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Supply Chain Sourcing Under Asymmetric Information

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We study a supply chain with two suppliers competing over a contract to supply components to a manufacturer. One of the suppliers is a *big* company for whom the manufacturer's business constitutes a small part of his business. The other supplier is a *small* company for whom the manufacturer's business constitutes a large portion of his business. We analyze the problem from the perspective of the *big* supplier and address the following questions: What is the optimal contracting strategy that the big supplier should follow? How does the information about the small supplier's production cost affect the profits and contracting decision? How does the existence of the small supplier affect profits? By studying various information scenarios regarding the small supplier's and the manufacturer's production cost, we show, for example, that the big supplier benefits when the small supplier keeps its production cost private. We quantify the value of information for the big supplier and the manufacturer. We also quantify the cost (value) of the alternative-sourcing option for the big supplier (the manufacturer). We determine when an alternative-sourcing option has more impact on profits than information. We conclude with extensions and numerical examples to shed light on how system parameters affect this supply chain.

Key words: sourcing; supply contracts; cost information; game theory; mechanism design
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1. Introduction

In many supply chains, a manufacturer often faces the dilemma of sourcing from an established supplier (the *big* supplier) or a relatively less-known supplier (the *small* supplier). From a supplier's perspective this means that, when negotiating with the manufacturer, the supplier needs to take into account the manufacturer's other sourcing option. In late 2004, before introducing the new flash memory-based iPods, Apple Computers had the choice of sourcing the flash memory from suppliers such as SigmaTel or Intel[1] (see, e.g., Freid 2004). This was a critical decision for Apple because the flash memory chip was an important part of the iPod's cost regardless of the supplier choice. From Intel's perspective, this possible competition from SigmaTel meant that it had to take Apple's contract option with SigmaTel into account when offering a contract to Apple. The dynamics of the possible sourcing contract would be different for each of the two suppliers. A relatively *small* supplier, such as SigmaTel, perceives the opportunity to work with a well-known manufacturer, such as Apple, as a way to establish reputation. The manufacturer's business constitutes a large proportion (if not all) of the small supplier's business. These dynamics enable the manufacturer to dictate contract terms. However, a relatively *big* supplier, such as Intel, can provide expertise and production scale which enables production at a cheaper cost. The big supplier often works with many other customers and the manufacturer's business constitutes a relatively small part of his business. These dynamics enable the big supplier to dictate the contract terms (see, e.g., Holloway 2002 for further discussions). Another example is from the hearing implants industry. In 2004, Cochlear Inc., the world leader in hearing implants, had to decide whether to stay with its current supplier of the electronic assembly, *Megaline*,[2] a company belonging to a large North American electronics corporation, or to start working with a new small supplier, *Tinytronics*[2] (Raz and Stonecash 2004). Although, in this case, the product was not new and the manufacturer (Cochlear) was already working with one of the suppliers, the power dynamics between the manufacturer and the two suppliers would be similar to the Intel/Apple/SigmaTel case.

In this paper, we study the contracting problem faced by a well-known *big* supplier (he) who sells custom components to a manufacturer (she). To win the manufacturer's business, the big supplier must consider the manufacturer's alternative sourcing option, a *small* supplier (it). We consider two types of bargaining power between the manufacturer and the suppliers. When working with the *big* supplier, the manufacturer can either accept or reject the big supplier's offer. When working with the *small* supplier, the manufacturer makes a take-it-or-leave-it offer and the small supplier can only accept or reject the manufacturer's offer. We analyze the problem from the perspective of the big supplier whose objective is to win the contract with the manufacturer over his small supplier rival.

The information structure regarding production and processing costs plays an important role in sourcing and contracting decisions. For example, in technologically mature environments, such as in the memory chip industry, the production cost for a component is often well known (Billington and Kuper 2003). However, when the technology is new or when a new manufacturer or supplier enters the market (such as in the case of the small supplier), assessing its production cost is often difficult. In addition, even if companies work together for a while, they might not share their costs. For example, in the case of Cochlear and Megaline, the companies do not have an open book policy and thus Megaline does not know Cochlear's processing cost. In this paper, we consider various scenarios regarding the cost information available to the parties. For each scenario, we examine the optimal contracting strategy that the big supplier should follow given the manufacturer's strategy to maximize her profits. We also investigate the effect of information about the small supplier's production cost and the manufacturer's processing cost, as well as the effect of competition on the contracting strategy and profits.

The present paper is related to three streams of literature. The first stream focuses on the value of information and information sharing. The second stream focuses on (and also examines the effect of) incentive conflicts and information asymmetries. The last stream examines supply chain competition and sourcing strategies.

The first stream of literature focuses on the value of information and information sharing in supply chains. Lee et al. (1997) study the value of information in countering the bullwhip effect, while Lee et al. (2000) quantify the value of information sharing in a two-level supply chain. Cachon and Fisher (2000) and Moinzadeh (2002), for example, examine the benefits of sharing information in a multi-period setting. This research stream has attracted several researchers from the production and operations management field (see, e.g., Mishra et al. 2009, Thomas et al. 2009 and references therein). In general these papers focus on the effect of information sharing on supply chain performance. This stream of research is related to ours; however, in addition we consider the effect of incentives within the supply chain that may cause parties not to share or even misrepresent information.

The second stream of research examines the effect of incentives and information on supply chain coordination. Tsay et al. (1999) and Cachon (2003) provide an extensive review of supply chain contracts and coordination. Chen (2003) provides a comprehensive review of the asymmetric information models in supply chain management literature. The papers in this stream can be divided into two groups. The first group, to which our paper belongs, analyzes the effect of private information with respect to the cost parameters such as the papers by Corbett (2001), Ha (2001), Corbett et al. (2004), Lutze and Özer (2008), and Kaya and Özer (2009). The second group focuses on demand information and its influence on the supply chain decision-making such as Gal-Or (1991), Porteus and Whang (1999), Cachon and Lariviere (2001), and Özer and Wei (2006). Corbett (2001) studies a stochastic one-supplier one-buyer model with asymmetric information about the setup cost and backordering cost. The author shows how traditional allocations of decision rights to supplier and buyer can lead to inefficient outcomes when information asymmetries exist. Ha (2001) studies supplier–buyer contracting for a stochastic additive price dependent demand, when the buyer possesses private information with respect to his cost. He shows that, in the case of full information, coordination can be achieved; however, when the buyer possesses private information, it is no longer possible to achieve the single firm solution and the supplier's profit is lowered while the buyer's profit is improved.

The third stream of literature analyzes the effect of supply chain competition and sourcing strategies on supply chain performance. Within this stream there are two types of papers: some papers (such as ours) focus on sourcing and thus on the competition between suppliers over a manufacturer's business, while other papers examine the competition between retailers sourcing from a manufacturer (such as Bernstein and Federgruen 2005, Chayet and Hopp 2002, Ha, Li and Ng 2003, Li 2002, Narayanan et al. 2005, Savaskan and Van Wassenhove 2006). Elmaghraby (2000) provides an excellent review of the earlier work on supplier competition and sourcing policies. This literature focuses on the manufacturer's (the buyer's) problem of how to select suppliers, award contracts, and allocate procurement among them. Elmaghraby divides the literature along two dimensions: single/multiple selection periods and single/multiple sourcing. Our paper also considers a single sourcing and single selection problem. However, we focus on the problem from one of the suppliers' perspective, i.e., we solve for the big supplier's problem in which she is the stronger party and does not participate in an auction. Both suppliers are equal in all dimensions (such as quality, delivery time, and performance) except in production cost and bargaining power. In such a setting, as Elmaghraby points out, there are several compelling reasons for the manufacturer to follow a sole sourcing strategy. Given this environment, we determine the big supplier's contracting strategy.

We note that the second stream of literature focuses on models with one supplier and one manufacturer that have conflicting incentives and information asymmetries. However, the supply chain competition and sourcing literature (that is related to our paper) considers a one-manufacturer, multiple-suppliers problem in which the manufacturer conducts an auction among suppliers and then chooses the one with lowest bid. Thus, this literature looks at the problem from the perspective of the manufacturer. To the best of our knowledge, the present paper is the first to combine these two streams of literature by studying a two-supplier, one-manufacturer sourcing problem. However, unlike the sourcing literature, we study the problem from the perspective of one of the suppliers, specifically the big supplier. Hence, the question we investigate is the contracting strategy that the big supplier should follow to maximize his profit. We investigate how the information the big supplier has about the manufacturer and the small supplier's production costs affects the big supplier's contracting decision. We also investigate how much the big supplier loses when the manufacturer has the small supplier as an alternative sourcing option.

The rest of the paper is organized as follows. In section 2, we describe the model. In section 3, we study the interaction between the big supplier and the manufacturer in the absence of the small supplier. In sections 4–6, we study various information scenarios with respect to the manufacturer's processing cost and the small supplier's production cost, when the small supplier is present. In section 7, we compare different information scenarios and sourcing alternatives to examine the value of information and value of competition. In section 8, we use a numerical example to gain additional insights into the drivers of the system. In section 9, we present some extensions to our model. In section 10, we conclude.

2. The Model

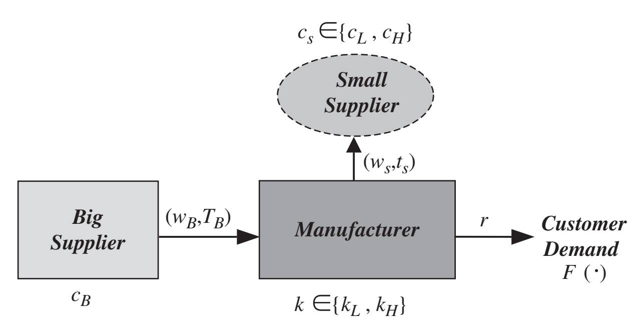
Consider a manufacturer who purchases custom components before observing demand for her product. She has two possible sourcing options: a small supplier who sells components at a wholesale price of w_s per unit and a fixed payment of t_s; or a big supplier who charges a wholesale price of w_B per unit and a fixed payment of T_B. The production costs for the small and big suppliers are c_s and c_B per unit, respectively. The big supplier has a cost advantage over the small supplier due to, for example, his scale and expertise,[3] and thus $c_B < c_s$. The value of c_s is equal to either c_L (if the small supplier is a low-cost supplier) or c_H (if it is a high-cost one), where $c_L < c_H$. This value can be either private information known only to the small supplier, or public information, depending on the information scenario we analyze. After purchasing the component from either of the suppliers, the manufacturer incurs a processing cost of k before she can sell the product to end customers. The value of k is equal to either k_L (if the manufacturer is a low-cost manufacturer) or k_H (if she is a high-cost one), where $k_L < k_H$. This value can be either private information known only to the manufacturer, or public information. The retail price for the product, r, is fixed and the salvage value is zero.

Demand for the product has a continuous distribution F with density function f, where F has a finite mean and an inverse F^{-1}. Also we define $\bar{F}(\xi) = 1 - F(\xi)$. The unmet demand is lost with no additional penalty cost. Figure 1 summarizes the model.

The sequence of events is as follows: (1) The big supplier offers the manufacturer a two-part pricing contract with a wholesale price of w_B per unit and a fixed payment T_B. (2) The manufacturer accepts or rejects the contract considering her possible contract option with the small supplier. If she accepts, she works with the big supplier only. If she rejects without having the small supplier option, the sequence of events terminates with both parties making zero profits. Otherwise, the manufacturer offers the two-part pricing contract (w_s, t_s) that the small supplier would accept. (3) The manufacturer orders from the supplier of her choice, the supplier delivers, the manufacturer produces. (4) The market uncertainty is realized, the manufacturer satisfies as much as possible, and the profits are realized.

Our main focus in this paper is on the first two stages of the game. To solve these two stages, we start with the third stage. The manufacturer's problem in the third stage is to decide how much to order from the supplier of her choice. Given a wholesale price $w \in \{w_B, w_s\}$ per unit and a fixed payment $T \in \{T_B, t_s\}$,

Figure 1 Model Summary



the manufacturer's expected profit for a stock level y is

$$\prod_M(y) = -(w+k)y + r\int_0^y \xi f(\xi)d\xi + ry\bar{F}(y) - T. \quad (1)$$

The profit function is concave, and the optimal order quantity is the critical fractile solution

$$y^*(w,k) = F^{-1}\left(\frac{r-(w+k)}{r}\right). \quad (2)$$

The manufacturer's optimal expected profit is thus:

$$\prod\nolimits_M^*(w,k) - T, \quad (3)$$

where

$$\prod\nolimits_M^*(w,k) = \prod_M(y^*(w,k)) = r\int_0^{y^*(w,k)} \xi f(\xi)d\xi. \quad (4)$$

The following lemma shows that the manufacturer's optimal expected profit is decreasing with the wholesale price and her processing cost. Specifically, the derivative of the manufacturer's profit with respect to her processing cost or the wholesale price is equal to the negative of her optimal order quantity. For every dollar increase in her cost, the manufacturer's profit decreases by the total amounts of units she orders. This lemma is useful in proving other results later in the paper. All proofs are deferred to Appendix A.

LEMMA 1. $\frac{\partial \prod_M^*(w,k)}{\partial k} = \frac{\partial \prod_M^*(w,k)}{\partial w} = -y^*(w,k).$

We analyze six cases to determine how the information structure and the existence of the small supplier in the market affect the big supplier's and the manufacturer's profits. Table 1 summarizes these six cases. The first two cases, SF and SA, represent the market scenarios in which the manufacturer does not have the option to work with the small supplier. The remaining four cases represent the scenario for which the manufacturer has the option to work with the small supplier. These four cases correspond to different information scenarios. In case F, all cost information is public. In particular, the big supplier knows the manufacturer's processing cost and both of them know the small supplier's production cost. In case A1, the small supplier's production cost is private information while the manufacturer's processing cost is known to the big supplier. In case A2, the small supplier's production cost is known to both the manufacturer and the big supplier while the manufacturer's processing cost is her private information. In case A3 both costs are private information. We investigate two important questions: First, how valuable is the information about the small supplier's production cost and the manufacturer's processing cost for the big supplier (*Value of Information*), and second, when and how much does the big supplier lose when the manufacturer has the small supplier as an alternative sourcing option (*Value of Competition*)? We note that when these values are negative they are interpreted as costs.

All six information and sourcing scenarios are plausible for a supply chain. Consider a supply chain that builds a commodity type product such as personal computers and the memory chips. The production cost of a memory chip is well known as well as the processing cost of putting this chip into a computer (Billington and Kuper 2003). The other extreme information scenario is when none of the supply chain partners have much information about others' production costs. Consider, for example, a new technology such as iPOD. Apple Computers is well known for keeping their new product introduction processes and costs private (Markoff and Lohr 2005). Often a new product requires custom made components or components that use recent technologies such as the flash memory. Hence, it is often difficult for others to know the cost of building such a technology. In sections 3–6, we study each of these scenarios separately. In section 7, we compare them to examine the value of information and value of competition.

Throughout the paper we use the following notation: We define w_B^z, T_B^z and $\Pi_B^z(\cdot)$ to be the big supplier's optimal wholesale price, transfer payment, and the resulting optimal expected profit for case z *where* $z \in \{SF, SA, F, A1, A2, A3\}$. Similarly we define $\Pi_M^z(\cdot)$ to be the manufacturer's optimal expected profit for case z.

Table 1 The Six Information Cases

		k known	k unknown
Without small supplier		Full info case (SF) Section 3.1	Asymmetric info case (SA) Section 3.2
With small supplier	c_s known	Full info case (F) Section 4	Asymmetric info case (A2) Section 6.1
	c_s unknown	Asymmetric info case (A1) Section 5	Two stage asymmetric info case (A3) Section 6.2

3. The Effect of Not Having Small Supplier Option

To determine the impact of the small supplier on the firms' profits, we first study the scenarios in which the manufacturer does not have the option to work with the small supplier. Two information scenarios are possible: Either the big supplier knows the manufacturer's processing cost (case SF) or the manufacturer's cost is her private information (Case SA).

3.1. The Single Supplier Full Information Case (Case SF)

The big supplier's objective is to maximize his profit by offering a wholesale price w_B, and a transfer payment T_B, while considering the manufacturer's possible outside option. Since the manufacturer does not have any other option (in this case), we assume without loss of generality that his outside profit is zero. Hence, the big supplier's problem is

$$\prod_B^{SF}(k) = \begin{cases} \underset{w_B,T_B}{\text{Max}} \prod_B(w_B,k,T_B) = (w_B - c_B)y^*(w_B,k) + T_B & (5) \\ \text{such that} & \\ \qquad \prod_M^*(w_B,k) - T_B \geq 0, & (6) \end{cases}$$

where $\prod_M^*(\cdot,\cdot)$ is defined in (4). The following theorem characterizes the solution.

THEOREM 1. *The big supplier's optimal wholesale price and transfer payments* (w_B^{SF}, T_B^{SF}) *are:*

$$w_B^{SF} = c_B,\ T_B^{SF} = \prod_M^*(c_B,k), \tag{7}$$

while the manufacturer and big supplier's optimal profits are

$$\prod_M^{SF}(k) = 0,\ \prod_B^{SF}(k) = \prod_M^*(c_B,k). \tag{8}$$

3.2. The Single Supplier Asymmetric Information Case (Case SA)

In some supply chains, the manufacturer's processing cost k is unknown to the big supplier, for example, when the manufacturer's product is a recent or a custom design product. The prior belief is such that the manufacturer has a low processing cost k_L with probability of q_L or a high processing cost $k_H > k_L$ with probability $q_H = 1 - q_L$. The big supplier can maximize his profit through a contract mechanism that screens the manufacturer's type. He also needs to ensure that this contract mechanism is at least as profitable for the manufacturer as her outside option, which is zero. To do so, the big supplier offers the manufacturer a menu of two-part pricing contracts, i.e., $(w_{BL}, T_{BL}), (w_{BH}, T_{BH})$ (for more on this type of analysis, see Kreps 1990). Given this menu of contracts, the sequence of events is similar to that in section 2. The big supplier's objective is to set the contract terms to maximize his expected profit

$$\prod_B((w_{BL},T_{BL}),(w_{BH},T_{BH})) = q_L[(w_{BL} - c_B)y^*(w_{BL},k_L) + T_{BL}] + q_H[(w_{BH} - c_B)y^*(w_{BH},k_H) + T_{BH}]. \tag{9}$$

Subject to

$$\prod_M^*(w_{BL},k_L) - T_{BL} \geq 0, \tag{10}$$

$$\prod_M^*(w_{BH},k_H) - T_{BH} \geq 0, \tag{11}$$

$$\prod_M^*(w_{BL},k_L) - T_{BL} \geq \prod_M^*(w_{BH},k_L) - T_{BH}, \tag{12}$$

$$\prod_M^*(w_{BH},k_H) - T_{BH} \geq \prod_M^*(w_{BL},k_H) - T_{BL}. \tag{13}$$

The first two inequalities are the participation constraints and the last two are the incentive compatibility constraints for the low- and high-cost manufacturers.

THEOREM 2. *The optimal solution to the big supplier's problem is*

(a) $w_{BL}^{SA} = c_B$ *and* $w_{BH}^{SA} = \bar{w}_{BH}$, *where* $\bar{w}_{BH}$ *is the solution to the equation*

$$w_{BH} = c_B + \frac{q_L}{q_H} r[y^*(w_{BH},k_L) - y^*(w_{BH},k_H)] \times f(y^*(w_{BH},k_H)). \tag{14}$$

$$T_{BL}^{SA} = \prod_M^*(c_B,k_L) - \prod_M^*(\bar{w}_{BH},k_L) + \prod_M^*(\bar{w}_{BH},k_H) \text{ and}$$

$$T_{BH}^{SA} = \prod_M^*(\bar{w}_{BH},k_H), \text{ where } \prod_M^*(\cdot,\cdot) \text{ is defined in (4).}$$

(b) $\prod_M^{SA}(k_L) = \prod_M^*(\bar{w}_{BH},k_L) - \prod_M^*(\bar{w}_{BH},k_H)$ *and* $\prod_M^{SA}(k_H) = 0.$ (15)

(c) $$\prod_B^{SA} = q_L T_{BL}^{SA} + q_H T_{BH}^{SA} + q_H(\bar{w}_{BH} - c_B)y^*(\bar{w}_{BH},k_H). \tag{16}$$

The theorem follows directly from properties of adverse selection in principal agent theory and the tradeoff between rent extraction and efficiency (see, e.g., Laffont and Mortimer 2001, Salanie 2005).

4. The Effect of Having Small Supplier Option under Full Information (Case F)

Starting with this section, we consider the scenario in which the manufacturer has the option of working with the small supplier. We study first the case in which both the small supplier's production cost, c_s, and the manufacturer's processing cost, k, are public information. Note that the small supplier's objective function is $(w_s - c_s)y^*(w_s,k) + t_s$, while the manufacturer's objective function is $\prod_M^*(w_s,k) - t_s$, where $\prod_M^*(w_s,k)$ is given in (4). Without loss of generality, the small supplier's reservation profit is assumed zero. The manufacturer optimally offers the small supplier the two-part pricing contract with $w_s = c_s$ and $t_s = 0$, because the manufacturer's profit is monotone in w_s (Lemma 1) and in t_s. Hence, the manufacturer's expected profit is $\prod_M^*(c_s,k)$.

The big supplier's problem is to maximize his profit by offering a wholesale price w_B and a transfer payment T_B. He must also consider the manufacturer's other sourcing option, i.e., the small supplier. Hence, the big supplier's problem is similar to the one in (5) where (6) is replaced by

$$\prod_M^*(w_B,k) - T_B \geq \prod_M^*(c_s,k). \tag{17}$$

This constraint ensures that the manufacturer's profit is at least as much as her profit when working with the small supplier.

THEOREM 3. *The big supplier's optimal wholesale price and transfer payments* (w_B^F, T_B^F) *are*

$$w_B^F = c_B,\ T_B^F = \prod\nolimits_M^*(c_B,k) - \prod\nolimits_M^*(c_s,k), \quad (18)$$

while the manufacturer and big supplier's optimal profits are

$$\begin{aligned}\prod\nolimits_M^F(c_s,k) &= \prod\nolimits_M^*(c_s,k),\\ \prod\nolimits_B^F(c_s,k) &= \prod\nolimits_M^*(c_B,k) - \prod\nolimits_M^*(c_s,k) > 0,\end{aligned} \quad (19)$$

where $\prod_M^*(\cdot,\cdot)$ *is defined in* (4).

Theorem 3 shows that the big supplier optimally sets the wholesale price equal to his cost and receives his payoff through the transfer payment, which is positive. The manufacturer's profit is equal to her profit under the contract with the small supplier. In other words, the big supplier sets the wholesale price in a way to leave the manufacturer indifferent between using him as the sole source or the small supplier. We assume that, when indifferent, the manufacturer chooses the big supplier as her supplier. Note that having the small supplier option helps the manufacturer to receive a better offer; i.e., $w_B^F \le w_B^{SF}$ and $T_B^F \le T_B^{SF}$. The big supplier, however, loses $\prod_M^*(c_s,k)$ due to the small supplier's existence. This analysis suggests that Apple Computers benefits from having SigmaTel as a potential source for the flash memory when dealing with Intel. The model helps quantify this benefit. As the above result shows, the size of this benefit closely depends on the production cost of Intel and SigmaTel as well as the iPod potential sales, i.e., the demand distribution.

5. The Effect of Asymmetric Information: When the Small Supplier's Production Cost is Private Information (Case A1)

Here we consider the case in which the manufacturer's processing cost k is public information while the small supplier's production cost c_s is its private information. Suppose the prior belief is such that the small supplier has a low production cost c_L with probability p_L or a high production cost $c_H > c_L$ with probability $p_H = 1 - p_L$. The manufacturer may design a contract mechanism to detect (or screen) the small supplier's type while maximizing her expected profit. Hence, the big supplier should offer the manufacturer a contract that is at least as profitable for the manufacturer as her possible screening contract with the small supplier.

5.1. The Manufacturer's Problem

The manufacturer offers the small supplier a menu of two-part pricing contracts that includes a wholesale price per unit plus a fixed payment, $(w_{sL}, t_{sL}), (w_{sH}, t_{sH})$. Given this menu of contracts, the small supplier chooses the contract that maximizes its profit. The manufacturer then decides on the order quantity that maximizes her expected profit. The small supplier delivers the ordered quantity and the manufacturer produces the final product. Demand realizes and the manufacturer satisfies demand as much as possible at a unit price r. The manufacturer's objective is to set the contract terms and maximize her expected profit

$$\begin{aligned}\prod\nolimits_M((w_{sL},t_{sL}),(w_{sH},t_{sH})) = p_L[\prod\nolimits_M^*(w_{sL},k) - t_{sL}]\\ + p_H[\prod\nolimits_M^*(w_{sH},k) - t_{sH}],\end{aligned} \quad (20)$$

where $\prod_M^*(\cdot,\cdot)$ is defined in (4), subject to participation and incentive compatibility constraints:

$$(w_{sL} - c_L)y^*(w_{sL},k) + t_{sL} \ge 0, \quad (21)$$

$$(w_{sH} - c_H)y^*(w_{sH},k) + t_{sH} \ge 0, \quad (22)$$

$$\begin{aligned}(w_{sL} - c_L)y^*(w_{sL},k) + t_{sL} \ge (w_{sH} - c_L)y^*(w_{sH},k)\\ + t_{sH},\end{aligned} \quad (23)$$

$$\begin{aligned}(w_{sH} - c_H)y^*(w_{sH},k) + t_{sH} \ge (w_{sL} - c_H)y^*(w_{sL},k)\\ + t_{sL}.\end{aligned} \quad (24)$$

These constraints ensure that the small supplier participates and self selects the contract designed for its type.

THEOREM 4.

(a) *The solution to the manufacturer's problem is*

$$w_{sL} = c_L \text{ and } t_{sL} = (c_H - c_L)y^*(w_{sH},k)$$
$$w_{sH} = c_L + (c_H - c_L)/p_H \text{ and } t_{sH} = -(p_L/p_H)t_{sL}.$$

(b) *The manufacturer's optimal expected profit is equal to* $\prod_M^*(\bar{w}_s,k)$, *where* $\bar{w}_s \in (c_L, c_H]$ *is the solution to the equation*

$$\prod\nolimits_M^*(\bar{w}_s,k) = p_L\prod\nolimits_M^*(c_L,k) + p_H\prod\nolimits_M^*(w_{sH},k), \quad (25)$$

and $\prod_M^*(\cdot,\cdot)$ *is defined in* (4).

Theorem 4 shows that the manufacturer can design a mechanism to induce truth-telling such that the low-cost small supplier chooses the contract (w_{sL}, t_{sL}) and the high-cost small supplier chooses the contract (w_{sH}, t_{sH}). The manufacturer's optimal expected profit is given in (25). From Theorem 4(a) we observe that the wholesale price offered to the high-cost small supplier is *decreasing* in the probability of the supplier having a high production cost. In other words, the manufacturer offers a lower wholesale price if she believes that the likelihood of facing an expensive supplier is high. This observation suggests that a small supplier benefits from keeping its manufacturing cost private. In the context of Apple Computers, SigmaTel has every incentive not to share its production cost of new flash memory technology. Being a relatively small supplier, SigmaTel benefits by keeping its production cost private.

5.2. The Big Supplier's Problem

The big supplier's problem is to maximize his profit, considering the manufacturer's other sourcing option with the small supplier. In this case, the manufacturer's reservation profit is given in (25). Hence, the big supplier's problem is similar to the one in (5) but (6) is replaced by

$$\prod\nolimits_M^*(w_B, k) - T_B \geq \prod\nolimits_M^*(\bar{w}_s, k), \tag{26}$$

where $\prod_M^*(\cdot,\cdot)$ is defined in (4) and $\prod_M^*(\bar{w}_s, k)$ is given by (25).

THEOREM 5. *The big supplier's optimal wholesale price and transfer payments* (w_B^{A1}, T_B^{A1}) *are*

$$w_B^{A1} = c_B,\ T_B^{A1} = \prod\nolimits_M^*(c_B, k) - \prod\nolimits_M^*(\bar{w}_s, k),$$

while the manufacturer and big supplier's profits are given by

$$\begin{aligned}\prod\nolimits_M^{A1}(k) &= \prod\nolimits_M^*(\bar{w}_s, k),\\ \prod\nolimits_B^{A1}(k) &= \prod\nolimits_M^*(c_B, k) - \prod\nolimits_M^*(\bar{w}_s, k) > 0,\end{aligned} \tag{27}$$

where $\prod_M^*(\cdot,\cdot)$ *is defined in* (4) *and* $\prod_M^*(\bar{w}_s, k)$ *is given by* (25).

6. The Effect of Asymmetric Information: When the Manufacturer's Processing Cost is Private Information (Cases A2 and A3)

Consider the case in which the manufacturer's processing cost k is unknown to the big supplier. Recall that the belief is such that the manufacturer has a low processing cost k_L with probability q_L or she has a high processing cost $k_H > k_L$ with probability $q_H = 1 - q_L$. As before, the big supplier maximizes his profit through a contract mechanism that screens the manufacturer's type. The big supplier offers the manufacturer a menu of two-part pricing contracts, $(w_{BL}, T_{BL}), (w_{BH}, T_{BH})$. However, he also needs to ensure that the contract mechanism is at least as profitable for the manufacturer as her possible contract with the small supplier. Hence, his objective is to set the contract terms to maximize his expected profit given in (9). His optimization problem is similar to that in (9)–(13) but (10) and (11) are replaced by the following participation constraints:

$$\prod\nolimits_M^*(w_{BL}, k_L) - T_{BL} \geq \prod\nolimits_M^R(k_L), \tag{28}$$

$$\prod\nolimits_M^*(w_{BH}, k_H) - T_{BH} \geq \prod\nolimits_M^R(k_H), \tag{29}$$

where $\prod_M^R(k)$ is the manufacturer's reservation profit from contracting with the small supplier. Note that, unlike the classical adverse selection problems (as in section 3.2), here the minimum reservation profits depend on the manufacturer's processing cost, i.e., her type. Next we consider the two information cases that affect the manufacturer's reservation profits.

6.1. The Small Supplier's Production Cost is Public Information (Case A2)

Recall that by (3) and Lemma 1, the manufacturer's optimal expected profit is decreasing in w and t. Hence, when the small supplier's production cost c_s is known, the manufacturer offers the small supplier a contract where $w_s = c_s$ and $t_s = 0$. Thus, her profit is equal to $\prod_M^*(c_s, k)$, which is defined in (4). In this case, the big supplier sets $(w_{BL}, T_{BL}), (w_{BH}, T_{BH})$ to maximize his objective function in (9) subject to the constraints (12), (13), (28) and (29) where the manufacturer's reservation profit is $\prod_M^R(k) = \prod_M^*(c_s, k)$. The supplier's and the manufacturer's resulting optimal expected profits are denoted by $\prod_B^{A2}(c_s)$ and $\prod_M^{A2}(c_s, k)$, respectively.

THEOREM 6. *The optimal solution to the big supplier's problem is*

(a) $w_{BL}^{A2} = c_B$ *and* $w_{BH}^{A2} = \min(\bar{w}_{BH}, c_s)$, *where* $\bar{w}_{BH}$ *is defined in (14)*

$$\begin{aligned}T_{BL}^{A2} &= \prod\nolimits_M^*(w_{BL}^{A2}, k_L) - \prod\nolimits_M^*(w_{BH}^{A2}, k_L)\\ &\quad + \prod\nolimits_M^*(w_{BH}^{A2}, k_H) - \prod\nolimits_M^*(c_s, k_H), \text{ and}\end{aligned}$$

$$T_{BH}^{A2} = \prod\nolimits_M^*(w_{BH}^{A2}, k_H) - \prod\nolimits_M^*(c_s, k_H),$$

where $\prod_M^*(\cdot,\cdot)$ *is defined in* (4).

(b) $$\begin{aligned}\prod\nolimits_M^{A2}(c_s, k_L) &= \prod\nolimits_M^*(w_{BH}^{A2}, k_L) - \prod\nolimits_M^*(w_{BH}^{A2}, k_H)\\ &\quad + \prod\nolimits_M^*(c_s, k_H), \text{ and}\end{aligned}$$

$$\prod\nolimits_M^{A2}(c_s, k_H) = \prod\nolimits_M^*(c_s, k_H)$$

(c) $$\begin{aligned}\prod\nolimits_B^{A2}(c_s) &= q_L T_{BL}^{A2} + q_H T_{BH}^{A2}\\ &\quad + q_H(w_{BH}^{A2} - c_B) y^*(w_{BH}^{A2}, k_H).\end{aligned}$$

Theorem 6 shows that the big supplier optimally offers the low-cost manufacturer a wholesale price that is equal to the big supplier's production cost. Yet, the manufacturer with a high processing cost receives a higher wholesale price offer.

6.2. The Small Supplier's Production Cost is Private Information (Case A3)

Next we analyze the case in which the small supplier's production cost c_s is private information. To maximize her expected profit, the manufacturer offers contracts to screen the small supplier. The resulting optimal expected profit would be the manufacturer's minimum reservation profit when contracting with the big supplier. The manufacturer's contract with the small supplier is exactly similar to that of section 5 and is characterized in Theorem 4. Thus, similar to the previous subsection, the big supplier sets (w_{BL}, T_{BL}), (w_{BH}, T_{BH}) to maximize his objective function in (9) subject to the constraints (12), (13), (28) and (29), where the manufacturer's reservation profit is $\prod_M^R(k) = \prod_M^*(\bar{w}_s, k)$, which is defined in (25).

THEOREM 7. *The optimal solution to the big supplier's problem is*

(a) $w_{BL}^{A3} = c_B$ *and* $w_{BH}^{A3} = \min(\bar{w}_{BH}, \bar{w}_s)$, *where* $\bar{w}_{BH}$ *and* $\bar{w}_s$ *are given in (14) and (25), respectively*
$T_{BL}^{A3} = \prod_M^*(w_{BL}^{A3}, k_L) - \prod_M^*(w_{BH}^{A3}, k_L) + \prod_M^*(w_{BH}^{A3}, k_H) - \prod_M^*(\bar{w}_s, k_H)$ *and*
$T_{BH}^{A3} = \prod_M^*(w_{BH}^{A3}, k_H) - \prod_M^*(\bar{w}_s, k_H)$, *where* $\prod_M^*(.,.)$ *is defined in (4).*

(b)
$$\prod_M^{A3}(k_L) = \prod_M^*(w_{BH}^{A3}, k_L) - \prod_M^*(w_{BH}^{A3}, k_H) + \prod_M^*(\bar{w}_s, k_H) \text{ and}$$
$$\prod_M^{A3}(k_H) = \prod_M^*(\bar{w}_s, k_H). \tag{30}$$

(c)
$$\prod_B^{A3} = q_L T_{BL}^{A3} + q_H T_{BH}^{A3} + q_H(w_{BH}^{A3} - c_B) y^*(w_{BH}^{A3}, k_H). \tag{31}$$

7. The Value of Information (*VOI*) and the Value of Competition (*VOC*)

We compare the six cases analyzed in sections 3–6 and examine the impact of information and competition on the big supplier and the manufacturer's profits as well as the supply chain as a whole.

7.1. The Value of Information about the Small Supplier's Cost

We determine the value of information on the small supplier's production cost by comparing case F with case A1 and case A2 with case A3. Recall that, for cases A1 and A3, the parties' profits depend on the costs of the two types of small suppliers. Hence, when comparing the four different cases for the manufacturer and the big supplier, we use the *expected* value of information on the small supplier's cost. Recall that the belief is such that the small supplier is a low-cost supplier (c_L) with probability p_L and a high-cost supplier (c_H) with probability $p_H = 1 - p_L$. Thus the big supplier and the manufacturer's ex ante expected profit in the full information case are

$$\prod_j^F(k) = p_L \prod_j^F(c_L, k) + p_H \prod_j^F(c_H, k) \quad \text{for } j \in \{B, M\}. \tag{32}$$

Using (19), the big supplier's profit can be expressed as a function of the manufacturer's profit

$$\prod_B^F(k) = \prod_M^*(c_B, k) - \prod_M^F(k). \tag{33}$$

Similarly, the manufacturer's ex ante expected profit in case A2 is

$$\prod_M^{A2}(k) = p_L \prod_M^{A2}(c_L, k) + p_H \prod_M^{A2}(c_H, k), \tag{34}$$

while the big supplier's expected profit in the A2 case is

$$\prod_B^{A2} = p_L \prod_B^{A2}(c_L) + p_H \prod_B^{A2}(c_H), \tag{35}$$

where $\prod_M^{A2}(c_s, k)$ and $\prod_B^{A2}(c_s)$ for $s = \{L, H\}$ are given in Theorem 6.

When the manufacturer's processing cost is public information, we define the big supplier and the manufacturer's expected value of information on the small supplier's production cost as

$$VOI_j^1(k) \equiv \prod_j^F(k) - \prod_j^{A1}(k), \text{ for } j \in \{B, M\}. \tag{36}$$

Similarly, when the manufacturer's cost is private, her value of information is

$$VOI_M^2(k) \equiv \prod_M^{A2}(k) - \prod_M^{A3}(k), \tag{37}$$

while the big supplier's expected value of information is

$$VOI_B^2 \equiv \prod_B^{A2} - \prod_B^{A3}, \tag{38}$$

where $\prod_M^z(k)$ and $\prod_B^z(k)$ for $z \in \{F, A1, A2, A3\}$ are defined in (27), and (30)–(35).

THEOREM 8. *When the manufacturer's processing cost is public, the value of information on the small supplier's cost is as follows.*

(a) $VOI_M^1(k) = p_H[\prod_M^*(c_H, k) - \prod_M^*(w_{sH}, k)] \geq 0$, *and*

(b) $VOI_B^1(k) = -VOI_M^1(k) \leq 0$

THEOREM 9. *When the manufacturer's processing cost is private:*

(a) For the manufacturer, the value of information on the small supplier's cost is as follows.

(i) If $q_H > \bar{q}_H$, *then* $VOI_M^2(k_i) = VOI_M^1(k_H) > 0$ *for* $i \in \{L, H\}$, *where*

$$\bar{q}_H = \frac{1}{1 + \frac{c_L - c_B}{\alpha}} \in (0, 1), \tag{39}$$

and
$$\alpha = r[y^*(\bar{w}_{BH}, k_L) - y^*(\bar{w}_{BH}, k_H)]f(y^*(\bar{w}_{BH}, k_H)) \qquad (40)$$
and $\bar{w}_{BH}$ *is given in (14).*

(ii) If $q_H < \bar{\bar{q}}_H$*, then* $VOI_M^2(k_i) = VOI_M^1(k_i) > 0$ *for* $i \in \{L, H\}$*, where*

$$\bar{\bar{q}}_H = \frac{1}{1 + \frac{c_H - c_B}{\alpha}} \in (0, 1). \qquad (41)$$

(iii) If $\bar{\bar{q}}_H \le q_H \le \bar{q}_H$*, then* $VOI_M^2(k_L) > 0$*, and* $VOI_M^2(k_H) = VOI_M^1(k_H) > 0$.

(b) For the big supplier, the value of information is $VOI_B^2 = -VOI_M^1(k_H) < 0$ *if* $q_H > \bar{q}_H$*, and inconclusive otherwise.*

Theorems 8 and 9 show that the manufacturer benefits if both the big supplier and she knew the small supplier's cost. In contrast, the big supplier might be better off when the small supplier's cost is its private information. With respect to the manufacturer, it is interesting to note that, while she is always better off with more information, as Theorem 9(a) shows, the value of this information depends on her processing cost as well as the belief about her processing cost. Note that the high-cost manufacturer's value of information depends only on her own cost (k_H) regardless of the belief about her cost. For the low-cost manufacturer the situation is more complex. When the belief is such that the manufacturer is more likely to have a low processing cost (as in Theorem 9(a)(ii)), her value of information depends on her own cost only. However, when the manufacturer is less likely to have a low processing cost (as in Theorem 9(a)(i)), her value of information depends also on the high processing cost k_H. Intuitively, it is more difficult for the big supplier to detect that a low-cost manufacturer pretends to have a high processing cost. This would allow a low-cost manufacturer to extract more information rent from the big supplier. This value also depends on the difference between the high and low processing costs. In other words, the big supplier has to pay more information rent to the low-cost manufacturer to induce her not to pretend to have high processing cost and choose the contract designed for her. For the supplier the situation is a bit more delicate. Although he benefits from the lack of information when the manufacturer is likely to have high processing cost, when the opposite is true, the big supplier might actually benefit from having the information about the small supplier. Thus in these cases, both the manufacturer and the big supplier benefit from knowing that information. We remark that we were unable to show either analytically or numerically whether VOI_B^2 is positive when q_H is high. Hence, we state this result to be inconclusive at this point.

Theorem 8 shows that when the manufacturer's cost is public the manufacturer benefits on average $VOI_M^1(k)$ from knowing the small supplier's production cost. Theorem 9 shows that when the manufacturer's cost information is private, and she is more likely to have a high processing cost, the manufacturer benefits on average $VOI_M^1(k_H)$. In both cases, the big supplier loses exactly the same amount on average. This leads us to the following corollary.

Corollary 10.

(a) $\prod_M^F(k) + \prod_B^F(k) = \prod_M^{A1}(k) + \prod_B^{A1}(k) = \prod_M^*(c_B, k)$

(b) If $q_H > \bar{q}_H$ *then* $\prod_M^{A2}(k_i) + \prod_B^{A2} = \prod_M^{A3}(k_i) + \prod_B^{A3}$ *for* $i \in \{L, H\}$*, where* $\bar{q}_H$ *is given by (39).*

By Corollary 10, when the manufacturer's processing cost is public, the total supply chain profits are the same regardless of whether the small supplier's cost information is public or private and it is equal to the coordinated/integrated supply chain profits. Thus, by Theorem 6 and Corollary 10, the total supply chain profits are independent of the information about the small supplier's cost; however, the share of profit that each party receives depends on the information regarding the small supplier's cost. When this information is known, the manufacturer receives a larger share of the total supply chain profit than when the information is private. By part (*b*) of Corollary 10, we observe that the total supply chain profits does not depend on the small supplier's cost information only when the manufacturer is likely to have a high cost.

7.2. The Value of Competition

The existence of the small supplier affects the big supplier and the manufacturer's profits. We refer to the difference in profits due to the small supplier as the *value of competition*. From the big supplier's perspective, this difference is the cost (since competition has a negative value for the big supplier) of having to compete with the small supplier on the manufacturer's business. We define the value of competition similar to the value of information as an expected value, which enables us to compare value of competition to value of information. In particular, when the manufacturer's cost is public information, we define the value of competition as

$$VOC_j^1(k) \equiv \prod_j^F(k) - \prod_j^{SF}(k) \text{ for } j \in \{B, M\}. \qquad (42)$$

Similarly, when the manufacturer's cost is private, the manufacturer's value of competition is

$$VOC_M^2(k) \equiv \prod_M^{A2}(k) - \prod_M^{SA}(k), \qquad (43)$$

while the big supplier's value of competition is

$$VOC_B^2 \equiv \prod_B^{A2} - \prod_B^{SA}, \tag{44}$$

where $\prod_M^z(k)$ and $\prod_B^z(k)$ for $z \in \{SF, SA, F, A2\}$ are defined in (8), (15)–(16) and (32)–(35).

THEOREM 11. *When the manufacturer's processing cost is public,*

(a) $VOC_M^1(k) = \prod_M^F(k) \geq 0.$

(b) $VOC_B^1(k) = -VOC_M^1(k) \leq 0.$

THEOREM 12. *When the manufacturer's processing cost is private,*

(a) *The value of competition for the manufacturer is as follows.*

(i) *If* $q_H > \bar{q}_H$, *then* $VOC_M^2(k_i) = VOC_M^1(k_H) > 0$ *for* $i \in \{L, H\}$, *where* $\bar{q}_H$ *is given by (39).*

(ii) *If* $q_H < \bar{\bar{q}}_H$, *then* $VOC_M^2(k_L) = \prod_M^F(k_L) - [\prod_M^*(\bar{w}_{BH}, k_L) - \prod_M^*(\bar{w}_{BH}, k_H)] > 0$, *and* $VOC_M^2(k_H) = VOC_M^1(k_H) > 0$, *where* $\bar{\bar{q}}_H$ *is given by (41) and* $\bar{w}_{BH}$ *is defined in (14).*

(iii) *If* $\bar{\bar{q}}_H \leq q_H \leq \bar{q}_H$, *then* $VOC_M^2(k_L) = p_L \prod_M^*(c_L, k_L) + p_H \prod_M^*(c_H, k_H) - p_L[\prod_M^*(\bar{w}_{BH}, k_L) - \prod_M^*(\bar{w}_{BH}, k_L)] > 0$, *and* $VOC_M^2(k_H) = VOC_M^1(k_H) > 0$.

(b) *The value of competition for the big supplier is* $VOC_B^2 = -VOC_M^1(k_H) < 0$ *if* $q_H > \bar{q}_H$, *and inconclusive otherwise.*

Next we compare the value of information to the value of competition.

THEOREM 13.

(a) $VOC_M^1(k) \geq VOI_M^1(k) \geq 0$ *and* $VOC_B^1(k) \leq VOI_B^1(k) \leq 0.$

(b) $VOC_M^2(k_i) \geq VOI_M^2(k_i) > 0$ *for* $i \in \{L, H\}$.

(c) $VOC_B^2 \leq VOI_B^2 \leq 0$ *if* $q_H > \bar{q}_H$, *and inconclusive otherwise.*

Theorem 13 shows that, from the manufacturer's perspective, having the small supplier as an alternative source (Value of Competition) always has higher impact on profits than having more information on the small supplier's production cost (Value of Information). From the big supplier's perspective, the competition effect dominates the information effect when the manufacturer's cost is public. However, when the manufacturer's cost is private, the competition effect dominates only when the manufacturer is likely to have a high processing cost.

7.3. The Value of Information about the Manufacturer's Cost

Next we examine the value of information on the manufacturer's processing cost by comparing case SF with case SA, Case F with case A2, and case A1 with case A3 (comparing columns instead of rows in Table 1). Similar to section 7.1, when comparing the different information cases for the big supplier, we define the expected value of information on the manufacturer's cost. Recall that the belief is such that the manufacturer is a low-cost manufacturer (k_L) with probability q_L and a high-cost manufacturer (k_H) with probability $q_H = 1 - q_L$. Thus the big supplier's ex ante expected profit in case SF (single supplier, full information) is

$$\prod_B^{SF} = q_L \prod_B^{SF}(k_L) + q_H \prod_B^{SF}(k_H), \tag{45}$$

his ex ante expected profit in case F (two-supplier, full information) is

$$\prod_B^F(c_s) = q_L \prod_B^F(c_s, k_L) + q_H \prod_B^F(c_s, k_H), \tag{46}$$

and his ex ante expected profit in case A1 (two-supplier manufacturer's cost is private)

$$\prod_B^{A1} = q_L \prod_B^{A1}(k_L) + q_H \prod_B^{A1}(k_H). \tag{47}$$

We start with the case where the manufacturer does not have an alternative sourcing option and examine the value of knowing the manufacturer's processing cost in this case.

THEOREM 14. *Without a small supplier, the value of information on the manufacturer's processing cost is as follows.*

(a) $\prod_M^{SF}(k_L) \leq \prod_M^{SA}(k_L)$ *and* $\prod_M^{SF}(k_H) = \prod_M^{SA}(k_H) = 0$ *for all* q_H.

(b) $\prod_B^{SF} \geq \prod_B^{SA}$ *for all* q_H.

The theorem states that, in the absence of a small supplier, the manufacturer has an incentive to keep her information private, while the big supplier will benefit from knowing the manufacturer's cost. As the next theorem shows, when there is another sourcing alternative the situation is a bit more intricate.

THEOREM 15. *With a small supplier, the value of information on the manufacturer's processing cost is as follows.*

(a)

(i) *If* $q_H > \bar{q}_H$, *then* $\prod_M^F(c_s, k_L) \leq \prod_M^{A2}(c_s, k_L)$ *and* $\prod_M^F(c_s, k_H) = \prod_M^{A2}(c_s, k_H)$ *for* $s \in \{L, H\}$, *while* $\prod_M^{A1}(k_L) \leq \prod_M^{A3}(k_L)$ *and* $\prod_M^{A1}(k_H) = \prod_M^{A3}(k_H)$, *where* $\bar{q}_H$ *is given by* (39).

(ii) *If* $q_H < \bar{\bar{q}}_H$, *then* $\prod_M^F(c_s, k_i) = \prod_M^{A2}(c_s, k_i)$ *and* $\prod_M^{A1}(k_i) = \prod_M^{A3}(k_i)$ *for* i, $s \in \{L, H\}$, *where* $\bar{\bar{q}}_H$ *is given by* (41).

(iii) *If* $\bar{\bar{q}}_H \leq q_H \leq \bar{q}_H$, *then* $\prod_M^F(c_L,k_L) = \prod_M^{A2}(c_L,k_L)$, $\prod_M^F(c_H,k_L) \leq \prod_M^{A2}(c_H,k_L)$, *and* $\prod_M^F(c_s,k_H) = \prod_M^{A2}(c_s,k_H)$, *while* $\prod_M^{A1}(k_L) \leq \prod_M^{A3}(k_L)$ *and* $\prod_M^{A1}(k_H) = \prod_M^{A3}(k_H)$, *where* $\bar{q}_H$ *is given by* (39) *and* $\bar{\bar{q}}_H$ *is given by* (41).

(b) $\prod_B^F(c_s) \geq \prod_B^{A2}(c_s)$ *for* $s \in \{L,H\}$, *and* $\prod_B^{A1} \geq \prod_B^{A3}$ *for every* $q_H \in [0,1]$.

Theorem 15 shows that when the manufacturer is likely to have high processing cost (i.e., $q_H > \bar{q}_H$) the manufacturer benefits from keeping her information private, while the big supplier benefits from knowing the manufacturer's cost. Thus, it is unclear whether the supply chain as a whole will benefit from having information regarding the manufacturer's processing cost. However, when the manufacturer is likely to have low processing cost (i.e., $q_H < \bar{\bar{q}}_H$), the manufacturer is indifferent between sharing her information with the big supplier or keeping it private, while the big supplier benefits from knowing the manufacturer's cost. Thus, in this case, from a supply chain perspective it is always beneficial to share information on the manufacturer's processing cost. When the probability of having a low processing cost is in the intermediate level ($\bar{q}_H \geq q_H \geq \bar{\bar{q}}_H$), the value of sharing information about the manufacturer's cost depends on the type of small supplier. When the manufacturer is facing a low-cost small supplier, she is indifferent between sharing her information with the big supplier or keeping it private, however, if she faces a high-cost small supplier, she benefits from keeping her information private.

8. A Numerical Example

In this section, we quantify the big supplier's and the manufacturer's profits as well as the wholesale price and order quantity using a numerical example. We show how changes in the parameters of the problem affect the value of information on the small supplier's production cost and the manufacturer's processing cost. We also quantify the value of competition on the big supplier's and manufacturer's profits and compare it with the value of information. Consider a supply chain in which the production cost for the big supplier is $c_B = \$1$. The production cost for the small supplier is either $c_L = \$2$, or $c_H = \$4$. The probability of the small supplier having low-cost is $p_L = 0.5$. The manufacturer's processing cost is either $k_L = \$1$ or $k_H = \$2$. The probability of the manufacturer having low-cost is $q_L = 0.5$. The retail price $r = \$10$ and demand is distributed uniformly on the interval $[0,1]$. These parameters are used throughout this section to illustrate our results. Appendix B presents the solution to our problem using uniform demand distribution that enables us to obtain closed form solutions to the problem, which is used to solve the numerical example in this section.

Table 2 presents the results. For example, when both the manufacturer's processing cost and the small supplier's production cost are private (Case A3), the big supplier offers the manufacturer a menu of contracts ($1.00, $1.55) and ($2.00, $0.80) such that the low-cost manufacturer would prefer to pay a wholesale price of $1.00 per unit and a transfer price of $1.55, while the high-cost manufacturer would pay a wholesale price of $2.00 per unit and a transfer price of $0.80. The resulting profits of the low- and high-cost manufacturers are $1.65 and $1.00, respectively, and the big supplier's profit is equal to $1.475.

The table illustrates that the manufacturer is worse off while the big supplier is better off when the small supplier's cost is private (as also shown by Theorem 8). For example, in case F, when the manufacturer has low processing cost, her expected profit is $\$1.85 = 0.5\times 2.45+0.5\times 1.25$, compared with $1.45 for case A1. In other words, the manufacturer loses $0.40 (22%) from her expected profit when the small supplier's cost information is private. However, this lack of information benefits the big supplier. The big supplier's expected profit is $\$1.35 = 0.5\times 1.95+0.5\times 0.75$ in case F whereas his expected profit is $1.75 in case A1. Hence, the big supplier benefits by $0.40. Thus, when the manufacturer has low processing cost, the value of information on the small supplier's production cost is $VOI_M^1(k_L) = \$0.40$ for the manufacturer and $VOI_B^1(k_L) = \$-0.40 < 0$ for the big supplier. This result also illustrates that the total expected supply chain profit (equal to $3.20) does not change when the small supplier's cost is private information (as shown by Corollary 10) and is equal to the coordinated supply chain profits.

Table 2 also shows that in case SF, when the manufacturer has a low processing cost, her profit is 0, while her expected profit in case F is $1.85. Thus, the value of having an alternative sourcing option (*VOC*) for the low-cost manufacturer in this case is $VOC_M^1(k_L) = \$1.85$. Similarly, from the big supplier's perspective, if the manufacturer has low processing cost, his profit in case SF is $3.20, while his expected profit in case F is $1.35. Thus, the competition with the small supplier costs the big supplier $VOC_B^1(k_L) = \$-1.85$. Figure 2 compares the value of competition and the value of information for the manufacturer and the big supplier, when the manufacturer's cost is private, as a function of q_L. For this particular example both for the big supplier and the manufacturer, the competition effect dominates the information effect. This result is shown in Theorem 13 for the manufacturer and for supplier when q_L is low. Figure 2 illustrates that it holds for the big supplier for all q_L values. The difference between value of competition and information gets larger with higher q_L.

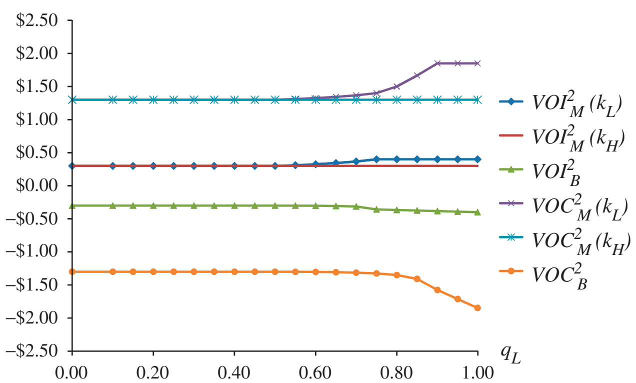
Table 2 Numerical Results

Case	Wholesale price, w_B and transfer price, T	Order quantity, y	Mfg's profit	Big supplier's profit
Case SF	$w_B^{SF}(k_i) = \$1.00$ for $i = L, H$	$y(w_B^{SF}, k_L) = 0.80$		
		$y(w_B^{SF}, k_H) = 0.70$		
	$T_B^{SF}(k_L) = \$3.20$		$\prod_M^{SF}(k_L) = \$0$	$\prod_B^{SF}(k_L) = \$3.20$
	$T_B^{SF}(k_H) = \$2.45$		$\prod_M^{SF}(k_H) = \$0$	$\prod_B^{SF}(k_H) = \$2.45$
Case SA	$w_{BL}^{SA}(k_L) = \$1.00$	$y(w_{BL}^{SA}, k_L) = 0.80$	$\prod_M^{SA}(k_L) = \$0.65$	$\prod_B^{SA} = \$2.475$
	$T_{BL}^{SA}(k_L) = \$2.55$			
	$w_{BH}^{SA}(k_H) = \$2.00$	$y(w_{BH}^{SA}, k_H) = 0.60$	$\prod_M^{A3}(k_H) = \$0$	
	$T_{BH}^{SA}(k_H) = \$1.80$			
Case F	$w_B^F(c_s, k_i) = \$1.00$ for $s = L, H, i = L, H$	$y(w_B^F, k_L) = 0.80$		
		$y(w_B^F, k_H) = 0.70$		
	$T_B^F(c_L, k_L) = \$0.75$		$\prod_M^F(c_L, k_L) = \$2.45$	$\prod_B^F(c_L, k_L) = \$0.75$
	$T_B^F(c_H, k_L) = \$1.95$		$\prod_M^F(c_H, k_L) = \$1.25$	$\prod_B^F(c_H, k_L) = \$1.95$
	$T_B^F(c_L, k_H) = \$0.65$		$\prod_M^F(c_L, k_H) = \$1.80$	$\prod_B^F(c_L, k_H) = \$0.65$
	$T_B^F(c_H, k_H) = \$1.65$		$\prod_M^F(c_H, k_H) = \$0.80$	$\prod_B^F(c_H, k_H) = \$1.65$
Case A1	$w_B^{A1}(k_i) = \$1.00$ for $i = L, H$	$y(w_B^{A1}, k_L) = 0.80$		
		$y(w_B^{A1}, k_H) = 0.70$		
	$T_B^{A1}(k_L) = \$1.75$		$\prod_M^{A1}(k_L) = \$1.45$	$\prod_B^{A1}(k_L) = \$1.75$
	$T_B^{A1}(k_H) = \$1.45$		$\prod_M^{A1}(k_H) = \$1.00$	$\prod_B^{A1}(k_H) = \$1.45$
Case A2	$w_{BL}^{A2}(k_L) = \$1.00$	$y(w_{BL}^{A2}, k_L) = 0.80$	$\prod_M^{A2}(c_L, k_L) = \$2.45$	$\prod_B^{A2}(c_L) = \$0.675$
	$T_{BL}^{A2}(c_L, k_L) = \$0.75$		$\prod_M^{A2}(c_H, k_L) = \$1.45$	$\prod_B^{A2}(c_H) = \$1.675$
	$T_{BL}^{A2}(c_H, k_L) = \$1.75$			
	$w_{BH}^{A2}(k_H) = \$2.00$	$y(w_{BH}^{A2}, k_H) = 0.60$	$\prod_M^{A2}(c_L, k_H) = \$1.80$	
	$T_{BH}^{A2}(c_L, k_H) = \$0$		$\prod_M^{A2}(c_H, k_H) = \$0.80$	
	$T_{BH}^{A2}(c_H, k_H) = \$1.00$			
Case A3	$w_{BL}^{A3}(k_L) = \$1.00$	$y(w_{BL}^{A3}, k_L) = 0.80$	$\prod_M^{A3}(k_L) = \$1.65$	$\prod_B^{A3} = \$1.475$
	$T_{BL}^{A3}(k_L) = \$1.55$			
	$w_{BH}^{A3}(k_H) = \$2.00$	$y(w_{BH}^{A3}, k_H) = 0.60$	$\prod_M^{A3}(k_H) = \$1.00$	
	$T_{BH}^{A3}(k_H) = \$0.80$			

Next we illustrate the effect of the belief structure regarding the small supplier's production cost. Figure 3 presents the *expected* profit of the manufacturer and the supplier as well as the total supply chain profits as a function of the probability of facing a low-cost small supplier for the parameters of the numerical example above. For example, when $p_L = 0.5$, the manufacturer's expected profit for the full information case is equal to $1.575 = 0.5\times0.5[2.45+1.25]+0.5\times0.5[1.80+0.80]$. The figure illustrates that when the probability of facing a low-cost small supplier increases, the manufacturer's share of the total supply chain profit increases, while the big supplier's share decreases. Note also that the total supply chain profits remain constant. These observations hold for both case F and case A1; however, in the case of full information the big supplier and the manufacturer split the profits equally when the probability of small supplier having low cost $p_L = 0.35$, while in case A1, their profits are equal when $p_L = 0.67$. It is also interesting to note that the value of information (which is the difference between $\prod_M^F$ and $\prod_M^{A1}$ or $\prod_B^F$ and $\prod_B^{A1}$) is first increasing and then decreasing in p_L with the maximum achieved when $p_L = 0.55$. Thus, when the probability of low-cost small supplier is very high or very low, the manufacturer does not lose much by not knowing what type of small supplier she is facing. When the probability of the low-cost supplier is close to 0.5, however, it becomes difficult to guess whether the small supplier has high or low production cost. Thus, the manufacturer needs to pay the low-cost small supplier high information rent, which reduces the manufacturer's expected profit from her contracting option with the small supplier. We have similar observations for cases A2 and A3.

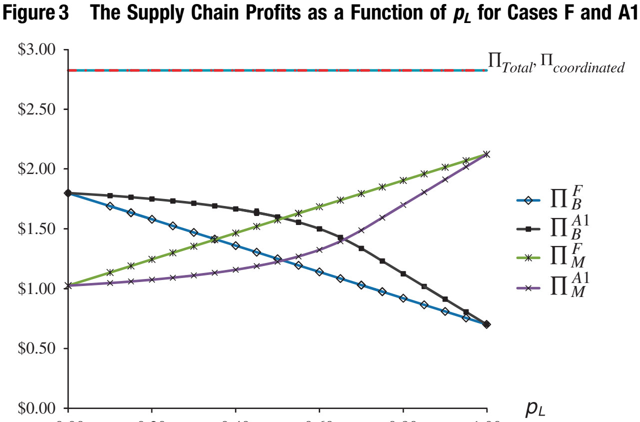
Finally, we investigate the effect of the belief about the manufacturer's processing cost. Figure 4 presents

Figure 2 Comparison of the Value of Information and Value of Competition



the *expected* profits as a function of the probability of the manufacturer having low processing cost when the small supplier's cost is public. The figure illustrates the results of Theorem 15 for the parameters of the numerical example above. Note that, when the manufacturer is likely to have low processing cost ($q_L \geq 0.75$, equivalently $q_H \leq 0.25$), then by Theorem 15(a)(ii) she is indifferent between sharing her information with the big supplier or keeping it private, however, when the manufacturer is less likely to have low cost ($q_L < 0.75$), then by parts (a)(i) and (a)(iii) of the theorem, the manufacturer benefits from keeping its information private (although when the manufacturer has high cost, she is still indifferent about the sharing of information and for part of these values of q_L, even the low-cost manufacturer will be indifferent if she is facing a low-cost small supplier). As expected, the big supplier benefits from knowing the manufacturer's cost for all values of q_L. In this case, from a supply chain perspective, sharing manufacturer's processing cost information is always beneficial because the total supply chain profit in case F dominates that for the case A2.

Figure 3 The Supply Chain Profits as a Function of p_L for Cases F and A1



9. Some Extensions

Here we discuss some extensions related to the manufacturer's processing cost, the small supplier's production cost, and the possible information asymmetry between the manufacturer and the big supplier regarding the small supplier's cost.

9.1. The Manufacturer's Processing Cost

So far we assumed that the manufacturer's processing cost, k, is independent of the production cost of the component she purchases from the supplier. It is possible, however, that a low-cost supplier will enable the manufacturer to reduce her own costs. Hence, we examine how the results change when the processing cost, k, is increasing in the production cost, c. We define k_s to be the processing cost when the manufacturer works with the small supplier and k_B when she contracts with the big supplier. Since $c_B < c_s$, the fact that k is increasing in c implies that $k_B < k_s$.

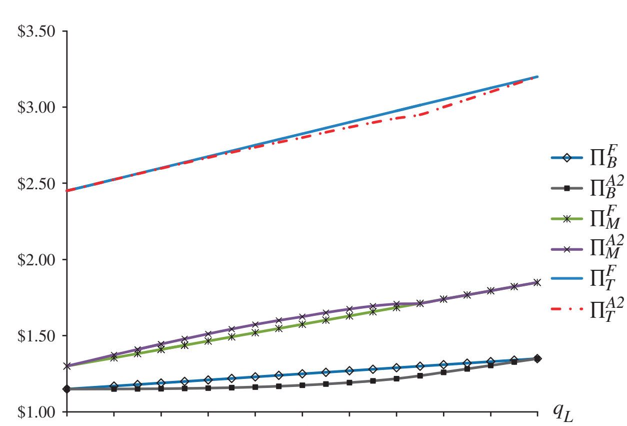
THEOREM 16. *When the manufacturer's processing cost k is increasing in the supplier's production cost c, then the big supplier (resp., manufacturer) is better (resp., worse) off than in the case where k is constant.*

The theorem shows that, due to its cost advantage over the small supplier, the big supplier is better off when the manufacturer has a lower processing cost when working with him. In this case, the big supplier needs to offer less to induce the manufacturer to work with him instead of the small supplier.

9.2. The Small Supplier's Cost Efficiency

So far we assumed that the big supplier has cost advantage over the small supplier due to his scale and expertise. Here we relax this assumption and study the case in which the small supplier might be more cost efficient than the big supplier. This could happen, for example, if the small supplier is in a low-cost

Figure 4 The Supply Chain Profits as a Function of q_L for Cases F and A2



country and thus its cost of material and/or labor are lower than the big supplier. There are two possible cases: (a) $c_L < c_H < c_B$ and (b) $c_L < c_B < c_H$. Under case (a), and using our analysis in sections 4–6, we observe that the big supplier will choose not to offer any contract to the manufacturer because by doing so he will have a negative expected profit. In this case the manufacturer will work with the small supplier. Under case (b), the big supplier has a cost advantage when the small supplier is of high cost but is less efficient when the small supplier is of low cost. We have the following results.

THEOREM 17. *When $c_L < c_B < c_H$, then*

(a) In cases F and A2, the big supplier will offer the manufacturer a contract if $c_s = c_H$, and will not offer a contract otherwise.
(b) In cases A1 and A3, the big supplier will offer the manufacturer a contract if $\bar{w}_s > c_B$, where $\bar{w}_s$ is defined in (25) and will not offer a contract otherwise.

9.3. The Information Asymmetry Between the Manufacturer and the Big Supplier (Case A4)

When examining the different information scenarios, we assumed that the big supplier and the manufacturer had the same knowledge of the small supplier's cost (either know it for certain or have the same belief on its distribution). It is possible that the manufacturer may have better information about the small supplier's cost. Here, we examine the case in which the manufacturer knows the small supplier cost with certainty while the big supplier does not. Other cases with different belief structures can be formulated similarly. All belief structures are assumed public information.

Similar to the full information case (Case F), the manufacturer optimally offers the small supplier a two-part pricing contract where $w_s = c_s$ and $t_s = 0$ and the manufacturer's expected profit is $\prod_M^*(c_s, k)$, which is defined in (4). The big supplier is, therefore, facing four different possible types of manufacturers: (i) A low-cost manufacturer that has the option to contract with a low-cost small supplier and thus earn $\prod_M^*(c_L, k_L)$. (ii) Low- cost manufacturer with high-cost small supplier with expected profit $\prod_M^*(c_H, k_L)$. (iii) High-cost manufacturer with low-cost small supplier with expected profit $\prod_M^*(c_L, k_H)$. (iv) High-cost manufacturer with high-cost small supplier with expected profit $\prod_M^*(c_H, k_H)$. From the big supplier's perspective, the probability of facing the first type manufacturer (Low–Low) is $p_L q_L$, while the second, third, and fourth types have a probability of $p_H q_L$, $p_L q_H$ and $p_H q_H$, respectively. The big supplier's objective is to set the contract terms to maximize his expected profit. He offers four contracts designed for four types of manufacturer to maximize his expected profit

$$\begin{aligned}
&\prod_B((w_{BLL}, T_{BLL}), (w_{BLH}, T_{BLH}), (w_{BHL}, T_{BHL}), (w_{BHH}, T_{BHH}))\\
&= p_L q_L[(w_{BLL} - c_B)y^*(w_{BLL}, k_L) + T_{BLL}]\\
&\quad + p_L q_H[(w_{BLH} - c_B)y^*(w_{BLH}, k_H) + T_{BLH}]\\
&\quad + p_H q_L[(w_{BHL} - c_B)y^*(w_{BHL}, k_L) + T_{BHL}]\\
&\quad + p_H q_H[(w_{BHH} - c_B)y^*(w_{BHH}, k_H) + T_{BHH}],
\end{aligned}$$

where $y^*(.,.)$ is defined in (2) subject to four participation constraints and 12 incentive compatibility constraints, which are deferred to Appendix C. We do not have a closed form solution for the resulting optimization problem; however, it can be solved numerically. We provide a procedure for solving this problem in Appendix C. The next table presents the solution for this problem with the parameter values given in section 8.

Comparing the results of Case A4 in Table 3 to those in Table 2, we observe that the big supplier is worse off with the current case as compared with other information scenarios. Note that, in this case, the supplier has limited information on the small supplier's production cost and the manufacturer's processing cost, while the manufacturer knows the small supplier's production cost. The expected profit for the big supplier is less than half of his profit under case A3 (\$0.72 versus \$1.475) where both he and the manufacturer don't know the small supplier production cost. With respect to the manufacturer, we observe that she is better off than both cases A3 and F because essentially the manufacturer in case A4 has information advantage over the big supplier.

10. Conclusion

In this paper, we study a supply chain in which a manufacturer decides to procure components from two sourcing options: a well-known *big* supplier or a starting *small* supplier. Different from the literature, we analyze the problem from the perspective of the big supplier whose objective is to win the contract with the manufacturer over his small supplier rival. We show that the information structure regarding the small supplier's production cost and the manufacturer's processing cost play a critical role in contracting decisions (information effect). In particular, we consider four cost information scenarios and examine their impact on the big supplier and the manufacturer. We also quantify the cost (value) of having an alternative sourcing option (competition effect) on the big supplier's (manufacturer's) profits. To further examine the impact of the small supplier on expected profits, we compare the competition effect to the information effect. We show that for the manufacturer the competition effect always dominates the information effect. For the big supplier, however, the results depend on the probability of facing a high-cost manufacturer. Table 4 summarizes our results with respect to the information effect.

Table 3 Numerical Results for Case A4

Case	Wholesale price, w_B and transfer price, T	Order quantity, y	Mfg's profit	Big supplier's profit
Case A4	$w^{A4}_{BLL}(c_L, k_L) = \$0.50$	$y(w^{A4}_{BLL}, k_L) = 0.85$		
	$w^{A4}_{BHL}(c_H, k_L) = \$1.00$	$y(w^{A4}_{BHL}, k_L) = 0.80$		
	$w^{A4}_{BLH}(c_L, k_H) = \$2.00$	$y(w^{A4}_{BLH}, k_H) = 0.60$		
	$w^{A4}_{BHH}(c_H, k_H) = \$0.50$	$y(w^{A4}_{BHH}, k_H) = 0.75$		
	$T^{A4}_{BLL}(c_L, k_L) = \$1.16$		$\prod^{A4}_M(w^{A4}_{BLL}, k_L) = \$2.45$	$\prod^{A4}_B = \$0.72$
	$T^{A4}_{BHL}(c_H, k_L) = \$0.75$		$\prod^{A4}_M(w^{A4}_{BHL}, k_L) = \$2.45$	
	$T^{A4}_{BLH}(c_L, k_H) = \$0$		$\prod^{A4}_M(w^{A4}_{BLH}, k_H) = \$1.80$	
	$T^{A4}_{BHH}(c_H, k_H) = \$1.16$		$\prod^{A4}_M(w^{A4}_{BHH}, k_H) = \$1.65$	

This paper also shows that the big supplier always offers a sole-sourcing contract that the manufacturer would find optimal when the big supplier has cost advantage over the small supplier. We note that, even in a relationship with multiple periods of interactions, the big supplier will offer a sole-sourcing contract by considering the manufacturer's outside option. Intuitively, the big supplier can foresee (by backward induction) the manufacturer's potential benefit for having the small supplier. Hence, the big supplier would design a sole-sourcing contract that leaves the manufacturer with a profit larger than her profit under any contract with the small supplier. Hence, in a supply chain with a strong big supplier, the small supplier will be left without a contract. This analysis suggests that sole-sourcing is an optimal outcome for supply chains with a big supplier. For the manufacturer to consider multiple sourcing strategies—at the very least—she needs to be in a position to dictate contract terms. Incidentally, in 2006 SigmaTel lost its contract with Apple Computers and also lost about \$100 million from its market value. Shortly after, in 2008, Freescale Semiconductor acquired SigmaTel.

The area of supply sourcing strategies offers a fertile avenue for future research. For example, both suppliers may have capacity limitation. Such constraints may enforce the use of both suppliers when the capacity constraint for the big supplier is binding. The empirical evidence supports the use of simple linear contracts (Arrow 1985) such as the two-part pricing contract we use in this paper. Nevertheless, studying the impact of other contracts on the relationships considered here would be interesting. In this paper, we studied a supply chain relationship with a big supplier who is stronger than a manufacturer who in turn is stronger than a small supplier. Other dynamics regarding negotiation power are also possible. For example, the manufacturer could be the stronger party who dictates contract terms. Such supply chain dynamics have been extensively studied in the literature, and possible research directions are also discussed in Elmaghraby (2000).

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Appendix A: Proofs

Proof of Lemma 1. Taking first derivative of $\prod^*_M(w,k)$ with respect to k we get,

$$\frac{\partial \prod^*_M(w,k)}{\partial k} = ry^*(w,k)f(y^*(w,k))\frac{\partial y^*(w,k)}{\partial k}. \quad \text{(A1)}$$

By (2), $F(y^*(w,k)) = \frac{r-(w+k)}{r}$. Taking the derivative of both sides with respect to k we get

$$f(y^*(w,k))\frac{\partial y^*(w,k)}{\partial k} = -\frac{1}{r}. \quad \text{(A2)}$$

Using (A1) and (A2) the result follows with respect to k. The proof with respect to w follows the same steps. □

Proof of Theorem 1. First, note that at optimality the constraint in (6) must be binding. Otherwise, one can increase T_B by $\varepsilon > 0$ and increase the objective function while keeping (6) satisfied. Thus, we can substitute $T_B = \prod^*_M(w_B, k)$ into the supplier's objective function in (5), which implies that the supplier needs to maximize $\Pi_B(w_B, k) = (w_B - c_B)y^*(w_B, k) + \prod^*_M(w_B, k)$ over the wholesale price w_B. We define $v \equiv F^{-1}\left(\frac{r-(w_B+k)}{r}\right)$. Then by (2) and (4) we have $w_B = r(1 - F(v)) - k$ and the supplier's profit in (5) can equivalently be written as

$$\prod_B(v) = [r(1 - F(v)) - c_B - k]v + r\int_0^v \xi f(\xi)d\xi,$$

hence

$$\begin{aligned}\frac{d\prod_B(v)}{dv} &= r(1 - F(v)) - (c_B + k) - rf(v)v + rf(v)v \\ &= r(1 - F(v)) - (c_B + k) = 0,\end{aligned}$$

Table 4 Summary of the Information Structure Results

Type of information	Condition	Big supplier	Manufacturer	Total supply chain
Information on the small supplier's production cost	Mfg's processing cost is public	Better off with less information	Better off with more information	Total SC profits are independent of the information being private or public and equal to the coordinated supply chain profits
	Mfg's processing cost is private and the probability of a high-cost mfg is high	Better off with less information	Better off with more information	Total SC profits are independent of the information and less than the coordinated supply chain profits
Information on the mfg's processing cost	The probability of a low-cost mfg is high	Better off with more information	The mfg's profits are independent of the information being private or public	Better off with more information
	The probability of a high-cost mfg is high	Better off with more information	The low-cost mfg is better off with less information, while the high-cost mfg is indifferent	Could be either better off or worse off with more information

which implies that $w_B = c_B$. Taking the second derivative, we get

$$\frac{d^2 \prod_B(v)}{dv^2} = -rf(v),$$

which is negative for all v and hence $\Pi_B(v)$ is strictly concave for all v and thus satisfies the condition for optimality. Since $w_B = c_B$, the result with respect to T_B follows. □

PROOF OF THEOREM 2. Using (11) and (12) and the fact that $\prod_M^*(w_{BH}, k)$ is decreasing in k, it follows that (10) is redundant. (11) binds, otherwise increase T_{BL} and T_{BH} by $\varepsilon > 0$, which will keep (12) and (13) satisfied, and the supplier is better off. (12) binds, otherwise increase T_{BL} by $\varepsilon > 0$, which will keep (11) and (13) satisfied. With respect to (13), assume it is not redundant, i.e., a solution to the problem subject only to (11) and (12) violates (13). This means that both the low type and the high type manufacturer prefer (w_{BL}, T_{BL}) to (w_{BH}, T_{BH}). If $[(w_{BL} - c_B)y(w_{BL}, k_L) + T_{BL}] > [(w_{BH} - c_B)y(w_{BH}, k_H) + T_{BH}]$ then the supplier can offer both the low type and the high type manufacturers $(w_{BL}, T_{BL} + \varepsilon)$. Otherwise, he can offer both (w_{BH}, T_{BH}). (11) and (12) are satisfied in both cases and the supplier is better off. Therefore, we have a contradiction and (13) is redundant. By (11), (12),

$$T_{BH} = \prod\nolimits_M^*(w_{BH}, k_H) \quad \text{and}$$
$$T_{BL} = \prod\nolimits_M^*(w_{BL}, k_L) - \prod\nolimits_M^*(w_{BH}, k_L) + \prod\nolimits_M^*(w_{BH}, k_H). \tag{A3}$$

By (9) and (A3), the big supplier's objective function is separable and can be separated to

$$\begin{aligned}
\operatorname*{Max}_{w_{BL}} \prod\nolimits_B(w_{BL}) &= q_L[(w_{BL} - c_B)y^*(w_{BL}, k_L) \\
&\quad + \prod\nolimits_M^*(w_{BL}, k_L)], \\
\operatorname*{Max}_{w_{BH}} \prod\nolimits_B(w_{BH}) &= q_L[\prod\nolimits_M^*(w_{BH}, k_H) - \prod\nolimits_M^*(w_{BH}, k_L)] \\
&\quad + q_H[(w_{BH} - c_B)y^*(w_{BH}, k_H) \\
&\quad + \prod\nolimits_M^*(w_{BH}, k_H)].
\end{aligned} \tag{A4}$$

Using Lemma 1 and taking the first derivative of the first problem with respect to w_{BL}, we have $w_{BL} = c_B$. Since $c_B < c_s$ we know that this solution is valid for the constrained problem. Similarly, using lemma 1 and taking the first derivative of the second objective function with respect to w_{BH}, we get that

$$w_{BH} = c_B + \frac{q_L}{q_H}\left(\frac{y^*(w_{BH}, k_H) - y^*(w_{BH}, k_L)}{\partial y^*(w_{BH}, k_H)/\partial w_{BH}}\right). \tag{A5}$$

By (2), $F(y^*(w, k)) = \frac{r-(w+k)}{r}$. Taking the derivative of both sides with respect to w and rearranging we have

$$\frac{\partial y^*(w, k)}{\partial w} = -\frac{1}{rf(y^*(w, k))}. \tag{A6}$$

Using (A5) and (A6), we derive (14) and the result then follows. □

PROOF OF THEOREM 3. The proof is similar to the proof of Theorem 1 where $T_B = \prod_M^*(w_B, k) - \prod_M^*(c_s, k)$, and thus $\Pi_B(w_B, k) = (w_B - c_B)y^*(w_B, k) + \prod_M^*(w_B, k)$

$-\prod_M^*(c_s, k)$ and $\prod_B(v) = [r(1 - F(v)) - c_B - k]v + r\int_0^v \xi f(\xi)d\xi - A$, where $A = \prod_M^*(c_s, k)$ is a constant that is independent of v. □

PROOF OF THEOREM 4. To prove part (a) note that Equations (22) and (23) together with $c_L < c_H$ imply that (21) is redundant. At optimality, Equation (22) must bind, otherwise one can decrease t_{sL} and t_{sH} by $\varepsilon > 0$ and increase the objective function while keeping (23) and (24) satisfied. Equation (23) must bind, otherwise one can decrease t_{sL} by $\varepsilon > 0$ and increase the objective function while keeping (24) satisfied. With respect to (24), assume for a contradiction that it is not redundant, i.e., a solution to the problem subject only to (22) and (23) violates (24). This means that both the low type and the high type suppliers prefer (w_{sL}, t_{sL}) to (w_{sH}, t_{sH}). If $[\prod_M^*(w_{sL}, k) - t_{sL}] > [\prod_M^*(w_{sH}, k) - t_{sH}]$ then the manufacturer can offer both the low type and the high type suppliers, $(w_{sL}, t_{sL} - \varepsilon)$. Otherwise, he can offer both (w_{sH}, t_{sH}). Equations (22) and (23) are satisfied in both cases and the manufacturer is better off. Therefore, we have a contradiction and (24) must be redundant. By (22), (23),

$$t_{sL} = (c_H - c_L)y(w_{sH}, k) - (w_{sL} - c_L)y(w_{sL}, k) \text{ and } t_{sH} = (c_H - w_{sH})y(w_{sH}, k). \quad \text{(A7)}$$

Using (20) and (A7), the manufacturer's objective function is separable and can be separated to:

$$\operatorname*{Max}_{w_{sL}} \prod_M(w_{sL}) = p_L[\prod_M^*(w_{sL}, k) + (w_{sL} - c_L)y(w_{sL}, k)], \quad \text{(A8)}$$

$$\operatorname*{Max}_{w_{sH}} \prod_M(w_{sH}) = p_L[(c_L - c_H)y(w_{sH}, k)] + p_H[\prod_M^*(w_{sH}, k) + (w_{sH} - c_H)y(w_{sH}, k)]. \quad \text{(A9)}$$

Using lemma 1 and taking the first derivative of (A8) with respect to w_{sL}, it follows that $w_{sL} = c_L$. Similarly, using lemma 1 and taking the first derivative of (A9) with respect to w_{sH}, we get that $w_{sH} = c_L + (c_H - c_L)/p_H$. Using (A7) the result follows with respect to t_{sL} and t_{sH}.

(20) and part (a) the result follows with respect to the manufacturer's optimal profit. The only part left to show is that $\bar{w}_s \in (c_L, c_H]$.

By Lemma 1, $\frac{\partial \prod_M^*(w,k)}{\partial w} = -y^*(w, k)$. Taking the second derivative of $\prod_M^*(w, k)$ with respect to w and using the fact that $y^*(w, k)$ is decreasing in w, we have $\frac{\partial^2 \prod_M^*(w,k)}{\partial w^2} > 0$ and thus $\prod_M^*(w, k)$ is convex in w. Using the definition of w_{sH} in part (a) and rearranging we get

$$c_H = p_L c_L + p_H w_{sH}. \quad \text{(A10)}$$

By (A10) and the fact that $\prod_M^*(w, k)$ is convex in w, we get

$$\begin{aligned}\prod_M^*(c_H, k) &\le p_L \prod_M^*(c_L, k) + p_H \prod_M^*(w_{sH}, k) \\ &= \prod_M^*(\bar{w}_s, k).\end{aligned} \quad \text{(A11)}$$

In addition since $w_{sH} > c_L$, $\prod_M^*(c_L, k) > \prod_M^*(w_{sH}, k)$ and thus,

$$\begin{aligned}\prod_M^*(c_L, k) &= p_L\prod_M^*(c_L, k) + p_H\prod_M^*(c_L, k) \\ &> p_L\prod_M^*(c_L, k) + p_H\prod_M^*(w_{sH}, k) \\ &= \prod_M^*(\bar{w}_s, k).\end{aligned} \quad \text{(A12)}$$

Thus, $\prod_M^*(c_L, k) > \prod_M^*(\bar{w}_s, k) \ge \prod_M^*(c_H, k)$ and using the fact that $\prod_M^*(w, k)$ is decreasing in w, we get $\bar{w}_s \in (c_L, c_H]$. □

PROOF OF THEOREM 5. It is similar to that of Theorem 3 with $\prod_M^*(\bar{w}_s, k)$ replacing $\prod_M^*(c_s, k)$.

We use the next lemma in the proof of several theorems below. □

LEMMA 2. *Let $\Delta \prod_M(k) \equiv \prod_M^*(w, k) - \prod_M^*(c_s, k)$. Then $\Delta \prod_M(k)$ is increasing in k when $w \ge c_s$ and decreasing in k, otherwise.*

PROOF OF LEMMA 2. Using lemma 1 and taking the first derivative of $\Delta \prod_M(k)$ with respect to k,

$$\frac{\partial \Delta \prod_M(k)}{\partial k} = -y^*(w, k) + y^*(c_s, k). \quad \text{(A13)}$$

Since by (2) $y^*(w, k)$ is a monotone decreasing function of w, the derivative of $\Delta \prod_M(k)$ in (A13) is negative when $w < c_s$ and non-negative otherwise. □

PROOF OF THEOREM 6. Using lemma 2, we have two cases to consider:

CASE 1. $w < c_s$: This case is similar to the proof of Theorem 2, where the redundancy of (28) is based on the fact that $\Delta \prod_M(k)$ is decreasing in k for $w \le c_s$. Similarly, we get that (12) and (29) bind, while (13) is redundant. Using (12) and (29), we replace (A3) with

$$\begin{aligned}T_{BH}(c_s) &= \prod_M^*(w_{BH}, k_H) - \prod_M^*(c_s, k_H) \quad \text{and} \\ T_{BL}(c_s) &= \prod_M^*(w_{BL}, k_L) - \prod_M^*(w_{BH}, k_L) \\ &\quad + \prod_M^*(w_{BH}, k_H) - \prod_M^*(c_s, k_H).\end{aligned} \quad \text{(A14)}$$

The rest of the proof for this case follows the proof of Theorem 2. Note that since $k_L < k_H$ and $y^*(w, k)$ is a monotone decreasing function of w, $\bar{w}_{BH} > c_B$. Thus the solution to the constrained problem is the minimum between c_s and the value of $\bar{w}_{BH}$ from (14).

Case 2. $w \geq c_s$: Using similar steps to the ones of the first case and the fact that $\Delta \prod_M(k)$ is non-deceasing in k for $w \geq c_s$, it can be shown that (12) and (29) are redundant and (13) and (28) bind. By (13) and (28),

$$T_{BL}(c_s) = \prod_M^*(w_{BL}, k_L) - \prod_M^*(c_s, k_L) \quad \text{and}$$
$$T_{BH}(c_s) = \prod_M^*(w_{BH}, k_H) - \prod_M^*(w_{BL}, k_H) + \prod_M^*(w_{BL}, k_L) - \prod_M^*(c_s, k_L). \tag{A15}$$

By (9) and (A15), the big supplier's objective function is separable and can be separated to

$$\underset{w_{BL}}{\text{Max}} \prod_B(w_{BL}) = q_L[(w_{BL} - c_B)y^*(w_{BL}, k_L) + \prod_M^*(w_{BL}, k_L)] + q_H[\prod_M^*(w_{BL}, k_L) - \prod_M^*(w_{BL}, k_H)],$$
$$\underset{w_{BH}}{\text{Max}} \prod_B(w_{BH}) = q_H[(w_{BH} - c_B)y^*(w_{BH}, k_H) + \prod_M^*(w_{BH}, k_H)].$$

Using lemma 1 and taking the first derivative of the first objective function with respect to w_{BL}, we observe that the objective function is decreasing in w_{BL} on the interval $[c_s, \propto]$. Thus the maximizer is achieved on the boundary point c_s. Similarly the second objective function is decreasing in w_{BH} on the same interval and thus the maximizer is achieved also on the boundary point c_s. Therefore, the solution that was found in the first case is dominating this solution for both w_{BL} and w_{BH}. The result then follows. □

Proof of Theorem 7. The proof is similar to the proof of Theorem 6 where the manufacturer's possible profit from her contract with the small supplier $\prod_M^*(c_s, k)$ is replaced with $\prod_M^*(\bar{w}_s, k)$ and thus $\Delta \prod_M(k)$ is changed to $\Delta \prod_M(k) \equiv \prod_M^*(w, k) - \prod_M^*(\bar{w}_s, k)$ and c_s is replaced by $\bar{w}_s$. □

Proof of Theorem 8. To prove part (a) note that from (25), (27), and (32), we get $VOI_M(k) = p_H[\prod_M^*(c_H, k) - \prod_M^*(w_H, k)]$. By Theorem 4(a), $w_{sH} - c_H = (p_L/p_H)(c_H - c_L) > 0$. Thus $w_{sH} > c_H$. Since $\prod_M^*(w, k)$ decreases in w from Lemma 1, we have $\prod_M^*(c_H, k) > \prod_M^*(w_{sH}, k)$, which proves the result with respect to the manufacturer's value of information. Part (b) follows from part (a), (27) and (33). □

Proof of Theorem 9.

(a)

(i) From Theorem 6(a) and (14), when

$$c_B + \frac{q_L}{q_H} r[y^*(\bar{w}_{BH}, k_L) - y^*(\bar{w}_{BH}, k_H)] f(y^*(\bar{w}_{BH}, k_H)) < c_L \tag{A16}$$

we get $w_{BH}^{A2} = \bar{w}_{BH}$. Since by Theorem 4(b), $\bar{w}_s > c_L$, Theorem 7(a) and (A16) imply that $w_{BH}^{A3} = \bar{w}_{BH}$. Using Theorems 6(b) and 7(b) and the definition of $\prod_M^{A2}(k)$ in (34), it follows that when (A16) holds, $\prod_M^{A2}(k_i) - \prod_M^{A3}(k_i) = \prod_M^F(k_H) - \prod_M^{A1}(k_H) = VOI_M(k_H) > 0$ for $i \in$ {L, H}. Rearranging (A16) and using the fact that $q_L = 1 - q_H$, it follows that (A16) translates to $q_H > \bar{q}_H$ where $\bar{q}_H$ is defined in (39). Note that by (40) and the definition of $y^*(\cdot, \cdot)$ in (2), α is positive and thus since $c_L > c_B$ it follows that $0 < \bar{q}_H < 1$.

(ii) By part (i), (14) and (40), when

$$c_B + \frac{q_L}{q_H} \alpha > c_H, \tag{A17}$$

we get $w_{BH}^{A2} = c_s$. Since by Theorem 4(b), $\bar{w}_s < c_H$, Theorem 7(a) and (A17) imply that $w_{BH}^{A3} = \bar{w}_s$. Using Theorems 6(b) and 7(b) and the definition of $\prod_M^{A2}(k)$ in (34), it follows that when (A17) holds, $\prod_M^{A2}(k_i) - \prod_M^{A3}(k_i) = \prod_M^F(k_i) - \prod_M^{A1}(k_i) = VOI_M(k_i) > 0$ for $i = L, H$. Rearranging (A17) and using the fact that $q_L = 1 - q_H$ it follows that (A17) translates to $q_H < \bar{\bar{q}}_H$ where $\bar{\bar{q}}_H$ is defined in (41). Note that by (40) and the definition of $y^*(\cdot, \cdot)$ in (2), α is positive and thus since $c_H > c_B$ it follows that $0 < \bar{\bar{q}}_H < 1$.

(iii) By the proofs for parts (i) and (ii) we have $\bar{\bar{q}}_H \leq q_H \leq \bar{q}_H$ is equivalent to

$$c_L \leq c_B + \frac{q_L}{q_H} \alpha \leq c_H. \tag{A18}$$

By Theorem 6(a) we get that in this case, $w_{BH}^{A2} = c_L$ when $c_s = c_L$, however, $w_{BH}^{A2} = \bar{w}_{BH}$ when $c_s = c_H$. By Theorem 6(b) this implies that

$$\prod_M^{A2}(c_L, k_i) = \prod_M^*(c_L, k_i) \text{ for } i \in \{L, H\},$$
$$\prod_M^{A2}(c_H, k_H) = \prod_M^*(c_H, k_H), \text{ and}$$
$$\prod_M^{A2}(c_H, k_L) = \prod_M^*(\bar{w}_{BH}, k_L) - \prod_M^*(\bar{w}_{BH}, k_H) + \prod_M^*(c_H, k_H). \tag{A19}$$

and thus using (32) and (A19),

$$\prod_M^{A2}(k_L) = p_L[\prod_M^*(c_L, k_L)] + p_H[\prod_M^*(c_H, k_H)] + p_H[\prod_M^*(\bar{w}_{BH}, k_L) - \prod_M^*(\bar{w}_{BH}, k_H)]$$
$$\text{and} \prod_M^{A2}(k_H) = \prod_M^F(k_H). \tag{A20}$$

Since by Theorem 4(b), $c_L < \bar{w}_s \leq c_H$, we have two cases for $\bar{w}_s$:

Case 1. $\bar{w}_s \leq c_B + \frac{q_L}{q_H} \alpha \leq c_H$.
By Theorem 7(a) we get that in this case, $w_{BH}^{A2} = \bar{w}_s$ and thus by Theorem 7(b) this implies that

$$\prod_M^{A3}(k_i) = \prod_M^{A1}(k_i) \text{ for } i \in \{L, H\}, \tag{A21}$$

Using (A20), (A21), it follows that

$$\prod_M^{A2}(k_H)-\prod_M^{A3}(k_H)=\prod_M^F(k_H)-\prod_M^{A1}(k_H)=VOI_M^1(k_H)>0,\ \text{and} \quad \text{(A22)}$$

$$\begin{aligned}\prod_M^{A2}(k_L)-\prod_M^{A3}(k_L) &= p_L[\prod_M^*(c_L,k_L)]+p_H[\prod_M^*(c_H,k_H)] \\ &\quad + p_H[\prod_M^*(\bar{w}_{BH},k_L)-\prod_M^*(\bar{w}_{BH},k_H)] \\ &\quad -\prod_M^{A1}(k_L) \\ &= p_L[\prod_M^*(c_L,k_L)] \\ &\quad + p_H[\prod_M^*(c_H,k_H)]+p_H[\prod_M^*(\bar{w}_{BH},k_L) \\ &\quad -\prod_M^*(\bar{w}_{BH},k_H)]-p_L[\prod_M^*(c_L,k_L)] \\ &\quad -p_H[\prod_M^*(w_{sH},k_L)]\geq p_H[(\prod_M^*(\bar{w}_{BH},k_L) \\ &\quad -\prod_M^*(c_H,k_L)) \\ &\quad -(\prod_M^*(\bar{w}_{BH},k_H)-\prod_M^*(c_H,k_H))]\geq 0. \end{aligned} \quad \text{(A23)}$$

where the second equality is based on the definition of $\prod_M^{A1}(k_L)$ in (25) and the first inequality is based on the fact that by Theorem 4(a), $w_{sH}>c_H$. The last inequality is based on lemma 2 and the fact that $\bar{w}_{BH}\leq c_H$.

Case 2. $c_L \leq c_B + \frac{q_L}{q_H} r[y^*(w_{BH},k_L)-y^*(w_{BH},k_H)]f(y^*(w_{BH},k_H))\leq \bar{w}_s$. By Theorem 7(a) we get that in this case, $w_{BH}^{A2}=\bar{w}_{BH}$ and thus by Theorem 7(b) this implies that

$$\prod_M^{A3}(k_H)=\prod_M^{A1}(k_H),\ \text{and}\ \prod_M^{A3}(k_L)=\prod_M^*(\bar{w}_{BH},k_L)-\prod_M^*(\bar{w}_{BH},k_H)+\prod_M^{A1}(k_H). \quad \text{(A24)}$$

Using (A20), and (A24), it follows that

$$\prod_M^{A2}(k_H)-\prod_M^{A3}(k_H)=\prod_M^F(k_H)-\prod_M^{A1}(k_H)=VOI_M(k_H)>0\ \text{and}$$

$$\begin{aligned}\prod_M^{A2}(k_L)-\prod_M^{A3}(k_L) &= p_L[\prod_M^*(c_L,k_L)]+p_H[\prod_M^*(c_H,k_H)] \\ &\quad + p_H[\prod_M^*(\bar{w}_{BH},k_L)-\prod_M^*(\bar{w}_{BH},k_H)] \\ &\quad -[\prod_M^*(\bar{w}_{BH},k_L)-\prod_M^*(\bar{w}_{BH},k_H) \\ &\quad +\prod_M^{A1}(k_H)] \\ &= p_L[\prod_M^*(c_L,k_L)]+p_H[\prod_M^*(c_H,k_H)] \\ &\quad -p_L[\prod_M^*(\bar{w}_{BH},k_L) \\ &\quad -\prod_M^*(\bar{w}_{BH},k_H)]-[\prod_M^{A1}(k_H)] \\ &= p_L[(\prod_M^*(c_L,k_L)-\prod_M^*(\bar{w}_{BH},k_L)) \\ &\quad -(\prod_M^*(c_L,k_H)-\prod_M^*(\bar{w}_{BH},k_H))] \\ &\quad +p_H[\prod_M^*(c_H,k_H)-\prod_M^*(w_{sH},k_H)]\geq 0. \end{aligned} \quad \text{(A25)}$$

where the third equality is based on (27) and the definition of $\prod_M^{A1}(k_H)$ in (25). Note that the first part is positive by lemma 2 and the fact that $c_L \leq \bar{w}_{BH}$, while the second part is positive using the definition of $\prod_M^*(\cdot,\cdot)$ in (4) and the fact that by Theorem 4(a), $w_{sH}>c_H$. The result then follows.

(b) Using Theorems 6(c) and 7(c) and the definition of $\prod_B^{A2}$ in (35), it follows that when $q_H>\bar{q}_H$, $\prod_B^{A2}-\prod_B^{A3}=\prod_M^{A1}(k_H)-\prod_M^F(k_H)=-VOI_M^1(k_H)<0$.

Following the other two cases in part (a) it can be shown that $\prod_B^{A2}-\prod_B^{A3}$ is inconclusive for these cases.

Proof of Corollary 10. To prove part (a) note that the first equality follows directly from the fact that by Theorem 8 $VOI_B^1(k)=-VOI_M^1(k)$ where $VOI_M^1(k)\equiv\prod_M^F(k)-\prod_M^{A1}(k)$ and $VOI_B^1(k)\equiv\prod_B^F(k)-\prod_B^{A1}(k)$.The second equality then follows using (19) and (32). Part (b) follows directly from Theorem 9. □

Proof of Theorem 11.

(a) Using (8),

$$VOC_M^1(k)\equiv\prod_M^F(k)-\prod_M^{SF}(k)=\prod_M^F(k)-0=\prod_M^F(k)>0.$$

(b) Using (8), (33), and the first part of the theorem,

$$VOC_B^1(k)\equiv\prod_B^F(k)-\prod_B^{SF}(k)=\prod_M^*(c_B,k)-\prod_M^F(k)-\prod_M^*(c_B,k)=-\prod_M^F(k)=-VOC_M^1(k)<0.$$

□

Proof of Theorem 12.

(a)

(i) From Theorems 6(a) and 9(a)(i), when $q_H>\bar{q}_H$, we get $w_{BH}^{A2}=\bar{w}_{BH}$. By (15), $\prod_M^{SA}(k_H)=0$ and $\prod_M^{SA}(k_L)=\prod_M^*(\bar{w}_{BH},k_L)-\prod_M^*(\bar{w}_{BH},k_H)$. Using 6(b) and the definition of $\prod_M^{A2}(k)$ in (34), when $q_H>\bar{q}_H$, $\prod_M^{A2}(k_L)=\prod_M^*(\bar{w}_{BH},k_L)-\prod_M^*(\bar{w}_{BH},k_H)+\prod_M^F(k_L)$ and $\prod_M^{A2}(k_H)=\prod_M^F(k_H)$. The result then follows.

(ii) From Theorems 6(a) and 9(a)(ii), when $q_H<\bar{\bar{q}}_H$, we get $w_{BH}^{A2}=c_s$. Using 6(b) and the definition of $\prod_M^{A2}(k)$ in (34), when $q_H<\bar{\bar{q}}_H$, $\prod_M^{A2}(k_L)=\prod_M^F(k_L)$ and $\prod_M^{A2}(k_H)=\prod_M^F(k_H)$. Using this and (15), the result then follows.

(iii) From Theorems 6(a) and 9(a)(iii), when $\bar{\bar{q}}_H\leq q_H\leq\bar{q}_H$, we get $w_{BH}^{A2}=c_L$ if $c_s=c_L$, however, $w_{BH}^{A2}=\bar{w}_{BH}$ if $c_s=c_H$. By (A19), $\prod_M^{A2}(k_L)=p_L\prod_M^*(c_L,k_L)+p_H\prod_M^*(c_H,k_H)+p_H[\prod_M^*(\bar{w}_{BH},k_L)-\prod_M^*(\bar{w}_{BH},k_H)]$. Using (15) and the fact that $\prod_M^*(c_L,k_L)\geq\prod_M^*(\bar{w}_{BH},k_L)$, the result then follows with respect to $VOC_M^2(k_L)$. Similarly, using (A19) and (15), the result follows with respect to $VOC_M^2(k_H)$.

(b) From Theorems 6(i) and 9(i), when $q_H>\bar{q}_H$, we get $w_{BH}^{A2}=\bar{w}_{BH}$. Using Theorems 2 and 6 and the definition of $\prod_B^{A2}$ in (35), it follows that when $q_H>\bar{q}_H$,

$\prod_B^{A2} - \prod_B^{SA} = -\prod_M^F(k_H) = -VOC_M^1(k_H) < 0$. Following the other two cases in part (a) it can be shown that $\prod_B^{A2} - \prod_B^{SA}$ is inconclusive for these cases. □

Proof of Theorem 13.

(a) Using Theorems 8 and 11, the result follows.
(b) We have three cases to consider:
  (i) When $q_H > \bar{q}_H$, using Theorems 9 and 12 and part (a) of the theorem, the result follows.
  (ii) When $q_H < \bar{\bar{q}}_H$, using Theorems 9 and 12 and part (a) of the theorem, we have $VOC_M^2(k_H) \geq VOI_M^2(k_H) > 0$. To show the result with respect to k_L, note that by Theorems 9(a)(ii) and 12(a)(ii),

$$VOC_M^2(k_L) - VOI_M^2(k_L) = \prod_M^{A1}(k_L) - [\prod_M^*(\bar{w}_{BH}, k_L) - \prod_M^*(\bar{w}_{BH}, k_H)] = [\prod_M^*(\bar{w}_s, k_L) - \prod_M^*(\bar{w}_{BH}, k_L)] + \prod_M^*(\bar{w}_{BH}, k_H) \geq 0,$$

where the first part is positive using the definition of $\prod_M^*(\cdot,\cdot)$ in (4) and the fact that in this case $\bar{w}_s < \bar{w}_{BH}$. The result then follows.
  (iii) When $\bar{\bar{q}}_H \leq q_H \leq \bar{q}_H$, using Theorems 9 and 12 and part (a) of the theorem, we have $VOC_M^2(k_H) \geq VOI_M^2(k_H) > 0$. To show the result with respect to k_L, we have two subcases to consider:

Case 1. When $\bar{w}_s \leq \bar{w}_{BH} \leq c_H$, by (A23) and Theorem 12(a)(ii),

$$VOC_M^2(k_L) - VOI_M^2(k_L) = \prod_M^{A1}(k_L) - [\prod_M^*(\bar{w}_{BH}, k_L) - \prod_M^*(\bar{w}_{BH}, k_H)] = [\prod_M^*(\bar{w}_s, k_L) - \prod_M^*(\bar{w}_{BH}, k_L)] + \prod_M^*(\bar{w}_{BH}, k_H) \geq 0,$$

where the first part is positive using the definition of $\prod_M^*(\cdot,\cdot)$ in (4) and the fact that in this case $\bar{w}_s \leq \bar{w}_{BH}$.

Case 2. When $\bar{w}_{BH} \leq \bar{w}_s \leq c_H$, using (A25), and Theorem 12(a)(iii), $VOC_M^2(k_L) - VOI_M^2(k_L) = \prod_M^{A1}(k_H) > 0$.

The result then follows.

(c) When $q_H > \bar{q}_H$, using Theorems 9 and 12 and part (a) of the theorem, the result follows. Following the other two cases it can be shown that $VOC_B^2 - VOI_B^2$ is inconclusive for these cases.

Proof of Theorem 14.

(a) Using (8) and (15) and the fact that $[\prod_M^*(\bar{w}_{BH}, k_L) - \prod_M^*(\bar{w}_{BH}, k_H)] \geq 0$ since $k_L \leq k_H$, the result follows.
(b) Using (8) and (14)–(16), the result follows. □

Proof of Theorem 15.

(a)

(i) By Theorems 6 and 9, when $q_H > \bar{q}_H$, $w_{BH}^{A2} = w_{BH}^{A3} = \bar{w}_{BH} < c_L < \bar{w}_s \leq c_H$, and thus $\prod_M^{A2}(c_s, k_L) = \prod_M^*(\bar{w}_{BH}, k_L) - \prod_M^*(\bar{w}_{BH}, k_H) + \prod_M^*(c_s, k_H) \geq \prod_M^*(c_s, k_L) - \prod_M^*(c_s, k_H) + \prod_M^*(c_s, k_H) = \prod_M^*(c_s, k_L) = \prod_M^F(c_s, k_L)$, where the second inequality is based on the fact that $\bar{w}_{BH} < c_s$ and thus by lemma 2,

$$\prod_M^*(\bar{w}_{BH}, k_L) - \prod_M^*(c_s, k_L) \geq \prod_M^*(\bar{w}_{BH}, k_H) - \prod_M^*(c_s, k_H). \tag{A26}$$

By Theorems 3 and 6, we get that $\prod_M^{A2}(c_s, k_H) = \prod_M^*(c_s, k_H) = \prod_M^F(c_s, k_H)$ which completes the proof with respect to $\prod_M^F$ and $\prod_M^{A2}$. The proof with respect to $\prod_M^{A1}$ and $\prod_M^{A3}$ is identical using Theorem 7 and replacing c_s with $\bar{w}_s$.

(ii) By Theorems 6 and 9, when $q_H < \bar{\bar{q}}_H$, $w_{BH}^{A2} = c_s$, and $w_{BH}^{A3} = \bar{w}_s$, and thus using Theorem 6(ii), $\prod_M^{A2}(c_s, k_i) = \prod_M^*(c_s, k_i) = \prod_M^F(c_s, k_i)$ for $i,s = L, H$. The proof with respect to $\prod_M^{A1}$ and $\prod_M^{A3}$ is identical using Theorem 7 and replacing c_s with $\bar{w}_s$.

(iii) The result with respect to $\prod_M^{A2}(c_s, k_i)$ and $\prod_M^F(c_s, k_i)$ for $(s,i) = (L,L)$, (L,H) and (H,H) follows directly from (A19). To show the result with respect $(s,i) = (H,L)$, note that by lemma 2 and the fact that $\bar{w}_{BH} \leq c_H$, $\prod_M^*(\bar{w}_{BH}, k_L) - \prod_M^*(c_H, k_L) \geq \prod_M^*(\bar{w}_{BH}, k_H) - \prod_M^*(c_H, k_H)$. Using this and (A19) implies that $\prod_M^{A2}(c_H, k_L) \geq \prod_M^*(c_H, k_L)$. The result with respect to $\prod_M^{A1}$ and $\prod_M^{A3}$ follows from (A21), (A24) and the fact that $\prod_M^*(\bar{w}_{BH}, k_L) - \prod_M^*(\bar{w}_{BH}, k_H) \geq 0$.

(b) In order to show the result for every $q_H \in [0, 1]$, we need to show it for the three cases analyzed in part (a):

Case 1. $q_H > \bar{q}_H$: Using (19) and (46), the big supplier's expected profit for the full information case is equal to

$$\prod_B^F(c_s) = q_L[\prod_M^*(c_B, k_L) - \prod_M^*(c_s, k_L)] + q_H[\prod_M^*(c_B, k_H) - \prod_M^*(c_s, k_H)]. \tag{A27}$$

By Theorem 6 and the fact that when $q_H > \bar{q}_H$, $w_{BH}^{A2} = \bar{w}_{BH} < c_s$, the big supplier's expected profit for case A2 is equal to

$$\prod_B^{A2}(c_s) = q_L[\prod_M^*(c_B, k_L) - \prod_M^*(\bar{w}_{BH}, k_L)] + \prod_M^*(\bar{w}_{BH}, k_H) - \prod_M^*(c_s, k_H) + q_H(\bar{w}_{BH} - c_B)y^*(\bar{w}_{BH}, k_H).$$

Using this and the big supplier's expected profit for the full information case in (A27) we get that

$$\begin{aligned}\textstyle\prod_B^F(c_s) - \prod_B^{A2}(c_s) = q_L[&\textstyle\prod_M^*(\bar{w}_{BH}, k_L) - \prod_M^*(c_s, k_L)\\ &\textstyle- (\prod_M^*(\bar{w}_{BH}, k_H) - \prod_M^*(c_s, k_H))]\\ &\textstyle+ q_H[(\prod_M^*(c_B, k_H) - \prod_M^*(\bar{w}_{BH}, k_H))\\ &- (\bar{w}_{BH} - c_B)y^*(\bar{w}_{BH}, k_H)] \geq 0,\end{aligned}$$

where the first part is nonnegative by (A26), and the second part is nonnegative based on the fact that

$$\textstyle\prod_M^*(c_B, k_H) - \prod_M^*(\bar{w}_{BH}, k_H) = r\displaystyle\int_{y^*(\bar{w}_{sH},k_H)}^{y^*(c_B,k_H)} \xi f(\xi)d\xi,$$

and

$$\begin{aligned}(\bar{w}_{BH} - c_B)y^*(\bar{w}_{BH}, k_H) &= ry^*(\bar{w}_{BH}, k_H)\int_{y^*(\bar{w}_{BH},k_H)}^{y^*(c_B,k_H)} f(\xi)d\xi\\ &= r\int_{y^*(\bar{w}_{BH},k_H)}^{y^*(c_B,k_H)} y^*(\bar{w}_{BH}, k_H)f(\xi)d\xi\end{aligned}$$

and thus,

$$\begin{aligned}&\textstyle\prod_M^*(c_B, k_H) - \prod_M^*(\bar{w}_{BH}, k_H) - (\bar{w}_{BH} - c_B)y^*(\bar{w}_{BH}, k_H)\\ &\quad= r\int_{y^*(\bar{w}_{BH},k_H)}^{y^*(c_B,k_H)} (\xi - y^*(\bar{w}_{BH}, k_H))f(\xi)d\xi \geq 0,\end{aligned}$$

which proves the result with respect to $\prod_B^F$ and $\prod_B^{A2}$. The proof with respect to $\prod_B^{A1}$ and $\prod_B^{A3}$ is identical using Theorem 7 and replacing c_s with $\bar{w}_s$.

Case 2. $q_H < \bar{\bar{q}}_H$: The big supplier's expected profit for the full information case is similar to case 1 and thus given by (A27). By Theorem 6 and the fact that when $q_H < \bar{\bar{q}}_H$, $w_{BH}^{A2} = c_s$ the big supplier's expected profit for case A2 c is equal to

$$\begin{aligned}\textstyle\prod_B^{A2}(c_s) = q_L[&\textstyle\prod_M^*(c_B, k_L) - \prod_M^*(c_s, k_L)]\\ &+ q_H(c_s - c_B)y^*(c_s, k_H).\end{aligned} \tag{A28}$$

Note that

$$\begin{aligned}r\int_{y^*(c_s,k_H)}^{y^*(c_B,k_H)} y^*(c_s, k_H)f(\xi)d\xi = ry^*(c_s, k_H)\\ \int_{y^*(c_s,k_H)}^{y^*(c_B,k_H)} f(\xi)d\xi = (c_s - c_B)y^*(c_s, k_H),\end{aligned} \tag{A29}$$

where the second equality is based on the definition of $y^*(\cdot,\cdot)$ in (2).

Using (4), (A28) and (A29), we get that

$$\begin{aligned}\textstyle\prod_B^F(c_s) - \prod_B^{A2}(c_s) &= r\int_{y^*(c_s,k_H)}^{y^*(c_B,k_H)} \xi f(\xi)d\xi\\ &\quad - r\int_{y^*(c_s,k_H)}^{y^*(c_B,k_H)} y^*(c_s, k_H)f(\xi)d\xi\\ &= r\int_{y^*(c_s,k_H)}^{y^*(c_B,k_H)} (\xi - y^*(c_s, k_H))f(\xi)d\xi \geq 0,\end{aligned} \tag{A30}$$

which proves the result with respect to $\prod_B^F$ and $\prod_B^{A2}$. The proof with respect to $\prod_M^{A1}$ and $\prod_M^{A3}$ is identical using Theorem 7 and replacing c_s with $\bar{w}_s$.

Case 3. $\bar{\bar{q}}_H \leq q_H \leq \bar{q}_H$: The big supplier's expected profit for the full information case is similar to case 1 and thus given by (A27). By Theorem 6, when $\bar{\bar{q}}_H \leq q_H \leq \bar{q}_H$, $w_{BH}^{A2} = c_L$ if $c_s = c_L$, and $w_{BH}^{A2} = \bar{w}_{BH}$ when $c_s = c_H$. Thus, using argument similar to cases 1 and 2, we have $\prod_B^F(c_L) \geq \prod_B^{A2}(c_L)$ and $\prod_B^F(c_H) \geq \prod_B^{A2}(c_H)$, and thus $\prod_B^F(c_s) \geq \prod_B^{A2}(c_s)$ for $s = L, H$. The same follows with respect to $\prod_M^{A1}$ and $\prod_M^{A3}$.

PROOF OF THEOREM 16. First, by examining Theorems 3, 5, 6, and 7, we observe that the wholesale price w is the same in cases when k is constant and increasing in c, due to the fact that both c_B and $\bar{w}_{BH}$ are independent of the small supplier's cost. The transfer prices, however, will be different. Thus, we need to compare the two cases with respect to the transfer prices. In the case where k is constant (as assumed throughout the paper), we can define without loss of generality $k_{si} = k_{Bi} = k_{1i}$, and when k is increasing in c, let $k_{2i} = k_{si} < k_{Bi} = k_{1i}$ for $i \in \{L, H\}$. For cases SF and SA, the transfer prices are the same due to the inexistence of the small supplier. In the other four cases the change is as follows:

Case F. $T_B^F\ (k \nearrow c) = \prod_M^*(c_B, k_{1i}) - \prod_M^*(c_s, k_{2i}) > \prod_M^*(c_B, k_{1i}) - \prod_M^*(c_s, k_{1i}) = T_B^F$ (k constant) for $i \in \{L, H\}$

Case A1. $T_B^{A1}\ (k \nearrow c) = \prod_M^*(c_B, k_{1i}) - \prod_M^{A1}(k_{2i}) > \prod_M^*(c_B, k_{1i}) - \prod_M^{A1}(k_{1i}) = T_B^{A1}$ (k constant) for $i \in \{L, H\}$.

Case A2. $T_{BL}^{A2}\ (k \nearrow c) = \prod_M^*(w_{BL}^{A2}, k_{1L}) - \prod_M^*(w_{BH}^{A2}, k_{1L}) + \prod_M^*(w_{BH}^{A2}, k_{1H}) - \prod_M^*(c_s, k_{2H}) > \prod_M^*(w_{BL}^{A2}, k_{1L}) - \prod_M^*(w_{BH}^{A2}, k_{1L}) + \prod_M^*(w_{BH}^{A2}, k_{1H}) - \prod_M^*(c_s, k_{1H}) = T_{BL}^{A2}$ (k constant)
$T_{BH}^{A2}\ (k \nearrow c) = \prod_M^*(w_{BH}^{A2}, k_{1H}) - \prod_M^*(c_s, k_{2H}) > \prod_M^*(w_{BH}^{A2}, k_{1H}) - \prod_M^*(c_s, k_{1H}) = T_{BH}^{A2}$ (k constant)

Case A3. $T_{BL}^{A3}\ (k \nearrow c) = \prod_M^*(w_{BL}^{A3}, k_{1L}) - \prod_M^*(w_{BH}^{A3}, k_{1L}) + \prod_M^*(w_{BH}^{A3}, k_{1H}) - \prod_M^{A1}(k_{2H}) > \prod_M^*(w_{BL}^{A3}, k_{1L}) - \prod_M^*(w_{BH}^{A3}, k_{1L}) + \prod_M^*(w_{BH}^{A3}, k_{1H}) - \prod_M^{A1}(k_{1H}) = T_{BL}^{A3}$ (k constant)
$T_{BH}^{A3}\ (k \nearrow c) = \prod_M^*(w_{BH}^{A3}, k_{1H}) - \prod_M^{A1}(k_{2H}) > \prod_M^*(w_{BH}^{A3}, k_{1H}) - \prod_M^{A1}(k_{1H}) = T_{BL}^{A3}$ (k constant)

The result follows from the fact that the transfer prices are higher when k increases in c, while the wholesale prices do not change. □

PROOF OF THEOREM 17.

(a)

Case F. By Theorem 3, if the small supplier is of low type, $\prod_B^F(k) = \prod_M^*(c_B, k) - \prod_M^*(c_L, k) < 0$, and thus the big supplier does not offer a contract to the manufacturer. However, if the small supplier is of high type, $\prod_B^F(k) = \prod_M^*(c_B, k) - \prod_M^*(c_H, k) > 0$, and thus the big supplier does offer a contract to the manufacturer.

Case A2. If the small supplier is of low type, then by Theorem 6 we get that $w_{BL}^{A2} = c_B$, and $w_{BH}^{A2}(c_L) = \min(\bar{w}_{BH}, c_L) = c_L$ (since $\bar{w}_{BH} > c_B > c_L$ by (14)), $T_{BL}(c_L) = \prod_M^*(c_B, k_L) - \prod_M^*(c_L, k_L) < 0$, and $T_{BH}(c_L) = 0$. Using this in (9), we get that $\prod_B(\cdot) = q_L T_{BL}(c_L) + q_H(c_L - c_B) y^*(c_L, k_H) < 0$, which means that the big supplier does not offer a contract to the manufacturer. If the small supplier is of high type, then by Theorem 6, $w_{BL}^{A2} = c_B$ and $w_{BH}^{A2}(c_H) = \min(\bar{w}_{BH}, c_H) > c_B$. If $c_H < \bar{w}_{BH}$ then $T_{BL}(c_H) = \prod_M^*(c_B, k_L) - \prod_M^*(c_H, k_L) > 0$, and $T_{BH}(c_H) = 0$. Otherwise, both $T_{BL}(c_H)$ and $T_{BH}(c_H)$ are positive. Using this in (9), we get that $\prod_B(\cdot) = q_L T_{BL}(c_H) + q_H T_{BH}(c_H) + q_H(w_{BH}^{A2}(c_H) - c_B) y^*(c_L, k_H) > 0$, and thus the big supplier does offer a contract to the manufacturer.

(b)

Case A1. By Theorem 5, $\Pi_B^{A1}(k) = \prod_M^*(c_B, k) - \prod_M^*(\bar{w}_s, k)$ which is positive when $\bar{w}_s > c_B$, and negative otherwise. The result follows. Note that by Theorem 4, $\bar{w}_s \in (c_L, c_H]$ and thus both cases ($\bar{w}_s > c_B$ and $\bar{w}_s < c_B$) are possible.

Case A3. If $\bar{w}_s < c_B$, then by Theorem 7 we get that $w_{BL}^{A3} = c_B$, and $w_{BH}^{A3} = \min(\bar{w}_{BH}, \bar{w}_s) = \bar{w}_s$, $T_{BL} = \prod_M^*(c_B, k_L) - \prod_M^*(\bar{w}_s, k_L) < 0$, and $T_{BH} = 0$. Using this in (9), we get that $\prod_B(\cdot) = q_L T_{BL} + q_H(\bar{w}_s - c_B) y^*(\bar{w}_s, k_H) < 0$, which means that the big supplier does not offer a contract to the manufacturer. If $\bar{w}_s > c_B$, we have two possible cases: (a) $c_B < \bar{w}_s < \bar{w}_{BH}$, and (b) $\bar{w}_s > \bar{w}_{BH}$. Under Case (a), $w_{BL}^{A3} = c_B, w_{BH}^{A3} = \bar{w}_s, T_{BL} = \prod_M^*(c_B, k_L) - \prod_M^*(\bar{w}_s, k_L) > 0$, and $T_{BH} = 0$, which by using (9) implies that $\prod_B(\cdot) > 0$. Under case (b), $w_{BL}^{A3} = c_B, w_{BH}^{A3} = \bar{w}_{BH}$ and both T_L and T_H are positive. Using this in (9), we get that $\prod_B(\cdot) = q_L T_{BL} + q_H T_{BH} + q_H(w_{BH}^{A3} - c_B) y^*(w_{BH}^{A3}, k_H) > 0$, and thus the big supplier does offer a contract to the manufacturer. □

Appendix B: Uniform Distribution

Suppose demand is distributed uniformly over the interval [*a*, *b*]. This demand distribution enables us to obtain closed form solutions to gain transparent insights on the drivers of the problem. The optimal ordering quantity *y* from (2), and the optimal profit of the manufacturer in (4) simplify to

$$y^*(w,k) = b - (b-a)\left(\frac{w+k}{r}\right) \text{ and } \quad \prod_M^*(w,k) = \frac{r[(y^*(w,k))^2 - a^2]}{2(b-a)}. \tag{A31}$$

Table A1 illustrates the results of our paper based on the uniform distribution:

Appendix C: Solution to the Four Types' Problem in Section 9.3

The participation constraints for the four types of manufacturers are

$$\prod_M^*(w_{BLL}, k_L) - T_{BLL} \geq \prod_M^*(c_L, k_L), \tag{A32}$$

$$\prod_M^*(w_{BLH}, k_H) - T_{BLH} \geq \prod_M^*(c_L, k_H). \tag{A33}$$

$$\prod_M^*(w_{BHL}, k_L) - T_{BHL} \geq \prod_M^*(c_H, k_L), \tag{A34}$$

$$\prod_M^*(w_{BHH}, k_H) - T_{BHH} \geq \prod_M^*(c_H, k_H). \tag{A35}$$

The incentive compatibility constraints for the four types of manufacturers are

$$-T_{BLL} + \prod_M^*(w_{BLL}, k_L) \geq -T_{BHL} + \prod_M^*(w_{BHL}, k_L), \tag{A36}$$

$$-T_{BLL} + \prod_M^*(w_{BLL}, k_L) \geq -T_{BLH} + \prod_M^*(w_{BLH}, k_L), \tag{A37}$$

$$-T_{BLL} + \prod_M^*(w_{BLL}, k_L) \geq -T_{BHH} + \prod_M^*(w_{BHH}, k_L), \tag{A38}$$

$$-T_{BHL} + \prod_M^*(w_{BHL}, k_L) \geq -T_{BLL} + \prod_M^*(w_{BLL}, k_L), \tag{A39}$$

$$-T_{BHL} + \prod_M^*(w_{BHL}, k_L) \geq -T_{BLH} + \prod_M^*(w_{BLH}, k_L), \tag{A40}$$

$$-T_{BHL} + \prod_M^*(w_{BHL}, k_L) \geq -T_{BHH} + \prod_M^*(w_{BHH}, k_L), \tag{A41}$$

$$-T_{BLH} + \prod_M^*(w_{BLH}, k_H) \geq -T_{BLL} + \prod_M^*(w_{BLL}, k_H), \tag{A42}$$

$$-T_{BLH} + \prod_M^*(w_{BLH}, k_H) \geq -T_{BHL} + \prod_M^*(w_{BHL}, k_H), \tag{A43}$$

$$-T_{BLH} + \prod_M^*(w_{BLH}, k_H) \geq -T_{BHH} + \prod_M^*(w_{BHH}, k_H), \tag{A44}$$

$$-T_{BHH} + \prod_M^*(w_{BHH}, k_H) \geq -T_{BLL} + \prod_M^*(w_{BLL}, k_H), \tag{A45}$$

$$-T_{BHH} + \prod_M^*(w_{BHH}, k_H) \geq -T_{BHL} + \prod_M^*(w_{BHL}, k_H), \tag{A46}$$

$$-T_{BHH} + \prod_M^*(w_{BHH}, k_H) \geq -T_{BLH} + \prod_M^*(w_{BLH}, k_H), \tag{A47}$$

In order to solve the big supplier's problem in this case we can use the following steps:

(i) Using (A36) and (A39) we get $-T_{BLL} + \prod_M^*(w_{BLL}, k_L) = -T_{BHL} + \prod_M^*(w_{BHL}, k_L)$, which

Table A1 Uniform Distribution

Case	Wholesale price, w_B	Transfer price, T
Case SF	$w_B^{SF} = c_B$	$T_B^{SF} = \frac{r(a+b)}{2} - (c_B + k)\left[b - (b-a)\left(\frac{c_B+k}{2r}\right)\right]$
Case SA	$w_{BL}^{SA} = c_B$	$T_{BL}^{SA} = \frac{r(a+b)}{2} - (w_{BH}^{SA} + k_H)\left[b - (b-a)\left(\frac{w_{BH}^{SA} + k_H}{2r}\right)\right] + (w_{BH}^{SA} - c_B)\left[b - (b-a)\left(\frac{w_{BH}^{SA} + c_B + 2k_L}{2r}\right)\right]$
	$w_{BH}^{SA} = c_B + \frac{q_L}{q_H}(k_H - k_L)$	$T_{BH}^{SA} = \frac{r(a+b)}{2} - (w_{BH}^{SA} + k_H)\left[b - (b-a)\left(\frac{w_{BH}^{SA}+k_H}{2r}\right)\right]$
Case F	$w_B^F = c_B$	$T_B^F = (c_s - c_B)\left[b - (b-a)\left(\frac{c_s+c_B+2k}{2r}\right)\right]$
Case A1	$w_B^{A1} = c_B$	$T_B^{A1} = (\bar{w}_s - c_B)\left[b - (b-a)\left(\frac{\bar{w}_s+c_B+2k}{2r}\right)\right]$
Case A2	$w_{BL}^{A2} = c_B$	$T_{BL}^{A2} = (c_s - c_B)\left[b - (b-a)\left(\frac{c_s + c_B}{2r}\right)\right] - \left(\frac{b-a}{r}\right)\left[(w_{BH}^{A2} - c_B)k_L + (c_s - w_{BH}^{A2})k_H\right]$
	$w_{BH}^{A2} = \min(c_B + \frac{q_L}{q_H}(k_H - k_L), c_s)$	$T_{BH}^{A2} = (c_s - c_B)\left[b - (b-a)\left(\frac{c_s+w_{BH}^{A2}+2k_H}{2r}\right)\right]$
Case A3	$w_{BL}^{A3} = c_B$ $w_{BH}^{A3} = \min(c_B + \frac{q_L}{q_H}(k_H - k_L), \bar{w}_s)$	$T_{BL}^{A3} = (c_s - c_B)\left[b - (b-a)\left(\frac{\bar{w}_s + c_B}{2r}\right)\right] - \left(\frac{b-a}{r}\right)\left[(w_{BH}^{A3} - c_B)k_L + (\bar{w}_s - w_{BH}^{A3})k_H\right]$ $T_{BH}^{A3} = (\bar{w}_s - c_B)\left[b - (b-a)\left(\frac{\bar{w}_s + w_{BH}^{A3} + 2k_H}{2r}\right)\right]$

means that (A36) is binding and we can ignore (A39) because it is identical

(ii) Using (A44) and (A47) we get $-T_{BHH} + \prod_M^*(w_{BHH}, k_H) = -T_{BLH} + \prod_M^*(w_{BLH}, k_H)$, which means that (A44) is binding and we can ignore (A47) because it is identical

(iii) (A34) is redundant (using (A32) and (A39) and the fact that $\prod_M^*(c_L, k_L) \geq \prod_M^*(c_H, k_L)$)

(iv) (A35) is redundant (using (A33) and (A47) and the fact that $\prod_M^*(c_L, k_H) \geq \prod_M^*(c_H, k_H)$)

(v) (A40) and (A41) are redundant (using (i), (A37) and (A38))

(vi) (A46) and (A47) are redundant (using (ii), (A43) and (A44))

Based on these steps we need to maximize the objective function in section 9.3 s.t. (A32), (A33), (A37), (A38), (A42), (A43), (A45), with (A36) and (A44) binding (in equality). Using the parameters in section 8, $c_B = \$1$, $c_L = \$2$, $c_H = \$4$, $k_L = \$1$, $k_H = \$2$, $r = \$10$, $p_L = 0.5$, $q_L = 0.5$ and demand is distributed uniformly on the interval [a, b] = [0, 1]. Using this and the fact that by (A31),

$$y^*(w,k) = b - (b-a)\left(\frac{w+k}{r}\right) \text{ and}$$

$$\prod_M^*(w,k) = \frac{r[(y^*(w,k))^2 - a^2]}{2(b-a)}.$$

We get the following problem:

$$\text{Maximize}\, 0.25\,[(w_{BLL} + w_{BHL} + 0.9(w_{BLH} + w_{BHH})) - 0.1(w_{BLL}^2 + w_{BLH}^2 + w_{BHL}^2 + w_{BHH}^2) + (T_{BLL} + T_{BLH} + T_{BHL} + T_{BHH}) - 3.4], \quad \text{(A48)}$$

s.t.

$$w_{BLL}^2 - 18w_{BLL} - 20T_{BLL} \geq -32 \quad \text{(A49)}$$

$$w_{BLH}^2 - 16w_{BLH} - 20T_{BLH} \geq -28, \quad \text{(A50)}$$

$$w_{BLL}^2 - w_{BHL}^2 - 18w_{BLL} + 18w_{BHL} - 20T_{BLL} + 20T_{BHL} = 0, \quad \text{(A51)}$$

$$w_{BLL}^2 - w_{BLH}^2 - 18w_{BLL} + 18w_{BLH} - 20T_{BLL} + 20T_{BLH} \geq 0, \quad \text{(A52)}$$

$$w_{BLL}^2 - w_{BHH}^2 - 18w_{BLL} + 18w_{BHH} - 20T_{BLL} + 20T_{HH} \geq 0, \quad \text{(A53)}$$

$$w_{BLH}^2 - w_{BLL}^2 - 16w_{BLH} + 16w_{BLL} - 20T_{BLH} + 20T_{BLL} \geq 0, \quad \text{(A54)}$$

$$w_{BLH}^2 - w_{BHL}^2 - 16w_{BLH} + 16w_{BHL} - 20T_{BLH} + 20T_{BHL} \geq 0, \quad \text{(A55)}$$

$$w_{BLH}^2 - w_{BHH}^2 - 18w_{BLH} + 18w_{BHH} - 20T_{BLH} + 20T_{BHH} = 0, \quad \text{(A56)}$$

$$w_{BHH}^2 - w_{BLL}^2 - 16w_{BHH} + 16w_{BLL} - 20T_{BHH} + 20T_{BLL} \geq 0. \quad \text{(A57)}$$

This is a general nonlinear programming (NLP) problem and was solved using Matlab. The solution to this problem is given in Table 3.

Notes

[1]In 2004, the market capitalization of Intel was approximately 10 times bigger than that of Apple Computers whose market capitalization was 100 times bigger than that of SigmaTel. As it was reflected in various trade news articles, Apple Computers was the stronger party in her relationship with SigmaTel whose existence depended very tightly on a possible supply contract with Apple. This was not the case for Intel.

[2]Actual names for these suppliers are concealed due to confidentiality.

[3]In section 9, we study the case in which the small supplier's cost could be lower than that of the big supplier.

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