \right)$. And if the CM decides to prebook $q_{s1} > K_s^D$, then both the supplier and the CM will produce up to q_{s1} , but note that it is never optimal for the CM to prebook $q_{s1} > K_m^D$. Under this scenario, the CM's profit function is

$$\Pi_m^D = \tilde{w}_{m1}q_{m1} + \tilde{w}_{m2}(D(q_{s1}) - D(q_{m1})) - c_m q_{s1} - w_{s1}q_{s1}.$$

Thus the optimal prebook $q_{s1}^D = \max \left(K_s^D, \bar{F}^{-1} \left(\frac{c_m + w_{s1}}{\tilde{w}_{m2}} \right) \wedge K_m^D \right)$. The CM will compare these above two decisions and choose the one that maximizes its own expected profit.

As to the OEM, knowing that the system capacity now is $\max(q_{s1}, K_s^D)$, it is going to decide q_{m1} to maximize its own profit:

$$pD(\max(q_{s1}, K_s^D)) - \tilde{w}_{m1}q_{m1} - \tilde{w}_{m2}(D(\max(q_{s1}, K_s^D)) - D(q_{m1})).$$

It can be shown that the optimal prebook quantity $q_{m1}^D = \left(\bar{F}^{-1} \left(\frac{\tilde{w}_{m1}}{\tilde{w}_{m2}} \right) \wedge K_s^D \right)$.

Next, if the prebook to the CM $K_s^D < q_{m1} < K_m^D$, then the CM has to prebook $q_{m1} \leq q_{s1} \leq K_m^D$, and the system capacity is again q_{s1} . Thus similarly, the CM is going to prebook $q_{s1}^D = \max \left(q_{m1}, \bar{F}^{-1} \left(\frac{c_m + w_{s1}}{\tilde{w}_{m2}} \right) \wedge K_m^D \right)$. And the corresponding OEM's profit function becomes $pD(q_{s1}) - \tilde{w}_{m1}q_{m1} - \tilde{w}_{m2}(D(q_{s1}) - D(q_{m1}))$. Plugging $q_{s1}^D = \max \left(q_{m1}, \bar{F}^{-1} \left(\frac{c_m + w_{s1}}{\tilde{w}_{m2}} \right) \wedge K_m^D \right)$ into the above profit function, we can derive the optimal prebook quantity is either $q_{m1}^D = q_{s1}^D = \max \left(K_s^D, \bar{F}^{-1} \left(\frac{\tilde{w}_{m1}}{p} \right) \wedge K_m^D \right)$ or

$$q_{m1}^D = \max \left(K_s^D, \bar{F}^{-1} \left(\frac{\tilde{w}_{m1}}{\tilde{w}_{m2}} \right) \wedge K_m^D \right), q_{s1}^D = \bar{F}^{-1} \left(\frac{c_m + w_{s1}}{\tilde{w}_{m2}} \right) \wedge K_m^D, \text{ and } q_{m1}^D < q_{s1}^D.$$

Last, if the OEM prebooks $q_{m1} > K_m^D$, then the CM will prebook $q_{s1}^D = q_{m1}$. Then the OEM's profit function is $\Pi_o^D = pD(q) - \tilde{w}_{m1}q$. And the optimal prebooks are

$$q_{m1}^D = q_{s1}^D = \max \left(\bar{F}^{-1} \left(\frac{\tilde{w}_{m1}}{p} \right), K_m^D \right).$$

Proof of Proposition 10: First consider the case $(K_m^C = K_m^D) \leq (K_s^C = K_s^D)$.

Assume the OEM adopts *partial commitment*, then according to Propositions 7 and 8, we have

$$q_{m1}^C = \bar{F}^{-1} \left(\frac{w_{m1}}{w_{m2}} \right), \quad q_{s1}^C = \bar{F}^{-1} \left(\frac{w_{s1}}{w_{s2}} \right) \wedge K_m^C, \quad q_{m1}^D = \bar{F}^{-1} \left(\frac{\tilde{w}_{m1}}{\tilde{w}_{m2}} \right) \wedge K_m^D = \bar{F}^{-1} \left(\frac{\tilde{w}_{m1}}{\tilde{w}_{m2}} \right) \wedge K_m^C.$$

Plugging them into the OEM's profit functions under control and delegation yields

$$\begin{aligned} \Pi_o^C - \Pi_o^D &= [pD(K_m^C) - w_{m1}q_{m1}^C - w_{m2}(D(K_m^C) - D(q_{m1}^C)) - w_{s1}q_{s1}^C - w_{s2}(D(K_m^C) - D(q_{s1}^C))] \\ &\quad - [pD(K_m^D) - \tilde{w}_{m1}q_{m1}^D - \tilde{w}_{m2}(D(K_m^D) - D(q_{m1}^D))] \\ &= [(w_{m2}D(q_{m1}^C) - w_{m1}q_{m1}^C) - (w_{m2}D(q_{m1}^D) - w_{m1}q_{m1}^D)] \\ &\quad + [(w_{s2}D(q_{s1}^C) - w_{s1}q_{s1}^C) - (w_{s2}D(q_{m1}^D) - w_{s1}q_{m1}^D)]. \end{aligned}$$

Note that $w_{m2}D(X) - w_{m1}X$ is maximized at $q_{m1}^C = \bar{F}^{-1} \left(\frac{w_{m1}}{w_{m2}} \right)$, therefore, we have $w_{m2}D(q_{m1}^C) - w_{m1}q_{m1}^C \geq w_{m2}D(q_{m1}^D) - w_{m1}q_{m1}^D$. Similarly, note that $w_{s2}D(X) - w_{s1}X$ is an increasing function for $X \leq \bar{F}^{-1} \left(\frac{w_{s1}}{w_{s2}} \right)$, we thus have $w_{s2}D(q_{s1}^C) - w_{s1}q_{s1}^C \geq w_{s2}D(q_{m1}^D) - w_{s1}q_{m1}^D$. Hence, $\Pi_o^C \geq \Pi_o^D$.

Next, assume the OEM adopts *pushing CM* strategy, so that

$$q_{m1}^C = \max \left(\bar{F}^{-1} \left(\frac{w_{m1}}{p - w_{s2}} \right) \wedge K_s^C, K_m^C \right), \quad q_{s1}^C = \bar{F}^{-1} \left(\frac{w_{s1}}{w_{s2}} \right) < q_{m1}^C,$$

$$q_{m1}^D = q_{s1}^D = \max \left(K_m^C, \bar{F}^{-1} \left(\frac{w_{m1} + w_{s1}}{p} \right) \wedge K_s^C \right).$$

Comparing the OEM's corresponding profits under control and delegation yields

$$\begin{aligned}
\Pi_o^C - \Pi_o^D &= [pD(q_{m1}^C) - w_{m1}q_{m1}^C - w_{s1}q_{s1}^C - w_{s2}(D(q_{m1}^C) - D(q_{s1}^C))] \\
&\quad - [pD(q_{m1}^D) - (w_{m1} + w_{s1})q_{m1}^D] \\
&= [((p - w_{s2})D(q_{m1}^C) - w_{m1}q_{m1}^C) - ((p - w_{s2})D(q_{m1}^D) - w_{m1}q_{m1}^D)] \\
&\quad + [(w_{s2}D(q_{s1}^C) - w_{s1}q_{s1}^C) - (w_{s2}D(q_{m1}^D) - w_{s1}q_{m1}^D)].
\end{aligned}$$

We then now consider all the possible cases.

Case 1: $q_{m1}^C = \bar{F}^{-1}\left(\frac{w_{m1}}{p-w_{s2}}\right)$ and $q_{s1}^C = \bar{F}^{-1}\left(\frac{w_{s1}}{w_{s2}}\right)$. Note that $(p - w_{s2})D(X) - w_{m1}X$ is concave and takes on its maximum value at $X = \bar{F}^{-1}\left(\frac{w_{m1}}{p-w_{s2}}\right)$, and $w_{s2}D(X) - w_{s1}X$ is also concave and takes on its maximum value at $X = \bar{F}^{-1}\left(\frac{w_{s1}}{w_{s2}}\right)$. So $\Pi_o^C > \Pi_o^D$.

Case 2: $q_{m1}^C = K_s^C$ and $q_{s1}^C = \bar{F}^{-1}\left(\frac{w_{s1}}{w_{s2}}\right)$, then $q_{m1}^D < K_s^C < \bar{F}^{-1}\left(\frac{w_{m1}}{p-w_{s2}}\right)$. Similar to case 1, $\Pi_o^C > \Pi_o^D$.

Case 3: $q_{m1}^C = K_m^C$ and $q_{s1}^C = \bar{F}^{-1}\left(\frac{w_{s1}}{w_{s2}}\right)$, then $\bar{F}^{-1}\left(\frac{w_{m1}}{p-w_{s2}}\right) < K_m^C < q_{m1}^D$, and thus again analogous to case 1, $\Pi_o^C > \Pi_o^D$.

Last, assume that the OEM adopts *push* strategy, then $q_{m1}^C = q_{s1}^C = q_{m1}^D = q_{s1}^D = \max\left(K_s^C, \bar{F}^{-1}\left(\frac{w_{m1}+w_{s1}}{p}\right)\right)$, therefore,

$$\Pi_o^C - \Pi_o^D = (pD(q_{m1}^C) - (w_{m1} + w_{s1})q_{m1}^C) - (pD(q_{m1}^D) - (w_{m1} + w_{s1})q_{m1}^D) = 0.$$

So if $K_m^C \leq K_s^C$, no matter which strategy the OEM adopts, $\Pi_o^C \geq \Pi_o^D$. As to the case $K_m^C > K_s^C$, the analysis for the *partial commitment* and *push* strategies are similar to those under $K_m^C \leq K_s^C$. Thus we omitted the details.

Proof of Proposition 11: If $\tilde{w}_{mt} = w_{mt} + w_{st}$ and $(w_{m2} - c_m)/w_{m2} = (w_{s2} - c_s)/w_{s2}$,

$K_m^C = K_s^C = K_m^D = K_s^D = K$. Then in Propositions 7, 8 and 9, we have only two prebooking strategies: *partial commitment* or *push*.

For the OEM, from Proposition 10, we have $\Pi_o^D \geq \Pi_o^C$.

As to the CM, we first compare its profits under control and delegation if *partial commitment* strategy is adopted:

$$\begin{aligned}\Pi_m^C - \Pi_m^D &= [w_{m1}q_{m1}^C + w_{m2}(D(K) - D(q_{m1}^C)) - c_m K] \\ &\quad - [w_{m1}q_{m1}^D + w_{m2}(D(K) - D(q_{m1}^D)) - c_m K - w_{s1}q_{s1}^D - w_{s2}D(K) + w_{s2}D(q_{s1}^D)] \\ &= -[(w_{m2}D(q_{m1}^C) - w_{m1}q_{m1}^C) - (w_{m2}D(q_{m1}^D) - w_{m1}q_{m1}^D)] \\ &\quad - [(w_{s2}D(q_{s1}^D) - w_{s1}q_{s1}^D) - (w_{s2}D(q_{m1}^D) - w_{s1}q_{m1}^D)].\end{aligned}$$

As $w_{m2}D(X) - w_{m1}X$ is maximized at $q_{m1}^C = \bar{F}^{-1}\left(\frac{w_{m1}}{w_{m2}}\right)$, we have $(w_{m2}D(q_{m1}^C) - w_{m1}q_{m1}^C) - (w_{m2}D(q_{m1}^D) - w_{m1}q_{m1}^D) \geq 0$; similarly, as $q_{s1}^D = \bar{F}^{-1}\left(\frac{w_{s1}}{w_{s2}}\right)$, we have $(w_{s2}D(q_{s1}^D) - w_{s1}q_{s1}^D) - (w_{s2}D(q_{m1}^D) - w_{s1}q_{m1}^D) \geq 0$. Therefore, $\Pi_m^C \leq \Pi_m^D$.

Next, we compare the CM's profits under control and delegation if *push* strategy is adopted: $q_{m1}^C = q_{s1}^C = q_{m1}^D = q_{s1}^D = \max(\bar{F}^{-1}(\frac{\tilde{w}_{m1}}{p}), K)$, so $\Pi_m^C = \Pi_m^D$.

For the supplier, under *partial commitment*, we have

$$\begin{aligned}\Pi_s^C - \Pi_s^D &= [w_{s1}q_{s1}^C + w_{s2}(D(K) - D(q_{s1}^C)) - c_s K] - [w_{s1}q_{s1}^D + w_{s2}(D(K) - D(q_{s1}^D)) - c_s K] \\ &= (w_{s1}q_{s1}^C - w_{s2}D(q_{s1}^C)) - (w_{s1}q_{s1}^D - w_{s2}D(q_{s1}^D)).\end{aligned}$$

As $q_{s1}^C = q_{s1}^D = \bar{F}^{-1}\left(\frac{w_{s1}}{w_{s2}}\right)$, we have $\Pi_s^C = \Pi_s^D$. Next, if *push* strategy is adopted, we have $q_{m1}^C = q_{s1}^C = q_{m1}^D = q_{s1}^D = \max(\bar{F}^{-1}(\frac{\tilde{w}_{m1}}{p}), K)$, so $\Pi_s^C = \Pi_s^D$.

And for the whole supply chain, we have

$$\begin{aligned}\Pi^C - \Pi^D &= [pD(\max(\bar{F}^{-1}(\frac{\tilde{w}_{m1}}{p}), K)) - (c_m + c_s) \max(\bar{F}^{-1}(\frac{\tilde{w}_{m1}}{p}), K)] \\ &\quad - [pD(\max(\bar{F}^{-1}(\frac{\tilde{w}_{m1}}{p}), K)) - (c_m + c_s) \max(\bar{F}^{-1}(\frac{\tilde{w}_{m1}}{p}), K)] = 0.\end{aligned}$$

Last, we compare the OEM's profits under the two strategies. Under control structure, if *partial commitment* strategy is adopted, $q_{m1}^C = q_{s1}^C = \bar{F}^{-1}(\frac{w_{m1}}{w_{m2}}) < K$, and hence, both the CM and the supplier will build capacity up to K , and the OEM's expected profit function is

$$\Pi_o^C = pD(K) - (w_{m1} + w_{s1})\bar{F}^{-1}\left(\frac{w_{m1}}{w_{m2}}\right) - (w_{m2} + w_{s2})[D(K) - D(\bar{F}^{-1}\left(\frac{w_{m1}}{w_{m2}}\right))].$$

If the OEM adopts *push* strategy, then $q_{m1}^C = q_{s1}^C = \max\left(\bar{F}^{-1}\left(\frac{w_{m1}+w_{s1}}{p}\right), K\right)$. If the condition $(w_{m1} + w_{s1})/p \geq (c_m/w_{m2} = c_s/w_{s2})$ holds, then $q_{m1}^C = q_{s1}^C = K$, and

$$\begin{aligned}\Pi_o^C &= pD(K) - (w_{m1} + w_{s1})K = pD(K) - (w_{m1} + w_{s1})K - (w_{m2} + w_{s2})[D(K) - D(K)] \\ &< pD(K) - (w_{m1} + w_{s1})\bar{F}^{-1}\left(\frac{w_{m1}}{w_{m2}}\right) - (w_{m2} + w_{s2})[D(K) - D(\bar{F}^{-1}\left(\frac{w_{m1}}{w_{m2}}\right))].\end{aligned}$$

Therefore, *partial commitment* strategy is beneficial to the OEM. Similar analysis can be derived for the delegation structure.

Proof of Lemma 2: First note that Π_o^C is independent of \tilde{w}_{m1} . Second, we have

$$\begin{aligned}\Pi_o^D &= pD(\max(K_m^D \wedge K_s^D, q_{s1}^D)) - \tilde{w}_{m1}q_{m1}^D - \tilde{w}_{m2}(D(\max(K_m^D \wedge K_s^D, q_{s1}^D)) - D(q_{m1}^D)) \\ &= \begin{cases} (p - \tilde{w}_{m2})D(\max(K_m^D \wedge K_s^D, q_{s1}^D)) + \tilde{w}_{m2}D(q_{m1}^D) - \tilde{w}_{m1}q_{m1}^D, & \text{if } q_{m1}^D < \max(K_m^D \wedge K_s^D, q_{s1}^D); \\ pD(q_{m1}^D) - \tilde{w}_{m1}q_{m1}^D, & \text{otherwise.} \end{cases}\end{aligned}$$

$(p - \tilde{w}_{m2})D(\max(K_m^D \wedge K_s^D, q_{s1}^D))$ is also independent of \tilde{w}_{m1} . As to $\tilde{w}_{m2}D(q_{m1}^D) -$

$\tilde{w}_{m1}q_{m1}^D, q_{m1}^D$ is unaffected by \tilde{w}_{m1} under all the equilibria except when $q_{m1}^D = \bar{F}^{-1}\left(\frac{\tilde{w}_{m1}}{\tilde{w}_{m2}}\right)$.

Applying the Envelope Theorem, we have

$$\frac{\partial \tilde{w}_{m2}D(q_{m1}^D) - \tilde{w}_{m1}q_{m1}^D}{\partial \tilde{w}_{m1}} = -q_{m1}^D.$$

Second, $\Pi_o^D = pD(q_{m1}^D) - \tilde{w}_{m1}q_{m1}^D$ when $q_{m1}^D = \bar{F}^{-1}\left(\frac{\tilde{w}_{m1}}{p}\right)$. Also applying the Envelope Theorem, we have

$$\frac{\partial pD(q_{m1}^D) - \tilde{w}_{m1}q_{m1}^D}{\partial \tilde{w}_{m1}} = -q_{m1}^D.$$

Thus Π_o^D is decreasing in \tilde{w}_{m1} , and so does γ .

Proof of Lemma 3: The proof is similar to that of Theorem 2 in Cachon (2004).

So we omit the details here.

Proof of Lemma 4: The proof is analogous to that of Theorem 2 in Cachon (2004).

So we omit the details here.

Appendix B

Proofs of Chapter 2

Proof of Proposition 12: Ω_{om} and Ω_{os} are log-concave. Solving the first-order conditions (FOCs) of $\log \Omega_{om}$ and $\log \Omega_{os}$ yields

$$w_{m1}^{CS}(w_{s1}) = \alpha c_m - (1 - \alpha)w_{s1} + (1 - \alpha)p \frac{\mu(q)}{q}, \quad (\text{B.1})$$

$$w_{s1}^{CS}(w_{m1}) = \beta c_s - (1 - \beta)w_{m1} + (1 - \beta)p \frac{\mu(q)}{q}. \quad (\text{B.2})$$

Since the OEM bargains with the CM and the supplier simultaneously, solving functions (B.1) and (B.2) simultaneously yields

$$\begin{aligned} w_{m1}^{CS}(q) &= \frac{(1 - \alpha)\beta}{\alpha + \beta - \alpha\beta} \frac{p\mu(q)}{q} + \frac{\alpha c_m - \beta(1 - \alpha)c_s}{\alpha + \beta - \alpha\beta}, \\ w_{s1}^{CS}(q) &= \frac{(1 - \beta)\alpha}{\alpha + \beta - \alpha\beta} \frac{p\mu(q)}{q} + \frac{\beta c_s - \alpha(1 - \beta)c_m}{\alpha + \beta - \alpha\beta}. \end{aligned}$$

Next, substituting $w_{m1}(q)$ and $w_{s1}(q)$ into the OEM's profit function results in

$$\Pi_o(q) = \frac{\alpha\beta}{\alpha + \beta - \alpha\beta} [p\mu(q) - (c_m + c_s)q].$$

Note that $p\mu(q) - (c_m + c_s)q$ is the total expected supply chain profit of producing q units of the end product. And the optimal prebook quantity is $q^{CS} = q^* = \bar{F}^{-1}\left(\frac{c_m + c_s}{p}\right)$. Let $\Pi = p\mu(q^*) - (c_m + c_s)q^*$ be the total supply chain profit. We can further show that

$$\Pi_o^{CS} = \frac{\alpha\beta}{\alpha + \beta - \alpha\beta} \Pi, \quad \Pi_m^{CS} = \frac{(1 - \alpha)\beta}{\alpha + \beta - \alpha\beta} \Pi, \quad \text{and} \quad \Pi_s^{CS} = \frac{(1 - \beta)\alpha}{\alpha + \beta - \alpha\beta} \Pi.$$

Lastly, we have

$$\begin{aligned}\frac{\partial \Pi_o^{CS}}{\partial \alpha} &= \frac{\beta^2 \Pi}{(\alpha + \beta - \alpha\beta)^2} > 0, \quad \frac{\partial \Pi_o^{CS}}{\partial \beta} = \frac{\alpha^2 \Pi}{(\alpha + \beta - \alpha\beta)^2} > 0, \quad \frac{\partial^2 \Pi_o^{CS}}{\partial \alpha \partial \beta} = \frac{2\alpha\beta \Pi}{(\alpha + \beta - \alpha\beta)^3} > 0; \\ \frac{\partial \Pi_m^{CS}}{\partial \alpha} &= \frac{-\beta \Pi}{(\alpha + \beta - \alpha\beta)^2} < 0; \quad \frac{\partial \Pi_s^{CS}}{\partial \beta} = \frac{-\alpha \Pi}{(\alpha + \beta - \alpha\beta)^2} < 0. \\ \frac{\partial w_{m1}^{CS}}{\partial \alpha} &= \frac{\beta[(c_m + c_s)q^{CS} - p\mu(q^{CS})]}{(\alpha + \beta - \alpha\beta)^2} < 0, \quad \frac{\partial w_{s1}^{CS}}{\partial \beta} = \frac{\alpha[(c_m + c_s)q^{CS} - p\mu(q^{CS})]}{(\alpha + \beta - \alpha\beta)^2} < 0.\end{aligned}$$

Proof of Proposition 13: Ω_{ms} is log-concave. Taking $\log \Omega_{ms}$ and solving its FOC yields $w_{s1}^{DS}(\tilde{w}_{m1}) = (1 - \gamma)(\tilde{w}_{m1} - c_m) + \gamma c_s$. Substituting $w_{s1}^{DS}(\tilde{w}_{m1})$ into Ω_{om} yields

$$\Omega_{om} = [p\mu(q) - \tilde{w}_{m1}q]^\alpha (\tilde{w}_{m1} - c_m - c_s)^{(1-\alpha)} q^{(1-\alpha)} \gamma^{(1-\alpha)},$$

which is also log-concave. Taking the FOC of $\log \Omega_{om}$ yields $\tilde{w}_{m1}^{DS} = \alpha(c_m + c_s) + (1 - \alpha)p^{\frac{\mu(q)}{q}}$. So $w_{s1}^{DS} = [\gamma + (1 - \gamma)\alpha]c_s + (1 - \gamma)(1 - \alpha)\left(p^{\frac{\mu(q)}{q}} - c_m\right)$.

Substituting \tilde{w}_{m1}^{DS} into the OEM's profit function, we have

$$\Pi_o(q) = p\mu(q) - (c_m + c_s)\alpha q - (1 - \alpha)p\mu(q) = \alpha[p\mu(q) - (c_m + c_s)q].$$

Again notice that $p\mu(q) - (c_m + c_s)q$ is the total expected profit of the whole supply chain given a production quantity q and the optimal prebook quantity is $q^{DS} = q^* = \bar{F}^{-1}\left(\frac{c_m + c_s}{p}\right)$. So under delegation and push contract, the optimal profits of the three parties are

$$\Pi_o^{DS} = \alpha \Pi, \quad \Pi_m^{DS} = \gamma(1 - \alpha)\Pi, \quad \text{and} \quad \Pi_s^{DS} = (1 - \gamma)(1 - \alpha)\Pi.$$

And

$$\frac{\partial \tilde{w}_{m1}^{DS}}{\partial \alpha} = \frac{(c_m + c_s)q^D - p\mu(q^{DS})}{q^{DS}} < 0, \quad \frac{\partial w_{s1}^{DS}}{\partial \gamma} = \frac{(1 - \alpha)[(c_m + c_s)q^{DS} - p\mu(q^{DS})]}{q^{DS}} < 0.$$

Proof of Corollary 3:

$$\begin{aligned}
w_{m1}^{CS} + w_{s1}^{CS} - \tilde{w}_{m1}^{DS} &= \frac{\alpha + \beta - 2\alpha\beta}{\alpha + \beta - \alpha\beta} \frac{p\mu(q^*)}{q^*} + \frac{\alpha\beta}{\alpha + \beta - \alpha\beta} (c_m + c_s) - \left[\alpha(c_m + c_s) + (1 - \alpha) \frac{p\mu(q^*)}{q^*} \right] \\
&= \frac{\alpha^2(1 - \beta)[p\mu(q^*) - (c_m + c_s)q^*]}{(\alpha + \beta - \alpha\beta)q^*} \geq 0.
\end{aligned}$$

$$\begin{aligned}
w_{s1}^{CS} - w_{s1}^{DS} &= \frac{(1 - \beta)\alpha}{\alpha + \beta - \alpha\beta} \frac{p\mu(q^*)}{q^*} + \frac{\beta c_s - (1 - \beta)\alpha c_m}{\alpha + \beta - \alpha\beta} \\
&\quad - \left[(\alpha + \gamma - \alpha\gamma)c_s + (1 - \gamma)(1 - \alpha) \left(\frac{p\mu(q^*)}{q^*} - c_m \right) \right] \\
&= \frac{[(1 - \beta)\alpha - (\alpha + \beta - \alpha\beta)(1 - \gamma)(1 - \alpha)](p\mu(q^*) - c_m q^*)}{(\alpha + \beta - \alpha\beta)q^*} \\
&\quad + \frac{[\beta - (\alpha + \beta - \alpha\beta)(\alpha + \gamma - \alpha\gamma)]c_s}{\alpha + \beta - \alpha\beta} \\
&= [(\alpha + \beta - \alpha\beta)(\alpha + \gamma - \alpha\gamma) - \beta] \frac{p\mu(q^*) - (c_m + c_s)q^*}{(\alpha + \beta - \alpha\beta)q^*}.
\end{aligned}$$

Therefore, $w_{s1}^{CS} \leq w_{s1}^{DS}$ if $(\alpha + \beta - \alpha\beta)(\alpha + \gamma - \alpha\gamma) \leq \beta$. Rearranging the condition yields that $w_{s1}^{CS} \leq w_{s1}^{DS}$ if $\beta \in \left[\frac{1}{1 + \frac{(1-\gamma)(1-\alpha)}{\alpha(\alpha+\gamma-\alpha\gamma)}}, 1 \right]$. Otherwise, $w_{s1}^{CS} > w_{s1}^{DS}$.

Proof of Corollary 4: Comparing the OEM' optimal profits under control and delegation in equations (3.1) and (3.2) shows that $\Pi_o^{CS} \leq \Pi_o^{DS}$. Comparing the CM and the supplier' profits under control and delegation yields

$$\begin{aligned}
\Pi_m^{CS} - \Pi_m^{DS} &= \left[\frac{(1 - \alpha)\beta}{\alpha + \beta - \alpha\beta} - \gamma(1 - \alpha) \right] \Pi = (1 - \alpha) \left(\frac{\beta}{\alpha + \beta - \alpha\beta} - \gamma \right) \Pi. \\
\Pi_s^{CS} - \Pi_s^{DS} &= \left[\frac{(1 - \beta)\alpha}{\alpha + \beta - \alpha\beta} - (1 - \gamma)(1 - \alpha) \right] \Pi = (1 - \alpha) \left[\gamma - \frac{(1 - \alpha + \alpha^2)\beta - \alpha^2}{(1 - \alpha)(\alpha + \beta - \alpha\beta)} \right] \Pi.
\end{aligned}$$

Therefore, we can derive corollary 4.

Proof of Proposition 14: The *Nash Products* between the OEM and the CM/supplier are

$$\begin{aligned}\text{Max}_{w_{m2}} \Omega_{om} &= [\Pi_{o2(w_{m2})}]^\alpha [\Pi_{m2(w_{m2})}]^{1-\alpha} = (p - w_{m2} - w_{s2})^\alpha (w_{m2} - c_m)^{1-\alpha} x \wedge q_m \wedge q_s, \\ \text{Max}_{w_{s2}} \Omega_{os} &= [\Pi_{o2(w_{s2})}]^\beta [\Pi_{s2(w_{s2})}]^{1-\beta} = (p - w_{m2} - w_{s2})^\beta (w_{s2} - c_s)^{1-\beta} x \wedge q_m \wedge q_s.\end{aligned}$$

Taking the log function of the above two expressions and maximizing them generates two equations on w_{m2} and w_{s2} . The equilibrium is obtained by solving the two equations simultaneously.

Proof of Proposition 15: We first derive the best response function of the CM, given the supplier's decision q_s . Since the CM and the supplier's products are complements, it is never optimal for the CM to install a capacity $q_m > q_s$. Thus give the supplier's production quantity q_s , the best response function of the CM is $q_m^*(q_s) = \min(Q_m^{CL}, q_s)$. Similarly, the best response function of the supplier is $q_s^*(q_m) = \min(Q_s^{CL}, q_m)$. The equilibrium is obtained from the above two best response functions.

Proof of Proposition 16: The *Nash Product* between the CM and the supplier is

$$\text{Max}_{w_{s2}} \Omega_{ms} = [\Pi_{m2(w_{s2})}]^\gamma [\Pi_{s2(w_{s2})}]^{1-\gamma} = (\tilde{w}_{m2} - w_{s2} - c_m)^\gamma (w_{s2} - c_s)^{1-\gamma} x \wedge q_m \wedge q_s.$$

Based on Ω_{ms} , we obtain the optimal wholesale price $w_{s2}^{DL}(\tilde{w}_{m2}) = \gamma c_s + (1-\gamma)(\tilde{w}_{m2} - c_m)$. Next, substituting $w_{s2}^{DL}(\tilde{w}_{m2})$ into the *Nash Product* between the OEM and CM, we have

$$\text{Max}_{\tilde{w}_{m2}} \Omega_{om} = [\Pi_{o2(\tilde{w}_{m2})}]^\alpha [\Pi_{m2(\tilde{w}_{m2})}]^{1-\alpha} = (p - \tilde{w}_{m2})^\alpha \gamma^{1-\alpha} (\tilde{w}_{m2} - c_m - w_{s2})^{1-\alpha} x \wedge q_m \wedge q_s.$$

Similarly, we can derive the optimal wholesale price $\tilde{w}_{m2}^{DL} = \alpha(c_m + c_s) + (1-\alpha)p$,

and thus $w_{s2}^{DL} = (\alpha + \gamma - \alpha\gamma)c_s + (1 - \gamma)(1 - \alpha)(p - c_m)$.

Proof of Proposition 17: Similar to the proof of Proposition 15.

Proof of Corollary 18: $Q_m^{CL} \leq Q_m^{DL}$ requires

$$\frac{(\alpha + \beta - \alpha\beta)}{(1 - \alpha)\beta(p - c_s) + \alpha c_m} \geq \frac{1}{\gamma(1 - \alpha)(p - c_s) + (1 - \gamma + \alpha\gamma)c_m}.$$

It can be rewritten as $[\alpha - (\alpha + \beta - \alpha\beta)(1 - \gamma + \alpha\gamma)](p - c_s - c_m) \geq 0$. Note that $p \geq (c_s + c_m)$, then the requirement reduces to $\alpha - (\alpha + \beta - \alpha\beta)(1 - \gamma + \alpha\gamma) \geq 0$. Rearranging this inequality in terms of α yields $-\gamma(1 - \beta)\alpha^2 + [\gamma(1 - \beta) + \beta(1 - \gamma)]\alpha - \beta(1 - \gamma) \geq 0$, that is, $[\gamma(1 - \beta)\alpha - \beta(1 - \gamma)](\alpha - 1) \leq 0$. We can therefore show that $Q_m^{CL} \leq Q_m^{DL}$ if $\alpha \in [\frac{\beta(1 - \gamma)}{\gamma(1 - \beta)}, 1]$ and $\beta \leq \gamma$.

Similarly, $Q_s^{CL} \leq Q_s^{DL}$ requires

$$\frac{(\alpha + \beta - \alpha\beta)}{(1 - \beta)\alpha(p - c_m) + \beta c_s} \geq \frac{1}{(1 - \gamma)(1 - \alpha)(p - c_m) + (\alpha + \gamma - \alpha\gamma)c_s}.$$

It can also be rewritten as $[\beta - (\alpha + \beta - \alpha\beta)(\alpha + \gamma - \alpha\gamma)](p - c_m - c_s) \geq 0$. Rearranging this inequality in terms of γ yields $\gamma(1 - \alpha) + \alpha \leq \frac{\beta}{\alpha + \beta - \alpha\beta}$. Then we can show that $Q_s^{CL} \leq Q_s^{DL}$ if $\gamma \in [0, \frac{\beta - \alpha(\alpha + \beta - \alpha\beta)}{(1 - \alpha)(\alpha + \beta - \alpha\beta)}]$ and $\beta \in [\frac{\alpha^2}{1 - \alpha + \alpha^2}, 1]$.

Proof of Corollary 5: Since $Q_s^{CL} \leq Q_s^{DL}$ if $\beta \in \left[\frac{1}{1 + \frac{(1 - \gamma)(1 - \alpha)}{\alpha(\alpha + \gamma - \alpha\gamma)}}, 1\right]$, we can derive that

$w_{s2}^{CL} \leq w_{s2}^{DL}$ if $\beta \in \left[\frac{1}{1 + \frac{(1 - \gamma)(1 - \alpha)}{\alpha(\alpha + \gamma - \alpha\gamma)}}, 1\right]$. And we can also show that

$$\begin{aligned} w_{m2}^{CL} + w_{s2}^{CL} - \tilde{w}_{m2}^{DL} &= \frac{\alpha + \beta - 2\alpha\beta}{\alpha + \beta - \alpha\beta}p + \frac{\alpha\beta}{\alpha + \beta - \alpha\beta}(c_m + c_s) - [\alpha(c_m + c_s) + (1 - \alpha)p] \\ &= \frac{\alpha^2(1 - \beta)[p - (c_m + c_s)]}{(\alpha + \beta - \alpha\beta)} \geq 0. \end{aligned}$$

Proof of Corollary 6: The expected profits of the OEM, the CM and the supplier under the two structures are, respectively,

$$\begin{aligned}\Pi_o^{CL} &= (p - w_{m2}^{CL} - w_{s2}^{CL})\mu(Q_m^{CL} \wedge Q_s^{CL}) = \frac{\alpha\beta(p - c_m - c_s)}{\alpha + \beta - \alpha\beta}\mu(Q_m^{CL} \wedge Q_s^{CL}), \\ \Pi_o^{DL} &= (p - \tilde{w}_{m2}^{DL})\mu(Q_m^{DL} \wedge Q_s^{DL}) = \alpha(p - c_m - c_s)\mu(Q_m^{DL} \wedge Q_s^{DL}).\end{aligned}$$

Proof of Proposition 19: $Q_m^{CL} \leq \bar{F}^{-1}\left(\frac{c_m+c_s}{p}\right)$ requires

$$\frac{(\alpha + \beta - \alpha\beta)c_m}{(1 - \alpha)\beta(p - c_s) + \alpha c_m} \geq \frac{c_m + c_s}{p}.$$

Rearranging the above inequality item yields $(\alpha c_m - (1 - \alpha)\beta c_s)(p - c_m - c_s) \geq 0$.

Since $p \geq (c_m + c_s)$, the requirement reduces to $c_m \geq \frac{(1-\alpha)\beta}{\alpha}c_s$.

And $Q_s^{CL} \leq \bar{F}^{-1}\left(\frac{c_m+c_s}{p}\right)$ requires

$$\frac{(\beta + \alpha - \alpha\beta)c_s}{(1 - \beta)\alpha(p - c_m) + \beta c_s} \geq \frac{c_m + c_s}{p}.$$

Again rearranging the above inequality yields $(\beta c_s - (1 - \beta)\alpha c_m)(p - c_m - c_s) \geq 0$,

which is reduced to $c_m \leq \frac{\beta}{\alpha(1-\beta)}c_s$. Notice that $\frac{(1-\alpha)\beta}{\alpha} < \frac{\beta}{\alpha(1-\beta)}$. We therefore prove

that $Q_m^{CL} \wedge Q_s^{CL} \leq \bar{F}^{-1}\left(\frac{c_m+c_s}{p}\right)$.

Similarly, $Q_m^{DL} \leq \bar{F}^{-1}\left(\frac{c_m+c_s}{p}\right)$ requires

$$\frac{c_m}{\gamma(1 - \alpha)(p - c_s) + (1 - \gamma + \alpha\gamma)c_m} \geq \frac{c_m + c_s}{p}.$$

Rearranging the above inequality item yields $((1 - \gamma + \alpha\gamma)c_m - (1 - \alpha)\gamma c_s)(p - c_m - c_s) \geq 0$

0, which reduces to $c_m \geq \frac{\gamma(1-\alpha)}{1-\gamma+\alpha\gamma}c_s$. And $Q_s^{DL} \leq \bar{F}^{-1}\left(\frac{c_m+c_s}{p}\right)$ requires

$$\frac{c_s}{(1-\gamma)(1-\alpha)(p-c_m) + (\alpha+\gamma-\alpha\gamma)c_s} \geq \frac{c_m+c_s}{p}.$$

Rearranging the above inequality item yields $((\alpha+\gamma-\alpha\gamma)c_s - (1-\alpha)(1-\gamma)c_m)(p-c_m-c_s) \geq 0$, which is reduced to $c_m \leq \frac{\alpha+\gamma-\alpha\gamma}{(1-\gamma)(1-\alpha)}c_s$. Since $\frac{\gamma(1-\alpha)}{1-\gamma+\alpha\gamma} \leq \frac{\alpha+\gamma-\alpha\gamma}{(1-\gamma)(1-\alpha)}$, we have $Q_m^{DL} \wedge Q_s^{DL} \leq \bar{F}^{-1}\left(\frac{c_m+c_s}{p}\right)$.

Proof of Proposition 21: It holds that $\bar{F}(x) = \bar{G}\left(\frac{x-a}{b}\right)$ and $\bar{F}^{-1}\left(\frac{c_m+c_s}{p}\right) = a + b\bar{G}^{-1}\left(\frac{c_m+c_s}{p}\right)$. Therefore,

$$\frac{\mu(q^*)}{q^*} = \frac{\int_0^{\bar{F}^{-1}\left(\frac{c_m+c_s}{p}\right)} \bar{F}(x)dx}{\bar{F}^{-1}\left(\frac{c_m+c_s}{p}\right)} = \frac{\int_0^{a+b\bar{G}^{-1}\left(\frac{c_m+c_s}{p}\right)} \bar{G}\left(\frac{x-a}{b}\right)dx}{a+b\bar{G}^{-1}\left(\frac{c_m+c_s}{p}\right)}.$$

Taking the derivative of the above expression with respect to b yields:

$$\begin{aligned} \frac{\partial\left(\frac{\mu(q^*)}{q^*}\right)}{\partial b} &= \frac{\frac{c_m+c_s}{p}\bar{G}^{-1}\left(\frac{c_m+c_s}{p}\right)\left[a+b\bar{G}^{-1}\left(\frac{c_m+c_s}{p}\right)\right] - \bar{G}^{-1}\left(\frac{c_m+c_s}{p}\right)\int_0^{a+b\bar{G}^{-1}\left(\frac{c_m+c_s}{p}\right)} \bar{G}\left(\frac{x-a}{b}\right)dx}{\left[a+b\bar{G}^{-1}\left(\frac{c_m+c_s}{p}\right)\right]^2} \\ &= \frac{\bar{G}^{-1}\left(\frac{c_m+c_s}{p}\right)}{a+b\bar{G}^{-1}\left(\frac{c_m+c_s}{p}\right)} \left(\frac{c_m+c_s}{p} - \frac{\int_0^{a+b\bar{G}^{-1}\left(\frac{c_m+c_s}{p}\right)} \bar{G}\left(\frac{x-a}{b}\right)dx}{a+b\bar{G}^{-1}\left(\frac{c_m+c_s}{p}\right)}\right) \\ &= \frac{\bar{G}^{-1}\left(\frac{c_m+c_s}{p}\right)}{a+b\bar{G}^{-1}\left(\frac{c_m+c_s}{p}\right)} \left(\frac{c_m+c_s}{p} - \frac{\mu(q^*)}{q^*}\right) \\ &< 0, \end{aligned}$$

where the last inequality follows from the fact that the centralized supply chain's profit, $p\mu(q^*) - (c_m+c_s)q^*$, is always positive.

Proof of Lemma 5: The proof is similar to that of the Theorem 2 in Cachon (2004).

Appendix C

Proofs and Companions for Chapter 3

C.1 Proofs

Proof of Proposition 22. For the “simultaneous”-move game, by maximizing (4.2) and (4.3), the best response functions are:

$$q_o(q_c) = \frac{m - bq_c - w}{2}; \quad q_c(q_o) = \frac{m - q_o}{2}.$$

Solving the above two equations yields the equilibrium quantities $q_o^S = \frac{(2-b)m-2w}{4-b}$, $q_c^S = \frac{m+w}{4-b}$. The corresponding equilibrium profits can be obtained by substituting q_o^S and q_c^S into functions (4.2) and (4.3):

$$\Pi_o^S = \frac{[(2-b)m - 2w]^2}{(4-b)^2}; \quad \Pi_c^S = \frac{(m+w)^2}{(4-b)^2} + \frac{[(2-b)m - 2w]\theta w}{4-b}.$$

For the OEM-as-leader game, substituting $q_c(q_o)$ into the profit function of the OEM yields $\Pi_o = (m - q_o - b\frac{m-q_o}{2} - w)q_o$. Maximizing the above objective function yields the optimal production quantity for the OEM: $q_o^L = \frac{(2-b)m-2w}{4-2b}$. Moreover, the corresponding optimal decision for the CM is $q_c^F = \frac{m-q_o^L}{2} = \frac{(2-b)m+2w}{8-4b}$. For the CM-as-leader game, the procedure is similar to the above analysis.

Proof of Proposition 23. When $m > \max \left\{ \frac{4-b^2\theta-b}{4-3b}, \frac{2}{2-b} \right\} w$, all three basic games exist. In the following, we will compare the performance of the OEM and CM under

these three basic games derived in Proposition 22. First, we show that

$$\begin{aligned}
\Pi_o^L - \Pi_o^S &= \frac{[(2-b)m - 2w]^2}{16 - 8b} - \frac{[(2-b)m - 2w]^2}{(4-b)^2} = \frac{[(2-b)m - 2w]^2 b^2}{8(4-b)^2(2-b)} > 0, \\
\Pi_c^L - \Pi_c^S &= \frac{[m + (1+b\theta)w][m + (1-b\theta)w]}{8(2-b)} + \frac{[(4-3b)m - (4-b^2\theta - b)w]\theta w}{4(2-b)} \\
&\quad - \frac{(m+w)^2}{(4-b)^2} - \frac{[(2-b)m - 2w]\theta w}{4-b} \\
&= \frac{b^2[(b^2\theta^2 - 8b\theta^2 + 16\theta^2 - 8\theta + 2b\theta + 1)w^2 + 2(1 - 4\theta + b\theta)mw + m^2]}{8(2-b)(4-b)^2} \\
&= \frac{b^2[(b\theta + 1 - 4\theta)w + m]^2}{8(2-b)(4-b)^2} \geq 0.
\end{aligned}$$

So $\Pi_o^L > \Pi_o^S$ and $\Pi_c^L > \Pi_c^S$. Next, we have

$$\begin{aligned}
\Pi_c^F - \Pi_c^S &= \left[\frac{(2-b)m + 2w}{4(2-b)} + \frac{w+m}{4-b} \right] \left[\frac{(2-b)m + 2w}{4(2-b)} - \frac{w+m}{4-b} \right] + \theta w[(2-b)m - 2w] \left(\frac{1}{2(2-b)} - \frac{1}{4-b} \right) \\
&= \frac{[(b^2 - 10b + 16)m + (16 - 6b)w][b((b-2)m + 2w)]}{16(2-b)^2(4-b)^2} + \frac{[(2-b)m - 2w]\theta wb}{2(2-b)(4-b)} \\
&= \frac{b[(2-b)m - 2w]}{16(2-b)^2(4-b)^2} [8\theta(2-b)(4-b) - 16 + 6b]w - (16 - 10b + b^2)m.
\end{aligned}$$

Then the sign of $\Pi_c^F - \Pi_c^S$ depends on that of

$$[8\theta(2-b)(4-b) - 16 + 6b]w - (16 - 10b + b^2)m. \quad (\text{C.1})$$

Note that if $\theta \leq \frac{1}{2-b}$, $\frac{4-b^2\theta-b}{4-3b}w \geq \frac{2}{2-b}w$, then $m \geq \frac{4-b^2\theta-b}{4-3b}w$; if $\frac{1}{2-b} < \theta \leq 1$, then $\frac{4-b^2\theta-b}{4-3b}w < \frac{2}{2-b}w$ and $m \geq \frac{2}{2-b}w$.

Case 1: $\theta \in [\frac{1}{2-b}, 1]$. If $\theta \in [\frac{1}{2-b}, 1]$, then $8\theta(2-b)(4-b) - 16 + 6b \geq 8(4-b) - 16 + 6b > 0$. Thus, if $w \geq \frac{(16-10b+b^2)m}{8\theta(2-b)(4-b)-16+6b} = w_{AL}$, then equation (C.1) is positive.

Furthermore, we show that

$$\begin{aligned}
w_{AL} - w_{AF} &= \frac{(16 - 10b + b^2)m}{8\theta(2-b)(4-b) - 16 + 6b} - \frac{1}{(4-b)\theta - 1}m \\
&= \frac{(-8b\theta + 6b^2\theta + 4b - b^3 - b^2)m}{[8\theta(2-b)(4-b) - 16 + 6b][(4-b)\theta - 1]} \\
&= \frac{(4-b)[b - \theta b(2-b)]m}{[8\theta(2-b)(4-b) - 16 + 6b][(4-b)\theta - 1]} \leq 0, \\
w_{AF} - \frac{2-b}{2}m &= \frac{(4-b)[1 - (2-b)\theta]m}{2[(4-b)\theta - 1]} \leq 0
\end{aligned}$$

Thus $w_{AL} \leq w_{AF} \leq \frac{2-b}{2}m$ if $\theta \in [\frac{1}{2-b}, 1]$. Therefore, $\Pi_c^F \geq \Pi_c^S$ if $w \in [w_{AL}, \frac{2-b}{2}m]$.

Otherwise, $\Pi_c^F < \Pi_c^S$.

Case 2: $\theta \in [0, \frac{1}{2-b})$. Equation (C.1) implies that $\Pi_c^F \geq \Pi_c^S$ if $m \leq \frac{[8\theta(2-b)(4-b) - 16 + 6b]w}{16 - 10b + b^2}$.

But

$$\begin{aligned}
&\frac{[8\theta(2-b)(4-b) - 16 + 6b]w}{16 - 10b + b^2} - \frac{(4 - b^2\theta - b)w}{4 - 3b} \\
&= \frac{w\{\theta(2-b)[(1-b)(128 + b^2) + 31b^2] - [(1-b)(128 + b^2) + 31b^2]\}}{(16 - 10b + b^2)(4 - 3b)} \\
&= \frac{w[(1-b)(128 + b^2) + 31b^2][\theta(2-b) - 1]}{(16 - 10b + b^2)(4 - 3b)} < 0.
\end{aligned}$$

So $\Pi_c^F \geq \Pi_c^S$ requires $m \leq \frac{(4-b^2\theta-b)w}{4-3b}$, which cannot hold. Thus $\Pi_c^F < \Pi_c^S$.

Similarly, we can show that the sign of $\Pi_o^F - \Pi_o^S$ is the same as the sign of

$$[(4-b)\theta - 1]w - m. \quad (\text{C.2})$$

Case 1: $\theta \in [\frac{1}{2-b}, 1]$. If $\theta \in [\frac{1}{2-b}, 1]$, $(4-b)\theta - 1 \geq \frac{4-b}{2-b} - 1 > 0$. Then, equation

(C.2) is positive if $w \geq \frac{1}{(4-b)\theta - 1}m = w_{AF}$. Therefore, $\Pi_o^F \geq \Pi_o^S$ if $w \in [w_{AF}, \frac{2-b}{2}m]$.

Otherwise, $\Pi_o^F < \Pi_o^S$.

Case 2: $\theta \in [0, \frac{1}{2-b})$. Equation (C.2) shows that $\Pi_o^F \geq \Pi_o^S$ requires $m \leq [(4-b)\theta - 1]w$. Notice that here, $m > \frac{[4-(1+\theta)b^2]w}{4-3b}$, but

$$\begin{aligned} [(4-b)\theta - 1]w - \frac{(4-b^2\theta - b)w}{4-3b} &= \frac{w[(4\theta - b\theta - 1)(4-3b) - (4-b^2\theta - b)]}{4-3b} \\ &= \frac{4w(2-b)[\theta(2-b) - 1]}{4-3b} < 0. \end{aligned}$$

Therefore $\Pi_o^F \geq \Pi_o^S$ cannot hold. So $\Pi_o^F < \Pi_o^S$ if $\theta \in [0, \frac{1}{2-b})$. In summary, we have

$$\begin{cases} \Pi_c^F \geq \Pi_c^S, & \text{if } \theta \in [\frac{1}{2-b}, 1] \text{ \& } w \in [w_{AL}, \frac{2-b}{2}m], \\ \Pi_c^F < \Pi_c^S, & \text{if } \theta \in [0, \frac{1}{2-b}) \text{ or } \theta \in [\frac{1}{2-b}, 1] \text{ \& } w \in [0, w_{AL}). \end{cases} \quad (\text{C.3})$$

$$\begin{cases} \Pi_o^F \geq \Pi_o^S, & \text{if } \theta \in [\frac{1}{2-b}, 1] \text{ \& } w \in [w_{AF}, \frac{2-b}{2}m], \\ \Pi_o^F < \Pi_o^S, & \text{if } \theta \in [0, \frac{1}{2-b}) \text{ or } \theta \in [\frac{1}{2-b}, 1] \text{ \& } w \in [0, w_{AF}). \end{cases} \quad (\text{C.4})$$

Since $\Pi_o^L \geq \Pi_o^S$ and $\Pi_c^L \geq \Pi_c^S$, based on Table 4.1, we have (L, F) which is a NE if $\Pi_c^F \geq \Pi_c^S$; (F, L) is a NE if $\Pi_o^F \geq \Pi_o^S$; if $\Pi_c^S \geq \Pi_c^F$, L is a dominant strategy for the CM; if $\Pi_o^S \geq \Pi_o^F$, L is a dominant strategy for the OEM; F is never a dominant strategy for the OEM or CM. Therefore, we prove Proposition 23 based on equations (C.3) and (C.4).

Proof of Corollary 7. Assume that $\theta \in [\frac{1}{2-b}, 1]$, then, $\max(\frac{4-b^2\theta-b}{4-3b}w, \frac{2}{2-b}w) = \frac{2}{2-b}w$.

Let $m = \frac{k}{2-b}w$, $k > 2$. Then, $w = \frac{(2-b)m}{k}$. Equation (C.3) indicates that $\Pi_c^F \geq \Pi_c^S$ requires that $w \geq w_{AL}$, which is equivalent to $\theta \geq \frac{k(8-b)+16-6b}{8(2-b)(4-b)} = \theta_{AL}$. Since

$$\theta_{AL} - \frac{1}{2-b} = \frac{k(8-b) + 16 - 6b - 8(4-b)}{8(2-b)(4-b)} = \frac{(k-2)(8-b)}{8(2-b)(4-b)} > 0,$$

$\Pi_c^F \geq \Pi_c^S$ requires $\theta_{AL} \leq \theta \leq 1$. Similarly, we can show that $\Pi_c^F < \Pi_c^S$ requires

$$\frac{1}{2-b} \leq \theta < \min(\theta_{AL}, 1).$$

From equation (C.4), we have $\Pi_o^F \geq \Pi_o^S$ which requires $w \geq w_{AF}$. This condition is equivalent to $\theta \geq \frac{k+(2-b)}{(2-b)(4-b)}$. Denote $\frac{k+(2-b)}{(2-b)(4-b)}$ as θ_{AF} . $k > 2$ implies that $\theta_{AF} > \frac{1}{2-b}$. Thus, $\Pi_o^F \geq \Pi_o^S$ if $\theta \in [\theta_{AF}, 1]$. Also, we can show that $\Pi_o^F < \Pi_o^S$ if $\frac{1}{2-b} \leq \theta < \min(\theta_{AF}, 1)$. In summary, we have

$$\begin{cases} \Pi_c^F \geq \Pi_c^S, & \text{if } \theta \in [\theta_{AL}, 1], \\ \Pi_c^F < \Pi_c^S, & \text{if } \theta \in [\frac{1}{2-b}, \min(\theta_{AL}, 1)). \end{cases} \quad \text{and} \quad \begin{cases} \Pi_o^F \geq \Pi_o^S, & \text{if } \theta \in [\theta_{AF}, 1], \\ \Pi_o^F < \Pi_o^S, & \text{if } \theta \in [\frac{1}{2-b}, \min(\theta_{AF}, 1)). \end{cases} \quad (\text{C.5})$$

Besides, since

$$\theta_{AL} - \theta_{AF} = \frac{k(8-b) + 16 - 6b}{8(2-b)(4-b)} - \frac{k + (2-b)}{(2-b)(4-b)} = \frac{b(2-k)}{8(2-b)(4-b)} < 0,$$

$\theta_{AL} < \theta_{AF}$. As well, we can show that

$$\begin{aligned} \frac{\partial \theta_{AL}}{\partial b} &= \frac{(-k-6)(2-b)(4-b) - [k(8-b) + 16 - 6b](-4+b-2+b)}{8(2-b)^2(4-b)^2} \\ &= \frac{-(k+6)(2-b)(4-b) + 2[k(8-b) + 16 - 6b](3-b)}{8(2-b)^2(4-b)^2} \\ &= \frac{(40 - 16b + b^2)k + 48 - 32b + 6b^2}{8(2-b)^2(4-b)^2} > 0, \\ \frac{\partial \theta_{AF}}{\partial b} &= \frac{-(2-b)(4-b) - (k+2-b)(-4+b-2+b)}{(2-b)^2(4-b)^2} \\ &= \frac{-8 + 6b - b^2 + 2(k+2-b)(3-b)}{(2-b)^2(4-b)^2} = \frac{2(3-b)k + 4 - 4b + b^2}{(2-b)^2(4-b)^2} > 0, \\ \frac{\partial(\theta_{AF} - \theta_{AL})}{\partial b} &= \frac{(k-2)(2-b)(4-b) - b(k-2)(-4+b-2+b)}{8(2-b)^2(4-b)^2} = \frac{(k-2)(8-b^2)}{8(2-b)^2(4-b)^2} > 0. \end{aligned}$$

Similar to Proposition 23, we can derive Corollary 7 based on equation (C.5).

Proof of Proposition 24: First, the “simultaneous”-move game. Taking the first

order condition (FOC) of the equilibrium production quantities yields

$$\frac{\partial q_o^S}{\partial b} = \frac{-2(m+w)}{(4-b)^2} < 0, \quad \frac{\partial q_c^S}{\partial b} = \frac{(m+w)}{(4-b)^2} > 0.$$

Correspondingly, we have

$$\begin{aligned} \frac{\partial \Pi_o^S}{\partial b} &= \frac{\partial \Pi_o^S}{\partial q_o^S} \frac{\partial q_o^S}{\partial b} = 2q_o^S \frac{\partial q_o^S}{\partial b} < 0, \\ \frac{\partial \Pi_c^S}{\partial b} &= \frac{2(m+w)^2}{(4-b)^3} + \frac{-(4-b)\theta mw + [(2-b)m - 2w]\theta w}{(4-b)^2} \\ &= \frac{2[m^2 + (2 - (4-b)\theta)mw + (1 - (4-b)\theta)w^2]}{(4-b)^3} \\ &= \frac{2(m+w)(m - ((4-b)\theta - 1)w)}{(4-b)^3}. \end{aligned}$$

So $\frac{\partial \Pi_c^S}{\partial b} > 0$ if $m > ((4-b)\theta - 1)w$. Note that we have assumed $m > \frac{2}{2-b}w$.

Comparing $((4-b)\theta - 1)w$ with $\frac{2}{2-b}w$ yields $\frac{2}{2-b}w - ((4-b)\theta - 1)w = \frac{(4-b)(1-(2-b)\theta)}{2-b}w$.

Therefore, Π_c^S is increasing in b if $\theta \in [0, \frac{1}{2-b}]$; if $\theta \in (\frac{1}{2-b}, 1]$, decreasing in b when $m \in [\frac{2}{2-b}w, ((4-b)\theta - 1)w]$ and increasing in b otherwise.

Second, the OEM-as-leader game. Similarly, we take the FOC of the equilibrium production quantities and have

$$\frac{\partial q_o^L}{\partial b} = \frac{-w}{(2-b)^2} < 0, \quad \frac{\partial q_c^F}{\partial b} = \frac{w}{2(2-b)^2} > 0, \quad \frac{\partial \Pi_o^L}{\partial b} = \frac{-[(2-b)m - 2w][(2-b)m + 2w]}{8(2-b)^2} < 0.$$

Meanwhile,

$$\begin{aligned} \frac{\partial \Pi_c^F}{\partial b} &= \frac{2[(2-b)m + 2w](-m)(2-b)^2 + 2[(2-b)m + 2w]^2(2-b)}{16(2-b)^4} + \frac{[(2-b)m - 2w - (2-b)m]\theta w}{2(2-b)^2} \\ &= \frac{[(2-b)m - (4(2-b)\theta - 2)w]w}{4(2-b)^3}. \end{aligned}$$

So $\frac{\partial \Pi_c^F}{\partial b} > 0$ if $m > \frac{4(2-b)\theta-2}{2-b}w$. Combining our assumption $m > \frac{2}{2-b}w$, we have $\frac{2}{2-b}w - \frac{4(2-b)\theta-2}{2-b}w = \frac{4[1-(2-b)\theta]}{2-b}$. Similarly, we can show that Π_c^F is increasing in b if $\theta \in [0, \frac{1}{2-b}]$; if $\theta \in (\frac{1}{2-b}, 1]$, decreasing in b when $m \in [\frac{2}{2-b}w, \frac{4(2-b)\theta-2}{2-b}w]$ and increasing in b otherwise.

Last, the CM-as-leader game. The FOC of the equilibrium production quantities are

$$\frac{\partial q_o^F}{\partial b} = \frac{-2m + (-2 + 4b\theta - b^2\theta)w}{4(2-b)^2}; \quad \frac{\partial q_c^L}{\partial b} = \frac{m - (2\theta - 1)w}{2(2-b)^2}.$$

Note that our assumption under this basic game is $m > \frac{4-b^2\theta-b}{4-3b}w$, therefore

$$\begin{aligned} -2m + (-2 + 4b\theta - b^2\theta)w &< \frac{-2(4 - b^2\theta - b) + (4 - 3b)(-2 + 4b\theta - b^2\theta)}{(4 - 3b)}w \\ &= \frac{(2-b)[(8-3b)b\theta - 8]}{(4-3b)}w < 0; \\ m - (2\theta - 1)w &> \frac{4 - b^2\theta - b - (4 - 3b)(2\theta - 1)}{4 - 3b}w \\ &= \frac{(2-b)(4 - (4-b)\theta)}{4 - 3b}w > 0. \end{aligned}$$

Thus $\frac{\partial q_o^F}{\partial b} < 0$ and $\frac{\partial q_c^L}{\partial b} > 0$. Then we can show that

$$\frac{\partial \Pi_o^F}{\partial b} = \frac{\partial \Pi_o^F}{\partial q_o^F} \frac{\partial q_o^F}{\partial b} = 2q_o^F \frac{\partial q_o^F}{\partial b} < 0.$$

And we also have

$$\begin{aligned} \frac{\partial \Pi_c^L}{\partial b} &= \frac{m^2 + 2(1-2\theta)mw + (1-4\theta+4b\theta^2-b^2\theta^2)}{8(2-b)^2} \\ &= \frac{[m + (1-b\theta)w][m - ((4-b)\theta - 1)w]}{8(2-b)^2}. \end{aligned}$$

So $\frac{\partial \Pi_c^L}{\partial b} > 0$ if $m > ((4 - b)\theta - 1)w$. Note that $\frac{4-b^2\theta-b}{4-3b}w - ((4 - b)\theta - 1)w = \frac{4(2-b)[1-(2-b)\theta]}{4-3b}w$, similarly, we can show that Π_c^L is increasing in b if $\theta \in [0, \frac{1}{2-b}]$; if $\theta \in (\frac{1}{2-b}, 1]$, decreasing in b when $m \in [\frac{4-b^2\theta-b}{4-3b}w, ((4 - b)\theta - 1)w]$ and increasing in b otherwise.

Proof of Proposition 25:

First, given the outsourcing decision θ and wholesale price w , and using Proposition 22, we can derive the equilibrium production quantities of the OEM and the CM as

$$q_o^{S*}(\theta, w) = \frac{(2 - b)m + 2(p_0 - w)\theta - 2p_0}{4 - b}, \quad q_c^{S*}(\theta, w) = \frac{m - (p_0 - w)\theta + p_0}{4 - b}.$$

Next, substituting q_o^{S*} and q_c^{S*} into the OEM's profit function (4.4) yields the OEM's equilibrium profit

$$\Pi_o^S(\theta) = \frac{[(2 - b)m + 2(p_0 - w)\theta - 2p_0]^2}{(4 - b)^2},$$

which increases in θ . Therefore, the OEM will set $\theta^* = 1$.

Also, substituting q_o^{S*} , q_c^{S*} and $\theta^* = 1$ into the CM's profit function (4.5) results in

$$\Pi_c^S(w) = \frac{[m - (p_0 - w)\theta + p_0]^2}{(4 - b)^2} + \frac{[(2 - b)m + 2(p_0 - w)\theta - 2p_0]w}{4 - b},$$

which is concave in w . Taking the first order derivative of $\Pi_c^S(w)$ w.r.t. w yields

$$\frac{\partial \Pi_c^S(\theta, w)}{\partial w} = \frac{[(10 - 6b + b^2)m - (14 - 4b)w]}{(4 - b)^2}.$$

Setting the above to be equal to 0 generates the optimal solution $\frac{10-6b+b^2}{14-4b}m$. According to the analysis in §3.1, $m > \frac{2}{2-b}w$ or $w < \frac{2-b}{2}m$ is required for the OEM to stay in

the market. It can be verified that $\frac{10-6b+b^2}{14-4b}m - \frac{2-b}{2}m = \frac{-(4-b)(1-b)}{14-4b}m \leq 0$.

Since $w \leq p_0$, the optimal pricing decision of the CM is to set

$$w^{S*} = \min \left\{ p_0, \frac{10-6b+b^2}{14-4b}m \right\}.$$

Substituting w^{S*} and θ^* into (4.4) and (4.5), we can obtain the optimal profits of the OEM and the competitive CM.

Proof of Corollary 8: If $p_0 > \frac{10-6b+b^2}{14-4b}m$, $w^{S*} = \frac{10-6b+b^2}{14-4b}m$. The maximum profit that the CM can obtain with the OEM in the market is $\Pi_c^{S*} = \frac{(8-4b+b^2)}{4(7-2b)}m^2$. It can be verified that $\frac{(8-4b+b^2)}{4(7-2b)}m^2 - \frac{m^2}{4} = \frac{(1-b)^2}{4(7-2b)}m^2 \geq 0$.

If $p_0 \leq \frac{10-6b+b^2}{14-4b}m$, $w^{S*} = p_0$. The maximum profit that the CM can obtain with the OEM in the market is $\Pi_c^{S*} = \frac{(m+p_0)^2}{(4-b)^2} + \frac{[(2-b)m-2p_0]p_0}{4-b}$. Comparing Π_c^{S*} and Π_c^m yields

$$\begin{aligned} \Pi_c^{S*} - \Pi_c^m &= \frac{(m+p_0)^2}{(4-b)^2} + \frac{[(2-b)m-2p_0]p_0}{4-b} - \frac{m^2}{4} \\ &= \frac{4(m+p_0)^2 + 4(4-b)[(2-b)m-2p_0]p_0 - (4-b)^2m^2}{4(4-b)^2} \\ &= \frac{-4(7-2b)p_0^2 + 4(10-6b+b^2)mp_0 - (2-b)(6-b)m^2}{4(4-b)^2} \\ &= \frac{[2(7-2b)p_0 - (6-b)m][(2-b)m-2p_0]}{4(4-b)^2}. \end{aligned}$$

So $\Pi_c^{S*} \leq \Pi_c^m$ if $p_0 \in [0, \frac{6-b}{14-4b}m]$. Otherwise, $\Pi_c^{S*} > \Pi_c^m$. It can be verified that $\frac{6-b}{14-4b}m \leq \frac{10-6b+b^2}{14-4b}m$.

Proof of Proposition 26: First, given the wholesale price w and the OEM's production quantity $q_o(\theta, w)$ and outsourcing decision θ , the CM maximizes its profit by

choosing an optimal production quantity. It can be shown that the optimal production quantity the CM should produce for its own-branded products is

$$q_c(q_o, \theta, w) = \frac{m - q_o(\theta, w)}{2}.$$

Second, anticipating the CM's optimal production decision, the OEM makes its production and outsourcing decisions to maximize its profit. Substituting the production decision of the CM into (4.4) yields:

$$\max_{q_o, \theta} \Pi_o^L(w) = \frac{-(2-b)q_o^2 + [(2-b)m + 2(p_0 - w)\theta - 2p_0]q_o}{2}.$$

The above objective function is increasing in θ and concave in w . It can be shown that the optimal decisions of the OEM and the corresponding quantity decision of the CM are

$$\theta^*(w) = 1, \quad q_o^{L*}(w) = \frac{(2-b)m - 2w}{2(2-b)}, \quad q_c^{F*}(w) = \frac{(2-b)m + 2w}{4(2-b)}.$$

Last, substituting the above production quantities and outsourcing decision into the CM's profit function $\Pi_c^F(w)$ yields

$$\max_w \Pi_c^F = \frac{[(2-b)m + 2w]^2}{16(2-b)^2} + \frac{[(2-b)m - 2w]w}{2(2-b)}.$$

Taking the first-order condition, we have

$$\frac{\partial \Pi_c^F}{\partial w} = \frac{4[(2-b)m + 2w]}{16(2-b)^2} + \frac{[(2-b)m - 2w] - 2w}{2(2-b)} = \frac{(2-b)(5-2b)m - 2(7-4b)w}{4(2-b)^2}.$$

So the optimal wholesale price

$$w^{F*} = \min\left\{p_0, \frac{(2-b)(5-2b)}{14-8b}m\right\}.$$

It can be verified that $w^{F*} < \frac{2-b}{2}m$. Substituting w^{F*} and θ^* into (4.4) and (4.5), we can obtain the optimal profits of the OEM and the competitive CM listed in Proposition 26.

Proof of Corollary 9: If $p_0 > \frac{(2-b)(5-2b)}{14-8b}m$, $w^{F*} = \frac{(2-b)(5-2b)}{14-8b}m$. The corresponding profit becomes $\Pi_c^{F*} = \frac{(2-b)(4-b)m^2}{4(7-4b)}$. It can be verified that $\Pi_c^{F*} - \Pi_c^m = \frac{(2-b)(4-b)m^2}{4(7-4b)} - \frac{m^2}{4} = \frac{(1-b)^2}{4(7-4b)}m^2 \geq 0$.

If $p_0 \leq \frac{(2-b)(5-2b)}{14-8b}m$, $w^{F*} = p_0$. Then we have

$$\begin{aligned}\Pi_c^{F*} - \Pi_c^m &= \frac{[(2-b)m + 2p_0]^2}{16(2-b)^2} + \frac{[(2-b)m - 2p_0]p_0}{2(2-b)} - \frac{m^2}{4} \\ &= \frac{[(2-b)m + 2p_0]^2 + 8(2-b)[(2-b)m - 2p_0]p_0 - 4(2-b)^2m^2}{16(2-b)^2} \\ &= \frac{-4(7-4b)p_0^2 + 4(2-b)(5-2b)mp_0 - 3(2-b)^2m^2}{16(2-b)^2} \\ &= \frac{[2(7-4b)p_0 - 3(2-b)m][(2-b)m - 2p_0]}{16(2-b)^2}.\end{aligned}$$

Note that $\frac{3(2-b)}{14-8b}m - \frac{(2-b)(5-2b)}{14-8b}m = \frac{-2(2-b)(1-b)}{(14-8b)}m \leq 0$. Hence, if $p_0 \in [0, \frac{3(2-b)}{14-8b}m]$,

$\Pi_c^{F*} \leq \Pi_c^m$; otherwise, $\Pi_c^{F*} > \Pi_c^m$.

Proof of Proposition 27: First, given the production quantity q_c and wholesale price w , the OEM will choose θ and production quantity to maximize its profit. Since the OEM's profit function (4.4) is increasing in θ , the OEM will set $\theta^* = 1$. And taking the first order condition with respect to (4.4) yields

$$q_o^*(q_c, w) = \frac{m - bq_c - w}{2}.$$

Next, anticipating the OEM's optimal decisions, the CM makes decisions about its

production quantity and wholesale price to maximize its own profit. Substituting $q_o^*(q_c, w)$ and $\theta^* = 1$ into (4.5) generates the following decision problem for the CM:

$$\max_{q_c, w} \Pi_c^L = \frac{[m - (2 - b)q_c + w]q_c}{2} + \frac{(m - bq_c - w)w}{2}.$$

The first-order conditions are

$$w(q_c) = \frac{m + (1 - b)q_c}{2}, \quad q_c(w) = \frac{m + (1 - b)w}{2(2 - b)}.$$

And solving these two equations yields $w^{L*} = \min\{p_0, \frac{5-3b}{7-2b-b^2}m\}$. It can be verified that $w^{L*} < \frac{4-3b}{4-b-b^2}m$. Substituting w^{L*} and θ^* into (4.4) and (4.5) yields the optimal profits of the OEM and the competitive CM.

Proof of Corollary 10: If $p_0 > \frac{5-3b}{7-2b-b^2}m$, $w^{L*} = \frac{5-3b}{7-2b-b^2}m$. The competitive CM's optimal profit is $\Pi_c^{L*} = \frac{(2-b)}{7-2b-b^2}m^2$. It can be verified that $\Pi_c^{L*} - \Pi_c^m = \frac{(1-b)^2}{4(7-2b-b^2)}m^2 \geq 0$.

If $p_0 \leq \frac{5-3b}{7-2b-b^2}m$, $w^{L*} = p_0$. The corresponding profit is

$$\Pi_c^{L*} = \frac{[m + (1 + b)p_0][m + (1 - b)p_0]}{8(2 - b)} + \frac{[(4 - 3b)m - (4 - b - b^2)p_0]p_0}{4(2 - b)}.$$

Taking the FOC on p_0 yields

$$\begin{aligned} \frac{\partial \Pi_c^{L*}}{\partial p_0} &= \frac{(1 + b)(m + p_0 - bp_0) + (1 - b)(m + p_0 + bp_0)}{8(2 - b)} + \frac{(4 - 3b)m - (4 - b - b^2)p_0 - (4 - b - b^2)p_0}{4(2 - b)} \\ &= \frac{(5 - 3b)m - (7 - 2b - b^2)p_0}{4(2 - b)} \geq 0. \end{aligned}$$

So Π_c^{L*} is increasing in p_0 , thus there exists a unique p_0 at which $\Pi_c^{L*} - \Pi_c^m = 0$.

Note that

$$\Pi_c^{L*}(p_0 = 0) - \Pi_c^m = \frac{-3 + 2b}{8(2 - b)}m^2 \leq 0, \text{ and } \Pi_c^{L*}(p_0 = \frac{5 - 3b}{7 - 2b - b^2}m) - \Pi_c^m = \frac{(1 - b)^2}{4(7 - 2b - b^2)}m^2 \geq 0.$$

Solving

$$\Pi_c^{L*} - \Pi_c^m = \frac{[m + (1 + b)p_0][m + (1 - b)p_0]}{8(2 - b)} + \frac{[(4 - 3b)m - (4 - b - b^2)p_0]p_0}{4(2 - b)} - \frac{m^2}{4} = 0$$

yields the feasible root $\frac{(5 - 3b) - (1 - b)\sqrt{2(2 - b)}}{7 - 2b - b^2}m$. Therefore, if $p_0 \in [0, \frac{(5 - 3b) - (1 - b)\sqrt{2(2 - b)}}{7 - 2b - b^2}m]$,

$\Pi_c^{L*} \leq \Pi_c^m$; Otherwise, $\Pi_c^{L*} > \Pi_c^m$.

Proof of Lemma 6: Comparing w_{AF} , w^S , w^F and w^L yields

$$\begin{aligned}
w^S - w^F &= \frac{10 - 6b + b^2}{14 - 4b}m - \frac{(2 - b)(5 - 2b)}{14 - 8b}m \\
&= \frac{(10 - 6b + b^2)(7 - 4b) - (2 - b)(5 - 2b)(7 - 2b)}{2(7 - 2b)(7 - 4b)}m \\
&= \frac{b(1 - b)}{2(7 - 2b)(7 - 4b)}m \geq 0; \\
w^S - w^L &= \frac{10 - 6b + b^2}{14 - 4b}m - \frac{5 - 3b}{7 - 2b - b^2}m \\
&= \frac{(10 - 6b + b^2)(7 - 2b - b^2) - (5 - 3b)(14 - 4b)}{2(7 - 2b)(7 - 2b - b^2)}m \\
&= \frac{-3b^2 + 4b^3 - b^4}{2(7 - 2b)(7 - 2b - b^2)}m. \\
&= \frac{-b^2(3 - b)(1 - b)}{2(7 - 2b)(7 - 2b - b^2)}m \leq 0. \\
w^F - w_{AF} &= \frac{(2 - b)(5 - 2b)}{14 - 8b}m - \frac{1}{3 - b}m \\
&= \frac{(2 - b)(5 - 2b)(3 - b) - (14 - 8b)}{2(7 - 4b)(3 - b)} \\
&= \frac{16 - 29b + 15b^2 - 2b^3}{2(7 - 4b)(3 - b)} \\
&= \frac{(1 - b)(16 - 13b + 2b^2)}{2(7 - 4b)(3 - b)} \geq 0.
\end{aligned}$$

Thus $w_{AL} \leq w_{AF} \leq w^F \leq w^S \leq w^L$.

Proof of Proposition 30: First, taking the first order derivative of Ω^S with respect

to w yields

$$\begin{aligned}\frac{\partial \Omega^S}{\partial w} &= \alpha (\Pi_c^S(w))^{\alpha-1} (\Pi_o^S(w))^{1-\alpha} \frac{\partial \Pi_c^S(w)}{\partial w} + (1-\alpha) (\Pi_c^S(w))^\alpha (\Pi_o^S(w))^{-\alpha} \frac{\partial \Pi_o^S(w)}{\partial w} \\ &= \underbrace{(\Pi_c^S(w))^{\alpha-1}}_1 \underbrace{(\Pi_o^S(w))^{-\alpha}}_2 \underbrace{\left[\alpha \Pi_o^S(w) \frac{\partial \Pi_c^S(w)}{\partial w} + (1-\alpha) \Pi_c^S(w) \frac{\partial \Pi_o^S(w)}{\partial w} \right]}_3.\end{aligned}$$

As the first two terms are positive, the first order condition (FOC) $\frac{\partial \Omega^S}{\partial w} = 0$ is reduced to let the third term to be zero, and substituting the CM's and the OEM's profit functions into the third term yields

$$\begin{aligned}(1-\alpha) \Pi_c^S(w) \frac{-\partial \Pi_o^S(w)}{\partial w} &= \alpha \Pi_o^S(w) \frac{\partial \Pi_c^S(w)}{\partial w} \\ (1-\alpha) \Pi_c^S(w) \frac{4[(2-b)m-2w]}{(4-b)^2} &= \alpha \Pi_o^S(w) \frac{(10-6b+b^2)m-2(7-2b)w}{(4-b)^2},\end{aligned}$$

which can be simplified as

$$4(7-2b)w^2 - 2[2(10-6b+b^2) + (1-b)(4-b)\alpha]mw + [(24-22b+8b^2-b^3)\alpha - 4]m^2 = 0,$$

a quadratic function of w . Solving it yields two optimal solutions:

$$\begin{aligned}w_1^S &= \frac{2(10-6b+b^2) + (1-b)(4-b)\alpha + (4-b)\sqrt{(1-b)^2\alpha^2 + 4(8-4b+b^2)(1-\alpha)}}{4(7-2b)}m, \\ w_2^S &= \frac{2(10-6b+b^2) + (1-b)(4-b)\alpha - (4-b)\sqrt{(1-b)^2\alpha^2 + 4(8-4b+b^2)(1-\alpha)}}{4(7-2b)}m.\end{aligned}$$

Note that $w_2^S = K^S$.

Next, taking the first order derivative of w_1^S with respect to α yields

$$\begin{aligned}
\frac{\partial w_1^S}{\partial \alpha} &= \frac{m}{4(7-2b)} \left[(1-b)(4-b) + \frac{(4-b)[2(1-b)^2\alpha - 4(8-4b+b^2)]}{2\sqrt{(1-b)^2\alpha^2 + 4(8-4b+b^2)(1-\alpha)}} \right] \\
&= \frac{(4-b)m}{4(7-2b)\sqrt{(1-b)^2\alpha^2 + 4(8-4b+b^2)(1-\alpha)}} \\
&\quad \times [(1-b)\sqrt{(1-b)^2\alpha^2 + 4(8-4b+b^2)(1-\alpha)} - (16-8b+2b^2 - (1-b)^2\alpha)] \\
&< 0,
\end{aligned}$$

where the last inequality is due to

$$\begin{aligned}
&\left[(1-b)\sqrt{(1-b)^2\alpha^2 + 4(8-4b+b^2)(1-\alpha)} \right]^2 - [16-8b+2b^2 - (1-b)^2\alpha]^2 \\
&= (1-b)^2[(1-b)^2\alpha^2 + 4(8-4b+b^2)(1-\alpha)] - (16-8b+2b^2)^2 \\
&\quad - (1-b)^4\alpha^2 + 2(16-8b+2b^2)(1-b)^2\alpha \\
&= -(16-8b+2b^2)^2 + 4(8-4b+b^2)(1-b)^2 \\
&= -4(8-4b+b^2)(7-2b) \\
&< 0.
\end{aligned}$$

So w_1^S is decreasing in α . Thus $w_1^S \geq w_1^S|_{\alpha=1} = \frac{2-b}{2}m$, which is in conflict with our pricing constraint $w < \frac{2-b}{2}m$. Therefore, w_1^S cannot be the optimal solution.

Similarly, we can show the first order derivatives of w_2^S with respect to α as

$$\begin{aligned}
\frac{\partial w_2^S}{\partial \alpha} &= \frac{m}{4(7-2b)} \left[(1-b)(4-b) - \frac{(4-b)[2(1-b)^2\alpha - 4(8-4b+b^2)]}{2\sqrt{(1-b)^2\alpha^2 + 4(8-4b+b^2)(1-\alpha)}} \right] \\
&= \frac{(4-b)m}{4(7-2b)\sqrt{(1-b)^2\alpha^2 + 4(8-4b+b^2)(1-\alpha)}} \\
&\quad \times [(1-b)\sqrt{(1-b)^2\alpha^2 + 4(8-4b+b^2)(1-\alpha)} + (16-8b+2b^2 - (1-b)^2\alpha)] \\
&> 0,
\end{aligned}$$

so w_2^S is increasing in α . Letting $w_2^S = 0$ yields $\alpha^S(0) = \frac{4}{(4-b)(6-4b+b^2)}$. Therefore, if $\alpha \geq \alpha^S(0)$, then $0 \leq w_2^S \leq w_2^S|_{\alpha=1} = \frac{10-6b+b^2}{2(7-2b)}m = w^S \leq \frac{2-b}{2}m$. But is w_2^S the maximizer of Ω^S ? To answer this question, we need to check the sign of $\frac{\partial \Omega^S}{\partial w}|_{w_2^S=0}$ and $\frac{\partial \Omega^S}{\partial w}|_{w_2^S=w^S}$. If the former is positive and the latter is negative, then w_2^S maximizes Ω^S and thus $\Omega^S(w)$ is unimodal for $w \in [0, \frac{2-b}{2}m]$.

We can show that

$$\begin{aligned} \frac{\partial \Omega^S}{\partial w}|_{w_2^S=0} &= (\Pi_c^S(0))^{\alpha-1} (\Pi_o^S(0))^{-\alpha} \left[\alpha \Pi_o^S(0) \frac{\partial \Pi_c^S(w)}{\partial w}|_{w_2^S=0} + (1-\alpha) \Pi_c^S(0) \frac{\partial \Pi_o^S(w)}{\partial w}|_{w_2^S=0} \right] \\ &= (\Pi_c^S(0))^{\alpha-1} (\Pi_o^S(0))^{-\alpha} \left[\alpha \frac{(2-b)^2 m^2 (10-6b+b^2)m}{(4-b)^2} + (1-\alpha) \frac{m^2}{(4-b)^2} \frac{-4(2-b)m}{(4-b)^2} \right] \\ &= (\Pi_c^S(0))^{\alpha-1} (\Pi_o^S(0))^{-\alpha} \frac{(2-b)m^3}{(4-b)^4} [(4-b)(6-4b+b^2)\alpha - 4]. \end{aligned}$$

Note that $w_2^S \geq 0$ requires $\alpha \geq \alpha^S(0) = \frac{4}{(4-b)(6-4b+b^2)}$. Substituting this condition into $\frac{\partial \Omega^S}{\partial w}|_{w_2^S=0}$, then we have $\frac{\partial \Omega^S}{\partial w}|_{w_2^S=0} \geq 0$. Similarly we have

$$\begin{aligned} \frac{\partial \Omega^S}{\partial w}|_{w_2^S=w^S} &= (\Pi_c^S(w^S))^{\alpha-1} (\Pi_o^S(w^S))^{-\alpha} \left[\alpha \Pi_o^S(w^S) \frac{\partial \Pi_c^S(w)}{\partial w}|_{w_2^S=w^S} + (1-\alpha) \Pi_c^S(w^S) \frac{\partial \Pi_o^S(w)}{\partial w}|_{w_2^S=w^S} \right] \\ &= (\Pi_c^S(w^S))^{\alpha-1} (\Pi_o^S(w^S))^{-\alpha} \left[(1-\alpha) \Pi_c^S(w^S) \frac{\partial \Pi_o^S(w)}{\partial w}|_{w_2^S=w^S} \right] < 0. \end{aligned}$$

Thus we prove that w_2^S is the optimal solution that maximizes Ω^S , and Ω^S is unimodal for $w \in [0, \frac{2-b}{2}m]$.

Next, let

$$\Pi_c^S(w) = \frac{(m+w)^2}{(4-b)^2} + \frac{[(2-b)m-2w]w}{4-b} = \Pi_c^{RS} = \frac{(m+p_0)^2}{(4-b)^2},$$

then it can be shown that the unique solution is

$$w = \frac{(10 - 6b + b^2)m - \sqrt{(10 - 6b + b^2)^2 m^2 - 4(7 - 2b)(p_0^2 + 2p_0 m)}}{2(7 - 2b)} = \underline{w}^S,$$

which is smaller than w^S . As $0 \leq p_0 < \frac{2-b}{2}m$ (otherwise the OEM cannot source from the non-competitive CM as it will get negative profit), we can show that

$$\begin{aligned} & (10 - 6b + b^2)^2 m^2 - 4(7 - 2b)(p_0^2 + 2p_0 m) \\ & > (10 - 6b + b^2)^2 m^2 - 4(7 - 2b) \left[\frac{(2 - b)^2}{4} m^2 + (2 - b)m^2 \right] \\ & = [(10 - 6b + b^2)^2 - (2 - b)(6 - b)(7 - 2b)]m^2 \\ & = (16 - 40b + 33b^2 - 10b^3 + b^4)m^2 \\ & = (1 - b)^2(4 - b)^2 m^2 \geq 0. \end{aligned}$$

Then the participation constraint is reduced to that the negotiated price is no less than \underline{w}^S .

Based on the forgoing analysis and recall that $K^S = w_2^S$, we obtain the GNB-characterized wholesale price as $w^{NS} = \min(p_0, \max(\underline{w}^S, K^S))$. Thus Proposition 30 is proved.

Proof of Proposition 31: Similar to the proof of Proposition 30, We also let the first-order derivative of Nash product Ω^F with respect to w to be zero to derive the extreme-value points. Substituting $\Pi_c^F(w)$ and $\Pi_o^L(w)$ into Ω^F , the FOC can be rewritten as

$$\begin{aligned} (1 - \alpha)\Pi_c^F(w) \frac{-\partial \Pi_o^L(w)}{\partial w} &= \alpha \Pi_o^L(w) \frac{\partial \Pi_c^F(w)}{\partial w} \\ (1 - \alpha)\Pi_c^F(w) \frac{4[(2 - b)m - 2w]}{8(2 - b)} &= \alpha \Pi_o^L(w) \frac{[(2 - b)(5 - 2b)m - 2(7 - 4b)w]}{4(2 - b)^2}. \end{aligned}$$

Rearranging the forgoing equation yields a quadratic function of w ,

$$4(7-4b)w^2 - 4[(2-b)(5-2b) + (1-b)(2-b)\alpha]mw + (2-b)^2[2(3-b)\alpha - 1]m^2 = 0,$$

which has two roots

$$w_1^F = \frac{(2-b)(5-2b) + (2-b)(1-b)\alpha + (2-b)\sqrt{(1-b)^2\alpha^2 + 4(2-b)(4-b)(1-\alpha)}}{2(7-4b)}m,$$

$$w_2^F = \frac{(2-b)(5-2b) + (2-b)(1-b)\alpha - (2-b)\sqrt{(1-b)^2\alpha^2 + 4(2-b)(4-b)(1-\alpha)}}{2(7-4b)}m.$$

Note that $w_2^F = K^F$.

Next we check whether w_1^F and w_2^F are the optimal solution. Taking the first-order derivative of w_1^F with respect to α yields

$$\begin{aligned} \frac{\partial w_1^F}{\partial \alpha} &= \frac{(2-b)m}{2(7-4b)} \left[(1-b) + \frac{2(1-b)^2\alpha - 4(2-b)(4-b)}{2\sqrt{(1-b)^2\alpha^2 + 4(2-b)(4-b)(1-\alpha)}} \right] \\ &= \frac{(2-b)m}{2(7-4b)} \times \frac{(1-b)\sqrt{(1-b)^2\alpha^2 + 4(2-b)(4-b)(1-\alpha)} - [16 - 12b + 2b^2 - (1-b)^2\alpha]}{\sqrt{(1-b)^2\alpha^2 + 4(2-b)(4-b)(1-\alpha)}} \\ &< 0, \end{aligned}$$

where the last inequality is because of

$$\begin{aligned} &\left[(1-b)\sqrt{(1-b)^2\alpha^2 + 4(2-b)(4-b)(1-\alpha)} \right]^2 - [16 - 12b + 2b^2 - (1-b)^2\alpha]^2 \\ &= (1-b)^2[(1-b)^2\alpha^2 + 4(2-b)(4-b)(1-\alpha)] - (16 - 12b + 2b^2)^2 \\ &\quad - (1-b)^4\alpha^2 + 2(16 - 12b + 2b^2)(1-b)^2\alpha \\ &= -4(2-b)(4-b)(7-4b) < 0. \end{aligned}$$

So w_1^F is decreasing in α . Thus $w_1^F \geq w_1^F|_{\alpha=1} = \frac{2-b}{2}m$, which contradicts our assumption that $w < \frac{2-b}{2}m$. Thus w_1^F cannot be the optimal solution.

And taking the first-order derivative of w_2^F with respect to α yields

$$\begin{aligned}\frac{\partial w_2^F}{\partial \alpha} &= \frac{(2-b)m}{2(7-4b)} \left[(1-b) - \frac{2(1-b)^2\alpha - 4(2-b)(4-b)}{2\sqrt{(1-b)^2\alpha^2 + 4(2-b)(4-b)(1-\alpha)}} \right] \\ &= \frac{(2-b)m}{2(7-4b)} \times \frac{(1-b)\sqrt{(1-b)^2\alpha^2 + 4(2-b)(4-b)(1-\alpha)} + 16 - 12b + 2b^2 - (1-b)^2\alpha}{\sqrt{(1-b)^2\alpha^2 + 4(2-b)(4-b)(1-\alpha)}} \\ &> 0.\end{aligned}$$

So w_2^F increases in α . Thus $0 \leq w_2^F \leq w_2^F|_{\alpha=1} = \frac{(2-b)(5-2b)}{2(7-4b)}m = w^F \leq \frac{2-b}{2}m$. Letting $w_2^F(\alpha) = 0$ yields $\alpha^F(0) = \frac{1}{2(3-b)}$. We then check the sign of $\frac{\partial \Omega^F}{\partial w}|_{w_2^F=0}$ and $\frac{\partial \Omega^F}{\partial w}|_{w_2^F=w^F}$. If the former is positive and the latter is negative, then w_2^F maximizes Ω^F and the constrained Ω^F is unimodal.

$$\begin{aligned}\frac{\partial \Omega^F}{\partial w}|_{w_2^F=0} &= (\Pi_c^F(0))^{\alpha-1} (\Pi_o^L(0))^{-\alpha} \left[\alpha \Pi_o^L(0) \frac{\partial \Pi_c^F(w)}{\partial w}|_{w_2^F=0} + (1-\alpha) \Pi_c^F(0) \frac{\partial \Pi_o^L(w)}{\partial w}|_{w_2^F=0} \right] \\ &= (\Pi_c^F(0))^{\alpha-1} (\Pi_o^L(0))^{-\alpha} \left[\alpha \frac{(2-b)m^2}{8} \frac{(2-b)(5-2b)m}{4(2-b)^2} + (1-\alpha) \frac{m^2}{16} \frac{-4(2-b)m}{8(2-b)} \right] \\ &= (\Pi_c^F(0))^{\alpha-1} (\Pi_o^L(0))^{-\alpha} \frac{m^3}{32} [2(3-b)\alpha - 1].\end{aligned}$$

As $w_2^F \geq 0$ requires $\alpha \geq \alpha^F(0) = \frac{1}{2(3-b)}$, substituting this condition into $\frac{\partial \Omega^F}{\partial w}|_{w_2^F=0}$ leads to $\frac{\partial \Omega^F}{\partial w}|_{w_2^F=0} \geq 0$.

Similarly we can show that

$$\begin{aligned}\frac{\partial \Omega^F}{\partial w}|_{w_2^F=w^F} &= (\Pi_c^F(w^F))^{\alpha-1} (\Pi_o^L(w^F))^{-\alpha} \left[\alpha \Pi_o^L(w^F) \frac{\partial \Pi_c^F(w)}{\partial w}|_{w_2^F=w^F} + (1-\alpha) \Pi_c^F(w^F) \frac{\partial \Pi_o^L(w)}{\partial w}|_{w_2^F=w^F} \right] \\ &= (\Pi_c^F(w^F))^{\alpha-1} (\Pi_o^L(w^F))^{-\alpha} \left[(1-\alpha) \Pi_c^F(w^F) \frac{\partial \Pi_o^L(w)}{\partial w}|_{w_2^F=w^F} \right] < 0.\end{aligned}$$

Therefore w_2^F is the optimal solution that maximizes Ω^F , and the constrained Ω^F is thus unimodal.

Next, Letting $\Pi_c^F(w) = \Pi_c^{RF}$ and solving it yields

$$\underline{w}^F = \frac{(2-b)(5-2b)m - \sqrt{(2-b)^2(5-2b)^2m^2 - 4(7-4b)[p_0^2 + (2-b)mp_0]}}{2(7-4b)},$$

which is smaller than w^F . As $0 \leq p_0 < \frac{2-b}{2}m$ (otherwise the OEM cannot source from the non-competitive CM as it will get negative profit), we can show that

$$\begin{aligned} & (2-b)^2(5-2b)^2m^2 - 4(7-4b)[p_0^2 + (2-b)mp_0] \\ > & (2-b)^2(5-2b)^2m^2 - 4(7-4b) \left[\frac{(2-b)^2}{4}m^2 + \frac{(2-b)^2}{2}m^2 \right] \\ = & [(2-b)^2(5-2b)^2 - 3(7-4b)(2-b)^2]m^2 \\ = & (2-b)^2[(5-2b)^2 - 3(7-4b)]m^2 \\ = & (1-b)^2(2-b)^2m^2 \geq 0, \end{aligned}$$

thus \underline{w}^F does exist and the participation constraint is reduced to the negotiated wholesale price is no less than \underline{w}^F .

Based on the forgoing analysis and recall that $K^F = w_2^F$, we obtain the GNB-characterized wholesale price as $w^{NF} = \min(p_0, \max(\underline{w}^F, K^F))$. Then Proposition 31 is proved.

Proof of Proposition 32: Similar to the proof of Proposition 30, We let the first-order derivative of Nash product Ω^L with respect to w to be zero to derive the extreme-value points. Substituting $\Pi_c^L(w)$ and $\Pi_o^F(w)$ into Ω^L , the FOC can be rewritten as

$$\begin{aligned} (1-\alpha)\Pi_c^L(w) \frac{-\partial\Pi_o^F(w)}{\partial w} &= \alpha\Pi_o^F(w) \frac{\partial\Pi_c^L(w)}{\partial w} \\ (1-\alpha)\Pi_c^L(w) \frac{(4-b-b^2)[(4-3b)m - (4-b-b^2)w]}{8(2-b)^2} &= \alpha\Pi_o^F(w) \frac{[(5-3b)m - (7-2b-b^2)w]}{4(2-b)}. \end{aligned}$$

Rearranging the forgoing equation yields a quadratic function of w as follows:

$$(4-b-b^2)(7-2b-b^2)w^2 - 2[(5-3b)(4-b-b^2) + 2(1-b)(2-b)\alpha]mw + [4(6-7b+2b^2)\alpha - (4-b-b^2)]m^2 = 0,$$

which has two roots,

$$w_1^L = \frac{(5-3b)(4-b-b^2) + 2(1-b)(2-b)\alpha + 2(2-b)\sqrt{(1-b)^2\alpha^2 + 2(16-8b-7b^2+2b^3+b^4)(1-\alpha)}}{(4-b-b^2)(7-2b-b^2)}m,$$

$$w_2^L = \frac{(5-3b)(4-b-b^2) + 2(1-b)(2-b)\alpha - 2(2-b)\sqrt{(1-b)^2\alpha^2 + 2(16-8b-7b^2+2b^3+b^4)(1-\alpha)}}{(4-b-b^2)(7-2b-b^2)}m.$$

Note that $w_2^L = K^L$.

Taking the first-order derivative of w_1^L with respect to α yields

$$\begin{aligned} \frac{\partial w_1^L}{\partial \alpha} &= \frac{2(2-b)m}{(4-b-b^2)(7-2b-b^2)} \left[(1-b) + \frac{2(1-b)^2\alpha - 2(16-8b-7b^2+2b^3+b^4)}{2\sqrt{(1-b)^2\alpha^2 + 2(16-8b-7b^2+2b^3+b^4)(1-\alpha)}} \right] \\ &= \frac{2(2-b)m}{(4-b-b^2)(7-2b-b^2)} \\ &\quad \times \frac{(1-b)\sqrt{(1-b)^2\alpha^2 + 2(16-8b-7b^2+2b^3+b^4)(1-\alpha)} - [16-8b-7b^2+2b^3+b^4 - (1-b)^2\alpha]}{\sqrt{(1-b)^2\alpha^2 + 2(16-8b-7b^2+2b^3+b^4)(1-\alpha)}} \\ &< 0, \end{aligned}$$

where the last inequality is due to

$$\begin{aligned} &\left[(1-b)\sqrt{(1-b)^2\alpha^2 + 2(16-8b-7b^2+2b^3+b^4)(1-\alpha)} \right]^2 - [16-8b-7b^2+2b^3+b^4 - (1-b)^2\alpha]^2 \\ &= (1-b)^2[(1-b)^2\alpha^2 + 2(16-8b-7b^2+2b^3+b^4)(1-\alpha)] - (16-8b-7b^2+2b^3+b^4)^2 \\ &\quad - (1-b)^4\alpha^2 + 2(16-8b-7b^2+2b^3+b^4)(1-b)^2\alpha \\ &= -(16-8b-7b^2+2b^3+b^4)(14-4b-9b^2+2b^3+b^4) < 0. \end{aligned}$$

So w_1^L is decreasing in α . Thus $w_1^L \geq w_1^L|_{\alpha=1} = \frac{4-3b}{4-b-b^2}m$, which violates our assumption that $w < \frac{4-3b}{4-b-b^2}m$. So w_1^L cannot be the optimal solution.

Next, taking the first-order derivative of w_2^L with respect to α yields

$$\begin{aligned}
\frac{\partial w_2^L}{\partial \alpha} &= \frac{2(2-b)m}{(4-b-b^2)(7-2b-b^2)} \left[(1-b) - \frac{2(1-b)^2\alpha - 2(16-8b-7b^2+2b^3+b^4)}{2\sqrt{(1-b)^2\alpha^2 + 2(16-8b-7b^2+2b^3+b^4)(1-\alpha)}} \right] \\
&= \frac{2(2-b)m}{(4-b-b^2)(7-2b-b^2)} \times \\
&\quad \frac{(1-b)\sqrt{(1-b)^2\alpha^2 + 2(16-8b-7b^2+2b^3+b^4)(1-\alpha)} + [16-8b-7b^2+2b^3+b^4 - (1-b)^2\alpha]}{\sqrt{(1-b)^2\alpha^2 + 2(16-8b-7b^2+2b^3+b^4)(1-\alpha)}} \\
&> 0.
\end{aligned}$$

So w_2^L is increasing in α . Thus $0 \leq w_2^L \leq w_2^L|_{\alpha=1} = \frac{5-3b}{7-2b-b^2}m = w^L \leq \frac{4-3b}{4-b-b^2}m$.

Letting $w_2^L(\alpha) = 0$ yields $\alpha = \frac{4-b-b^2}{4(2-b)(3-2b)} \equiv \alpha^L(0)$. Then we check the sign of

$\frac{\partial \Omega^L}{\partial w}|_{w_2^L=0}$ and $\frac{\partial \Omega^L}{\partial w}|_{w_2^L=w^L}$. If the former is positive and the latter is negative, then w_2^L maximizes Ω^L and the constrained Ω^L is unimodal. We can show that

$$\begin{aligned}
\frac{\partial \Omega^L}{\partial w}|_{w_2^L=0} &= (\Pi_c^L(0))^{\alpha-1} (\Pi_o^F(0))^{-\alpha} \left[\alpha \Pi_o^F(0) \frac{\partial \Pi_c^L(w)}{\partial w}|_{w_2^L=0} + (1-\alpha) \Pi_c^L(0) \frac{\partial \Pi_o^F(w)}{\partial w}|_{w_2^L=0} \right] \\
&= (\Pi_c^L(0))^{\alpha-1} (\Pi_o^F(0))^{-\alpha} \left[\alpha \frac{(4-3b)^2 m^2}{16(2-b)^2} \frac{(5-3b)m}{4(2-b)} + (1-\alpha) \frac{m^2}{8(2-b)} \frac{-2(4-b-b^2)(4-3b)m}{16(2-b)^2} \right] \\
&= (\Pi_c^L(0))^{\alpha-1} (\Pi_o^F(0))^{-\alpha} \frac{(4-3b)m^3}{64(2-b)^3} [4(2-b)(3-2b)\alpha - (4-b-b^2)].
\end{aligned}$$

As $w_2^L \geq 0$ requires $\alpha \geq \frac{4-b-b^2}{4(2-b)(3-2b)}$, substituting this requirement into $\frac{\partial \Omega^L}{\partial w}|_{w_2^L=0}$

leads to $\frac{\partial \Omega^L}{\partial w}|_{w_2^L=0} \geq 0$.

Similarly we have

$$\begin{aligned}
\frac{\partial \Omega^L}{\partial w}|_{w_2^L=w^L} &= (\Pi_c^L(w^L))^{\alpha-1} (\Pi_o^F(w^L))^{-\alpha} \left[\alpha \Pi_o^F(w^L) \frac{\partial \Pi_c^L(w)}{\partial w}|_{w_2^L=w^L} + (1-\alpha) \Pi_c^L(w^L) \frac{\partial \Pi_o^F(w)}{\partial w}|_{w_2^L=w^L} \right] \\
&= (\Pi_c^L(w^L))^{\alpha-1} (\Pi_o^F(w^L))^{-\alpha} \left[(1-\alpha) \Pi_c^L(w^L) \frac{\partial \Pi_o^F(w)}{\partial w}|_{w_2^L=w^L} \right] < 0.
\end{aligned}$$

Therefore, w_2^L is the optimal solution that maximizes Ω^L , and the constrained Ω^L is

unimodal.

Next, solving $\Pi_c^L(w) = \Pi_c^{RL}$ yields $\underline{w}^L = \frac{(5-3b)m - \sqrt{(5-3b)^2m^2 - (7-2b-b^2)[p_0^2 + 2p_0m]}}{7-2b-b^2}$.

As $0 \leq p_0 < \frac{4-3b}{4-b}m$ (otherwise the OEM cannot source from the non-competitive CM as it will get negative profit), we can show that

$$\begin{aligned}
& (5-3b)^2m^2 - (7-2b-b^2)[p_0^2 + 2p_0m] \\
> & (5-3b)^2m^2 - (7-2b-b^2) \left[\frac{(4-3b)^2}{(4-b)^2}m^2 + \frac{2(4-3b)}{4-b}m^2 \right] \\
= & [(4-b)^2(5-3b)^2 - (4-3b)(12-5b)(7-2b-b^2)] \frac{m^2}{(4-b)^2} \\
= & 4(4-8b+6b^2)(2-b)^2 \frac{m^2}{(4-b)^2} \geq 0,
\end{aligned}$$

where the last inequality is due to the fact that $4-8b+6b^2$ is always positive for $b \in [0, 1]$. Therefore, \underline{w}^L does exist and the participation constraint is reduced to the negotiated wholesale price is no less than \underline{w}^L .

Based on the forgoing analysis and recall that $K^L = w_2^L$, we obtain the GNB-characterized wholesale price as $w^{NL} = \min(p_0, \max(\underline{w}^L, K^L))$. Then Proposition 32 is proved.

Proof of Proposition 33

If the OEM determines the wholesale prices, the price lower bounds will be reached under there basic games. The competitive CM will receive the reserved profits re-

spectively: Π_c^{RS} , Π_c^{RF} and Π_c^{RL} . We have the following relationship among them.

$$\begin{aligned}
\Pi_c^{RL} - \Pi_c^{RS} &= \frac{(m + p_0)^2}{8(2 - b)} - \frac{(m + p_0)^2}{(4 - b)^2} \\
&= \frac{b^2(m + p_0)^2}{8(2 - b)(4 - b)^2} \\
&\geq 0 \\
\Pi_c^{RS} - \Pi_c^{RF} &= \frac{(m + p_0)^2}{(4 - b)^2} - \frac{[(2 - b)m + 2p_0]^2}{16(2 - b)^2} \\
&= \left[\frac{(2 - b)m + 2p_0}{4(2 - b)} + \frac{m + p_0}{4 - b} \right] \left[\frac{(2 - b)m + 2p_0}{4(2 - b)} - \frac{m + p_0}{4 - b} \right] \\
&= \frac{b[(2 - b)(8 - b)m + (16 - 6b)p_0][(2 - b)m - 2p_0]}{16(2 - b)^2(4 - b)^2} \\
&\geq 0.
\end{aligned}$$

The last inequality is due to our assumption $p_0 \leq \frac{2-b}{2}m$. Therefore, we have $\Pi_c^{RL} \geq \Pi_c^{RS} \geq \Pi_c^{RF}$ and hence the competitive CM always prefers the price leadership.

C.2 Another Decision-making Order

Here, we consider decision order 2 where the OEM decides the outsourcing proportion θ first and then the competitive CM decides its wholesale price w .

“simultaneous”-move game

The game sequence under the “simultaneous”-move game is as follows. First, the OEM makes the outsourcing decision θ and then the competitive CM announces the wholesale price w . Next, the OEM and the competitive CM decide their production quantities simultaneously. We solve it backwards.

First, we can derive the equilibrium production quantities as

$$q_o^{S*}(\theta, w) = \frac{(2-b)m + 2(p_0 - w)\theta - 2p_0}{4-b}, \quad q_c^{S*}(\theta, w) = \frac{m - (p_0 - w)\theta + p_0}{4-b}.$$

Next, by substituting $q_o^{S*}(\theta, w)$ and $q_c^{S*}(\theta, w)$ into (4.5), the competitive CM's profit is

$$\Pi_c^S(w) = \frac{[m - (p_0 - w)\theta + p_0]^2}{(4-b)^2} + \frac{[(2-b)m + 2(p_0 - w)\theta - 2p_0]w}{4-b}.$$

Taking the FOC and setting it to zero generates the optimal solution

$$w^S = \frac{(8-6b+b^2+2\theta)m - 2(1-\theta)(4-b-\theta)p_0}{2\theta(8-2b-\theta)}.$$

Therefore, $w^{S*} = \min\{p_0, w^S\}$. It can be verified that if $p_0 \geq \frac{8-6b+b^2+2\theta}{2(4-b+3\theta-b\theta)}m$, $w^{S*} = w^S$; otherwise, $w^{S*} = p_0$. When $w^{S*} = p_0$,

$$\Pi_o^S(\theta) = \frac{[(2-b)m + 2(p_0 - w^{S*})\theta - 2p_0]^2}{(4-b)^2},$$

so Π_o^S is constant in θ if $w^{S*} = p_0$. Then, if $p_0 \in [\frac{8-6b+b^2+2\theta}{2(4-b+3\theta-b\theta)}m, \frac{2-b}{2}m]$, substituting $w^{S*} = w^S$ into Π_o^S and rearranging it yields

$$\begin{aligned} \Pi_o^S &= \left[\frac{(2-b-\theta)m - 2(1-\theta)p_0}{8-2b-\theta} \right]^2 \\ \frac{\partial \Pi_o^S}{\partial \theta} &= \frac{2[(2-b-\theta)m - 2(1-\theta)p_0]}{8-2b-\theta} \frac{(-6+b)m + (14-4b)p_0}{(8-2b-\theta)^2}. \end{aligned}$$

Since

$$\begin{aligned}
\frac{2[(2-b-\theta)m - 2(1-\theta)p_0]}{8-2b-\theta} &\geq \frac{2[(2-b-\theta)m - (1-\theta)(2-b)m]}{8-2b-\theta} = \frac{2\theta(1-b)}{8-2b-\theta}m \geq 0; \\
\frac{(-6+b)m + (14-4b)p_0}{(8-2b-\theta)^2} &\geq \frac{(-6+b)(4-b+3\theta-b\theta) + (7-2b)(8-6b+b^2+2\theta)}{(4-b+3\theta-b\theta)(8-2b-\theta)^2}m \\
&= \frac{(1-b)(4-b)((8-2b-\theta))}{(4-b+3\theta-b\theta)(8-2b-\theta)^2}m \\
&= \frac{(1-b)(4-b)}{(4-b+3\theta-b\theta)(8-2b-\theta)} \geq 0,
\end{aligned}$$

$\frac{\partial \Pi_o^S}{\partial \theta} \geq 0$. Thus, the OEM will set $\theta^* = 1$.

OEM-as-leader game

Under this game, the OEM first decides its production quantity and the outsourcing proportion. Then the CM decides its wholesale price and production quantity. We also solve it backwards. According to function 4.5, we can show that Π_c^F is increasing in w , so it will set $w^{F*} = p_0$. The production quantity is $q_c(q_o) = \frac{m-q_o(\theta)}{2}$. Substituting w^{F*} and $q_c(q_o)$ into the OEM's profit function yields

$$\Pi_o^L = \frac{-(2-b)q_o^2 + [(2-b)m - 2p_0]q_o}{2},$$

which is constant in θ and reaches the maximum when $q_0 = \frac{(2-b)m-2p_0}{4-2b}$. We assume the OEM outsources all the production orders to the competitive CM if $w^{F*} = p_0$ ¹, so $\theta^* = 1$.

CM-as-leader game

The game sequence is as follows. First, the OEM makes the outsourcing decision θ . Then, the competitive CM decides on the wholesale price w and its production

¹This assumption is reasonable in practice, as the competitive CM normally can offer more value-added service other than product manufacturing. So it can win the OEM's orders when the non-competitive CMs do not have price advantage.

quantity q_c . Next, the OEM decides on its production quantity q_o .

We can show that the best response function of the OEM's production decision is

$$q_o^*(q_c, w) = \frac{m - bq_c - \theta w - (1 - \theta)p_0}{2}.$$

Then we can derive the competitive CM's profit function as

$$\Pi_c^L = \frac{[m - (2 - b)q_c + \theta w + (1 - \theta)p_0]q_c}{2} + \frac{(m - bq_c - \theta w - (1 - \theta)p_0)\theta w}{2}.$$

The competitive CM will decide w and q_c simultaneously. Their best response functions are

$$q_c(w) = \frac{m + (1 - \theta)p_0 + (1 - b)\theta w}{2(2 - b)}, \quad w(q_c) = \frac{m + (1 - b)q_c - (1 - \theta)p_0}{2\theta}.$$

Solving the above two equations yields

$$w^L = \frac{(5 - 3b)m - (3 - b)(1 - \theta)p_0}{(7 - 2b - b^2)\theta}, \quad q_c^L = \frac{(3 - b)m + (1 - \theta)(1 + b)p_0}{7 - 2b - b^2}.$$

Therefore, if $p_0 < \frac{5-3b}{3-b+(4-b-b^2)\theta}m$, we have $w^{L*} = p_0$; otherwise, $w^{L*} = w^L$.

When $w^{L*} = p_0$, the OEM's profit function is

$$\Pi_o^F = (q_o^F)^2 = \left[\frac{(7 - 5b)m - (7 - b)p_0 + b(1 + b)\theta p_0}{7 - 2b - b^2} \right]^2,$$

which is increasing in θ , so $\theta^* = 1$. When $w^{L*} = w^L$, the OEM's profit function is

$$\Pi_o^F = \left[\frac{2(1 - b)m - 4p_0 + 4\theta p_0}{7 - 2b - b^2} \right]^2,$$

which is also increasing in θ , so $\theta^* = 1$.

Since the results under decision order 2 for the three basic games are similar to

those under decision order 1, the equilibrium quantity timing decision shall be also the same as those in Proposition 29.

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