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Delegation vs. Control of Component Procurement Under Asymmetric Cost Information and Simple Contracts

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A manufacturer must choose whether to *delegate* component procurement to her tier 1 supplier or *control* it directly. Because of information asymmetry about suppliers' production costs and the use of simple quantity discount or price-only contracts, either delegation or control can yield substantially higher expected profit for the manufacturer. Delegation tends to outperform control when (1) the manufacturer is uncertain about the tier 1 supplier's cost and believes that it is likely to be high; (2) the manufacturer and the tier 1 supplier know the tier 2 supplier's cost or at least that it will be high; (3) the manufacturer has an alternative to engaging the tier 1 and tier 2 suppliers, such as in-house production; and (4) the firms use price-only contracts as opposed to quantity discount contracts. These results shed light on practices observed in the electronics industry.

Key words: multitier supply chain; delegation; control; asymmetric information; component procurement; contract design; price-only contracts; quantity discount contracts; robust optimization
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1. Introduction

Should a manufacturer contract with component (tier 2) suppliers or delegate that responsibility to a direct (tier 1) supplier? Retailers and service providers, as well as manufacturers, have wrestled repeatedly with that question and, even within the same industry or over time, arrived at different answers. In the electronics industry, Cisco delegates component procurement to its contract manufacturers (Nagarajan and Bassok 2008, Souza 2003), whereas Sun Microsystems was known for controlling component and even subcomponent procurement (Chin 2003). Between these extremes, Hewlett-Packard (HP) delegates procurement of some components to its contract manufacturers but controls the purchase of others (Carbone 2004). Historically, General Motors (GM) and other American automobile manufacturers relied on large purchasing departments to contract with thousands of component suppliers (Carr and Truesdale 1992), but over the past two decades, they have increasingly delegated responsibility to tier 1 suppliers for component procurement and assembly (McIvor et al. 1998). Historically and now, in comparison with American automobile manufacturers, Japanese automobile manufacturers delegate greater responsibility for component procurement to select tier 1 suppliers (McIvor et al. 1998). Prior to 2005, retailer Walmart purchased consumer goods from tier 1 suppliers. In 2006, to obtain innovative, environmentally friendly products, Walmart temporarily started to contract directly with lower-tier suppliers, notably organic cotton farmers, but has recently returned that responsibility to its tier 1 suppliers (Denend and Plambeck 2007, 2010). Increasingly, airline carriers like Delta and Emirates contract directly with aircraft engine manufacturers like General Electric (GE) and United Technologies in addition to aircraft assemblers like Boeing and Airbus (GE Aviation 2007, CNN World Business 2003).

Many factors influence whether a firm should delegate or control component procurement. Amaral et al. (2006) provide an excellent survey of these practices and the inherent trade-offs. A high cost of labor or pressure to cut operating costs (as in the recent recession) favors delegation, because delegation reduces managerial effort and head count in the purchasing department (Riverwood Solutions 2009). In some cases, control involves long-distance transport of the component to a manufacturer's facility for inspection and then to the tier 1 supplier's assembly facility;

delegation eliminates the costs, delays, and inventory requirements inherent in such transport (Lee and Tang 1998). However, control may be necessary to ensure quality and on-time delivery (Amaral et al. 2006). Depending on reputation, sophistication, relationships, and volume of procurement, either a firm or its tier 1 supplier may have the power to negotiate more favorable terms with the tier 2 supplier (Kagel and Roth 1995, Shell 1999, Ellram and Billington 2001, Amaral et al. 2006, Chen et al. 2012). To the extent that the firm has the greater bargaining power than its tier 1 supplier, it should control component procurement. In doing so, however, it should take steps to prevent the tier 1 supplier from observing its terms of payment with the tier 2 supplier, because the tier 1 supplier might use that information to its own advantage and the detriment of the firm (Deshpande et al. 2011).

Economists have abstracted from the aforementioned drivers of delegation versus control and have instead focused on asymmetric information regarding production costs. Most have assumed that the firm (and, in the delegation scenario, its tier 1 supplier) makes a take-it-or-leave-it offer of an optimal contract, which may be arbitrarily complex, and that the revelation principle holds. Those basic assumptions immediately imply that control is optimal; economists have focused on identifying additional conditions for delegation to perform equally well as control (see Mookherjee 2006 for an extensive survey of the economics literature on delegation versus control). When the revelation principle breaks, either control or delegation may be optimal. Mookherjee and Tsumagari (2004) allow the suppliers to collude and find that control continues to be optimal. Poitevin (2000) shows that allowing renegotiation favors delegation. In the paper most closely related to ours, Melumad et al. (1997) constrain the firm and its suppliers to use contracts that specify a limited number of possible production quantities and associated transfer payments, contingent on the cost information reported by each supplier. They prove that *delegation is always optimal*. In his survey, Mookherjee (2006) calls for more effort to account for information processing and communication costs (which constrain contract complexity) to provide a full-blown theory of the trade-off between delegation and control and render the theory useful in applied work.

In response, this paper examines delegation versus control with simple contracts (price-only or quantity discount, with or without an additional transfer payment), which are common in supply chain management practice and literature. Indeed, our assumptions regarding contract structure are motivated by our interactions with a leading electronics manufacturer. That firm controls procurement of a subset of its components while delegating procurement of others. With both tier 1 and component suppliers, it commonly specifies only the per-unit wholesale price. However, in some cases, the firm does specify the unit price as a decreasing, piecewise-constant function of quantity (typically with only two or three different unit prices and associated threshold quantities) or make an additional transfer payment. The literature on supply chain management with simple contracts predominantly assumes that firms use a price-only contract (see Lariviere and Porteus 2001, Guo et al. 2010, and references therein) or quantity discount contract (see Altintas et al. 2008 and references therein).

We prove that either delegation or control may be strictly optimal, which contradicts the well-known result by Melumad et al. (1997) that delegation is always optimal under simple contracts. Their notion of simplicity is to limit the number of contractual contingencies, each associated with a different payment and quantity. However, they allow for the payment to be an arbitrarily complex, nonlinear function of the quantity, which eliminates the problem of double marginalization under delegation. In contrast, under our assumption that firms use price-only or quantity discount contracts, delegation causes double marginalization. Its countervailing benefit is the *adjustment effect*: Delegation enables the tier 1 supplier to *adjust* the terms offered to the tier 2 supplier based on the private knowledge of his own production cost, which ultimately benefits the manufacturer. We prove that delegation outperforms control when the manufacturer is uncertain about the tier 1 supplier's production cost and anticipates that it is sufficiently likely to be high (relative to the difference between the cost of the manufacturer's best alternative source and the tier 2 supplier's least possible production cost). These are best understood as conditions that mitigate the problem of double marginalization under delegation and magnify the value of the adjustment effect.

Using quantity discount contracts, as opposed to price-only contracts, can flip a manufacturer's optimal decision from delegation to control, but never from control to delegation. The reason is that contract complexity and the adjustment effect under delegation are substitutes. In a complex optimal contract, the manufacturer offers terms that are contingent on suppliers' reports of their production costs, and that induces suppliers to report truthfully. The adjustment effect under delegation is qualitatively similar in making the terms for the tier 2 supplier contingent on the tier 1 supplier's cost. By the taxation principle, the complex optimal contract can be written contingent on quantities, rather than suppliers' cost reports (Martimort and Stole 2002). A quantity discount contract provides a better approximation to that complex optimal contract than does a price-only contract. Hence, using quantity discount contracts, rather than price-only contracts, favors control of component procurement.

The structure of this paper is as follows: Section 2 formulates our basic model of a multitier supply chain with asymmetric cost information and simple contracts. Section 3 provides sufficient conditions for control of component procurement to be optimal and sufficient conditions for delegation to be optimal, which hold under both quantity discount and price-only contracts. It also characterizes conditions under which control is strictly optimal under quantity discount contracts, whereas delegation is strictly optimal under price-only contracts. Section 4 presents a numerical study that suggests that the necessary and sufficient conditions for optimality of delegation have a simple threshold structure (qualitatively similar to our analytic sufficient conditions) and that the threshold shifts upward when the firms use quantity discount contracts. Moreover, the decision to delegate versus control component procurement often has a large effect on a manufacturer's expected profit. Section 5 discusses how our results help to explain procurement practices in the electronics industry.

2. Model Formulation

A manufacturer (M) has a serial, 2-tier supply chain. The tier 2 supplier (S2) incurs cost c_2 per unit to produce a component. The tier 1 supplier (S1) incurs cost c_1 per unit to transform the component into a final product and deliver it to M. Each supplier knows his own cost c_i. The other supplier and the manufacturer know that c_i has probability density function $f_i(c_i)$ with associated cumulative distribution function $F_i(c_i)$ and support $\Omega_i := [\underline{c}_i, \bar{c}_i]$, where $0 \le \underline{c}_i \le \bar{c}_i < \infty$, and that c_1 and c_2 are independent. Throughout, we assume $h_i(c_i) := F_i(c_i)/f_i(c_i)$ increases with c_i, which is equivalent to log-concavity of $F_i(c_i)$ and satisfied by many common distributions, including uniform, normal, exponential, and triangular (Bagnoli and Bergstorm 2005). We define $k_i(c_i) := c_i + h_i(c_i)$.

We assume that M, S1, and S2 are risk neutral: each seeks to maximize its own expected profit. M has expected revenue of $R(Q)$ when she stocks Q units of the final product, where $R(Q)$ is a finite, increasing, and strictly concave function of Q with $R(0) = 0$. For example, in a newsvendor setting with stochastic demand D for the final product, a selling price of p per unit, and salvage value of zero, $R(Q) = pE_D[\min(D, Q)]$; our numerical studies focus on this newsvendor setting. Finally, we assume $R'(0) > \underline{c}_1 + \underline{c}_2$ (otherwise, production would never be profitable).

M has an alternative source from which she can purchase additional units of the product. The unit price of this alternative source is $\bar{w}$, which may be known or unknown to the suppliers. (All our results hold in either case.) The alternative source could be in-house production by M. For simplicity of presentation, we assume without loss of generality that $\bar{w} \in (\underline{c}_1 + \underline{c}_2, R'(0)]$; the case where M has no alternative source is represented by $\bar{w} = R'(0)$. Define, for general $w \ge 0$,

$$Q^*(w) := \arg\max_{q \ge 0}[R(q) - wq] = R'^{-1}(w),$$

and let Q denote the number of units procured from S1 and S2, and let Q_A denote the number of units procured from the alternative source. Given Q, M chooses Q_A to maximize $R(Q + Q_A) - \bar{w}Q_A$. It follows that Q_A is equal to $(Q^*(\bar{w}) - Q)^+$.

Taking M's perspective, we focus on the fundamental question: Should M *delegate* or *control* component procurement? If M chooses control, then she contracts with both S1 and S2 herself. If M chooses delegation, she contracts only with S1, and S1 contracts with S2. We assume that in offering a contract, a firm makes a take-it-or-leave-it offer. This assumption is motivated by the fact that a firm that makes a take-it-or-leave-it offer (and has developed a reputation for always doing so) achieves greater expected profit than if, after a supplier rejects an offer, it offers an alternative contract (Fudenberg et al. 1985). For analytic tractability, this assumption is employed throughout the academic literature on delegation versus control with the unique exception of Poitevin (2000).

Regarding contract structure, we consider two scenarios. In the first scenario, the firms are constrained to use price-only contracts. That is, the buyer offers a constant wholesale price per unit w. In the second scenario, they may use simple quantity discount contracts, in which the buyer offers to pay T to the supplier for the right to procure up to Q^H units at unit price w^H, and additional units up to $(Q^L - Q^H)$ at unit price w^L, where $w^L \le w^H$. Note that a price-only contract is a special case of a quantity discount contract ($T = 0$, $w = w^L = w^H$, and $Q^H \ge Q^*(w)$). Our main result, Theorem 1, holds for both scenarios. Its proof has the same fundamental arguments, but is far more complicated for quantity discount contracts than the price-only contracts. Therefore, for brevity and clarity, we provide the proof for price-only contracts, and we relegate the proof for quantity discount contracts to the online appendix (available at http://dx.doi.org/10.1287/msom.1120.0395). In addition, in describing the intuition for the result, we will focus on the case with price-only contracts.

We now characterize M's price-optimization problem in the control and delegation scenarios.

2.1. Control Scenario

The sequence of events is that M offers a constant per-unit price w_1 to S1 and w_2 to S2 such that $w_1 + w_2 \le \bar{w}$.

Supplier i accepts w_i if and only if $c_i \le w_i$. If both suppliers accept, then M orders her optimal quantity $Q^*(w_1+w_2)$ from both suppliers and in return pays $t_i = w_i Q^*(w_1+w_2)$ to supplier i. If both suppliers accept her offer, M purchases zero units from her alternative source, which is more costly. If either one of the suppliers rejects the price offered by M, M purchases only from her alternative source. Her procurement quantity is $Q_A = Q^*(\bar{w})$, and she receives a net profit of $\underline{\pi} := R(Q^*(\bar{w})) - \bar{w}Q^*(\bar{w})$. Therefore, M's optimal expected profit is

$$\mathbf{P_c}: \quad \max_{w_1, w_2} \Big\{F_1(w_1)F_2(w_2)[R(Q^*(w_1+w_2)) - (w_1+w_2)Q^*(w_1+w_2) - \underline{\pi}] + \underline{\pi}\Big\}$$
$$\text{s.t.} \quad \underline{c}_i \le w_i \le \bar{c}_i \quad i=1,2$$
$$w_1 + w_2 \le \bar{w}.$$

2.2. Delegation Scenario

The sequence of events is that M offers a per-unit price $w_1 \le \bar{w}$ to S1. If $w_1 \le c_1$, S1 rejects M's offer right away without extending a contract to S2, and M buys only from the alternative source at price $\bar{w}$ per unit. Otherwise, the events unfold as follows: S1 offers a per-unit price w_2 to S2. M knows that S1 will use a price-only contract, but cannot observe the price he offers to S2. S2 accepts S1's offer if and only if $w_2 \ge c_2$. If S2 accepts w_2, then S1 accepts w_1 offered by M. M purchases $Q^*(w_1)$ units from S1 at price w_1 per unit, and S1 purchases $Q^*(w_1)$ units from S2 at price w_2 per unit. Because the alternative source is costlier, M does not procure any additional capacity from the alternative source in this case. If S2 rejects S1's offer, then S1 is forced to reject M's offer, and M buys only from the alternative source at price $\bar{w}$ per unit. To derive M's optimal price, we must first consider S1's response to any given price. S1, contingent on his cost c_1 and the price w_1 offered by M, selects the price w_2 to maximize his expected profit:

$$\mathbf{P_{dM}}: \quad \max_{\underline{c}_2 \le w_2 \le \min(\bar{c}_2,\, w_1 - c_1)} F_2(w_2)(w_1 - w_2 - c_1)Q^*(w_1);$$

the optimal price must be in the interval $[\underline{c}_2, \min(\bar{c}_2, w_1 - c_1)]$ because S1 cannot profitably pay more than $w_1 - c_1$ and S2 will always accept $\bar{c}_2$ but will never accept less than $\underline{c}_2$. As we show in Proposition O1 in the online appendix, optimal contract S1 offers to S2 is

$$w_2^d(c_1, w_1) = \begin{cases} \underline{c}_2 & \text{if } w_1 - c_1 < \underline{c}_2, \\ k_2^{-1}(w_1 - c_1) & \text{if } \underline{c}_2 \le w_1 - c_1 \le k_2(\bar{c}_2), \\ \bar{c}_2 & \text{otherwise.} \end{cases} \qquad (1)$$

Clearly, M should offer $w_1 \le \bar{c}_1 + k_2(\bar{c}_2)$ because offering a higher price would not increase the probability of having both suppliers accept the contract and thus could only decrease her expected profit. Using this fact and S1's best response function $w_2^d(c_1, w_1)$, we can formulate M's problem:

$$\mathbf{P_d}: \quad \max_{\underline{c}_1 + \underline{c}_2 \le w_1 \le \min(\bar{c}_1 + k_2(\bar{c}_2),\, \bar{w})} \Big\{E_{c_1}[F_2(w_2^d(c_1, w_1))] \cdot [R(Q^*(w_1)) - w_1 Q^*(w_1) - \underline{\pi}] + \underline{\pi}\Big\},$$

where the term $E_{c_1}[F_2(w_2^d(c_1, w_1))]$ is the probability that S2 accepts the price offered by S1.

3. Analytic Results

In contrast to the well-known result by Melumad et al. (1997) that delegation is always optimal when contract complexity is limited, Theorem 1 shows that under price-only and quantity discount contracts, either delegation or control may be strictly optimal for M, depending on what M knows about S1's cost c_1 and S2's cost c_2.

Theorem 1. *Control is strictly optimal if M knows c_1 but is uncertain about c_2. Delegation is optimal if M knows c_2.*

In the case that M is uncertain about both c_1 and c_2,

(i) *if $f_1(c_1)$ is decreasing in c_1, then control is optimal and may be strictly so; and*

(ii) *if $f_1(c_1)$ is a unimodal density function with mode $m_1 \ge \bar{w} - \underline{c}_2$, then delegation is optimal and may be strictly so.*

The proof of Theorem 1 adapts Popescu's (2005) generalized moment bound to address supply chain contracting. This robust optimization technique gives us distribution-free sufficient conditions for the optimality of delegation versus control. They are weak optimality conditions because one can construct (odd) cost distributions to ensure that M has exactly the same expected profit under delegation and control. The proof of Theorem 1(i) shows that control is *strictly* optimal, for example, when the suppliers' costs c_1 and c_2 have a symmetric uniform distribution with sufficiently high $\bar{w}$. The proof of Theorem 1(ii) shows that delegation is strictly optimal, for example, when, in addition to the inequality in (ii), the suppliers' costs have a symmetric triangular distribution.

The next four paragraphs provide intuition for the results in Theorem 1. The initial part is straightforward. When M knows c_1 but is uncertain about c_2, she must control component procurement and pay S1 exactly c_1 per unit, to avoid the problem of double marginalization. In contrast, when M knows c_2, M can optimally delegate component procurement, knowing that S1 will pay S2 exactly c_2 per unit, so the optimal price to offer S1 and resulting expected profit are the same as under control. That relies on our assumption that M and S1 have the same prior information about c_2.

In the interesting case that M is uncertain about c_1 and c_2, delegation has a beneficial *adjustment effect* but causes double marginalization. The conditions given in Theorem 1 for delegation to outperform control are ones that magnify the value of the adjustment effect and mitigate the problem of double marginalization (and vice versa for control to outperform delegation). The *adjustment effect* is that S1 adjusts the terms for S2 based on private knowledge of c_1. When S1's cost is low (unbeknownst to M), S1 offers a higher price to S2 than M would offer in the control scenario, and can thus engage S2 even when S2 has a high cost and would reject M's offer under control. When S1's cost is sufficiently high that he would reject M's offer under control, S1 can accept M's offer under delegation by offering a lower price to S2. Thus, the adjustment effect increases the likelihood that M engages S1 and S2.

Intuitively, the adjustment effect of delegation becomes more valuable to the extent that M is uncertain about c_1. Less obviously, the adjustment effect of delegation is more valuable when S1's cost is likely to take high values. The rationale is as follows. When S1's cost is likely to be small, M can offer a low price to S1 and relatively high price to S2, with confidence that both suppliers will likely accept those prices. Control performs well. However, when S1's cost is likely to be high, control does not perform well. To be confident of engaging S1, M must offer a high price to S1. This requires that M offers a lower price to S2, to maintain a reasonable total cost, and thus increases the probability of rejection by S2. To increase the probability of engaging both suppliers at a reasonable total cost, M must delegate component procurement, to allow S1 to adjust the price offered to S2.

Delegation also tends to be optimal when M has an attractive alternative source ($\bar{w}$ is small) and S2's cost is certainly high ($\underline{c}_2$ is large) because those conditions mitigate the problem of double marginalization. Under delegation, S1 keeps a margin for himself by quoting S2 a price w_2^d that is smaller than $w_1 - c_1$. To motivate S1 to offer a higher price to S2, M must increase the price she offers to S1. As a result, M generally has a higher total cost under delegation than control if M engages both S1 and S2. Under delegation, the price that M offers S1 is bounded above by the price of the alternative source $\bar{w}$, and S1 must offer S2 at least S2's minimum cost $\underline{c}_2$. Hence, S1 can take little margin when $\bar{w} - \underline{c}_2$ is small. The meaning of the inequality in Theorem 1(ii) is that S1's cost is likely to be high relative to $\bar{w} - \underline{c}_2$, so the beneficial adjustment effect outweighs the double marginalization problem and delegation is optimal.

In Theorem 1, the sufficient conditions for optimality of delegation versus control are identical for price-only and quantity discount contracts. However, there exist conditions (not addressed in Theorem 1) under which using quantity discount contracts instead of price-only contracts flips M's optimal decision from delegation to control.

Proposition 1. *Suppose that each supplier's cost has a binary distribution. If control is optimal under price-only contracts, then it is optimal under quantity discount contracts. There exist conditions under which delegation is strictly optimal under price-only contracts, whereas control is strictly optimal under quantity discount contracts.*

We conjecture that Proposition 1 holds without the binary cost assumption, based on our numerical study in §4. As discussed in §1, the reason that an increase in contract complexity favors control is that contract complexity and the adjustment effect of delegation are substitutes. That is, both serve to make the contract terms for S2 contingent on S1's cost.

4. Numerical Results

We consider 7,937 exogenous parameter settings, constructed as follows. S2's cost c_2 has a uniform distribution with minimum cost $\underline{c}_2 = E[c_2](1-\triangle_2)$ and maximum cost $\bar{c}_2 = E[c_2](1+\triangle_2)$, where $E[c_2] \in \{0.2, 0.4, 0.8, 1\}$ and cost dispersion $\triangle_2 = (\bar{c}_2 - \underline{c}_2)/(2E[c_2]) \in \{0.1, 0.3, 0.5, 0.7\}$. S1's cost c_1 is known to be zero or it has a triangular distribution with minimum $\underline{c}_1 = E[c_1](1-\triangle_1)$, mode $m_1 \in \{1.1\underline{c}_1, E[c_1], 0.9\bar{c}_1\}$, and maximum $\bar{c}_1 = E[c_1](1+\triangle_1)$, where $E[c_1] \in \{0.2, 0.4, 0.8, 1\}$ and the cost dispersion $\triangle_1 = (\bar{c}_1 - \underline{c}_1)/(2E[c_1]) \in \{0.1, 0.3, 0.5, 0.7\}$. (The uniform distribution of c_2 simplifies computation of M's optimal expected profit, which allows us to consider a large number of parameter settings. We assume that c_1 has a triangular, rather than uniform, distribution so that either delegation or control may be optimal, according to Theorem 1; if c_1 had a uniform distribution, then control would always be optimal.) M is a newsvendor with selling price $p = 1$. For the demand distribution and the price of the alternative source $\bar{w}$, we consider two different settings. In the first setting, $\bar{w}$ is $\min(1, \underline{c}_1 + \underline{c}_2 + \delta)$, where δ varies from 0.05 to 1 in increments of 0.2 and demand D is the maximum of zero and a normally distributed random variable with mean $\mu_D = 100$ and standard deviation $\sigma_D \in \{10, 20, 50, 100\}$. This gives us 7,400 different parameter settings, which we evaluate only for the scenario with price-only contracts. For the scenario with price-only contracts and the scenario with quantity discount contracts, we consider the case that demand is uniformly distributed between 0 and 10 and $\bar{w} = p = 1$, meaning that M has no viable alternative source. Using that simple demand structure, and with considerable effort, we can reliably compute the optimal quantity discount contracts for all our 537 different cost parameter settings. In general, M's expected profit has multiple local optima as a function of the parameters of a quantity discount contract, which makes numerical optimization slow and unreliable.

Strengthening the result in Theorem 1(ii), under both price-only and quantity discount contracts, we observe a threshold structure for the optimality of delegation versus control with respect to each of the following parameters: the mode m_1 of S1's cost, the dispersion $\Delta_1 = (\bar{c}_1 - \underline{c}_1)/(2E[c_1])$ of S1's cost, the mean $E[c_2]$ of S2's cost, and the minimum $\underline{c}_2$ of S2's cost. Specifically, as we vary m_1, Δ_1, or $E[c_2]$, while holding everything else constant, we observe that delegation is optimal if and only if that parameter is above a threshold. (In our numerical study, we set $\underline{c}_2 = E[c_2](1-\Delta_2)$, so $\underline{c}_2$ grows in proportion to $E[c_2]$.) Similarly, for price-only contracts, we observe that delegation is optimal if and only if $\bar{w}$ is below a threshold. We conjecture that the same result holds under quantity discount contracts, though we experienced difficulties with the numerical optimization at low levels of $\bar{w}$.

We also observe that Proposition 1 holds. Using quantity discount contracts rather than price-only contracts can flip M's optimal decision from delegation to control, but never from control to delegation. Using quantity discount contracts rather than price-only contracts slightly increases the threshold above which delegation is optimal. Hence, the flip occurs only at parameter settings where M is nearly indifferent between delegation and control.

M's gain in expected profit from choosing the optimal procurement strategy (which may be either delegation or control) ranges from zero to over 80%. That maximum gain occurs where control is optimal, because m_1 is minimal and M has no viable alternative source ($\bar{w} = p$). The maximum gain in M's expected profit from choosing delegation instead of control is just over 12%. Remarkably, these statistics are the same for our experiments in which firms use price-only contracts and in which they use quantity discount contracts. We conclude that either delegation or control can yield substantially higher expected profits for a manufacturer, because of information asymmetry about suppliers' production costs and the use of simple quantity discount or price-only contracts.

5. Discussion

Should a manufacturer control component procurement or delegate that responsibility to its tier 1 supplier? By focusing on asymmetry of information regarding suppliers' production costs and simple quantity discount or price-only contracts (motivated by our interactions with a leading electronics manufacturer and by the supply chain management literature), we prove that either delegation or control may be strictly optimal. Our conditions for delegation to outperform control (and vice versa) help to explain procurement practices in the electronics industry. For example, we have proven that control outperforms delegation when the manufacturer is uncertain about both suppliers' costs but anticipates that the tier 1 supplier's cost is likely to be relatively low. This helps to explain the fact that HP controls procurement of most of its components. Components drive most of the cost of its products, whereas assembly by a tier 1 supplier (contract manufacturer) is relatively cheap (Yuksel 2011).

We have proven that delegation is optimal when the manufacturer and tier 1 supplier know the tier 2 supplier's component production cost or the manufacturer has an attractive alternative source. Correspondingly, HP delegates procurement of "commodity" components, for which cost information is publicly available or there are many alternative sources (Carbone 2004). HP recently lost its alternative sources for brushed aluminum because Apple locked up those suppliers in long-term contracts. In response, HP is starting to control procurement of brushed aluminum, rather than allow its tier 1 supplier to do so (Yuksel 2011). The price of raw aluminum has become increasingly volatile in recent years (Schuh et al. 2011), which translates into increased uncertainty for both Apple and HP regarding a brushed aluminum supplier's production cost and, according to our analysis, favors control of the procurement of brushed aluminum.

We have proven that control is optimal when the manufacturer knows the tier 1 supplier's cost. In recent years, HP and many other original equipment manufacturers (with the notable exception of Apple) have increasingly outsourced design in addition to manufacturing to their tier 1 suppliers. Outsourcing design implies that HP will have uncertainty regarding a tier 1 supplier's production costs (Amaral et al. 2006), which favors delegation of component procurement. Conversely, Apple, by maintaining control of design and working closely with a tier 1 supplier to develop the manufacturing process, has little or no uncertainty about the tier 1 supplier's cost structure (Yuksel 2011), which favors control of component procurement. This is consistent with the observation that Apple has recently moved first, before HP, to take control of procurement of brushed aluminum, damage-resistant glass, and various other materials (Yuksel 2011, Savitz 2011).

In previous sections, we have also assumed that the manufacturer and the tier 1 supplier have the same prior information about the tier 2 supplier's cost. However, when the suppliers' costs are highly correlated—which may arise because the suppliers have common materials with volatile prices (e.g., aluminum) or common uncertainty regarding energy and labor costs—the tier 1 supplier effectively learns the tier 2 supplier's cost by observing his own cost (for an extension of our model to correlated supplier costs, see the online appendix). Moreover, in the electronics industry, a tier 1 supplier may have better information about a tier 2 component supplier due to physical proximity, employees with close personal relationships, and (particularly in China) local government officials that disseminate information (Yuksel 2011). Intuitively, to the extent that the tier 1 supplier obtains better information about the tier 2 supplier's cost, delegation will tend to outperform control. We conclude that trends toward regional concentration of manufacturing supply chains (by improving a tier 1 supplier's information about a tier 2 supplier's cost structure) will drive multinational buyers like HP toward delegation of component procurement. A related observation is that a multinational buyer like Cisco that has historically outsourced all of its manufacturing will naturally have less information regarding a tier 2 supplier's production cost, which favors delegation. Indeed, Cisco delegates all component procurement to its tier 1 suppliers (Ansley 2000, Souza 2003).

Since 2009, many original electronics manufacturers (OEMs) have been forced by the economic recession to cut procurement staff and delegate component procurement to tier 1 suppliers (Riverwood Solutions 2009). Those OEMs are also encouraging their tier 1 suppliers to integrate vertically into component production (Riverwood Solutions 2009). In our model formulation, assuming that the manufacturer cannot control component procurement, vertical integration by the tier 1 and tier 2 suppliers is equivalent to allowing the tier 1 supplier to perfectly observe the tier 2 supplier's cost. Therefore, vertical integration by the tier 1 and tier 2 suppliers increases the manufacturer's expected profit. This helps to explain the fact that, since the economic downturn, Foxconn and other contract manufacturers have integrated vertically into production of batteries and LCD displays for laptops, among other components (Clarke 2011, Yuksel 2011).

In theory, in the setting of our paper, a firm achieves greater expected profit by using quantity discount contracts rather than price-only contracts. However, quantity discount contracts are more difficult to implement, which restricts their use in practice. For example, in our work with a leading electronics manufacturer, we have learned that with some suppliers, the firm must use a price-only contract because the supplier's information technology systems lack the functionality to implement a quantity discount contract or other more complex contract. Quantity discount contracts also require greater managerial effort to optimize the parameters. Even in the simple model formulation considered in this paper, numerical optimization is difficult because the manufacturer's expected profit has multiple local optima as a function of the parameters of a quantity discount contract. We have proven that using price-only contracts instead of quantity discount contracts favors delegation of component procurement. The reason is that delegation allows the tier 1 supplier to adjust the price offered to the tier 2 supplier contingent on his own production cost, which is a substitute for contract complexity.

Electronic Companion

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Appendix. Proofs

The superscripts c and d are mnemonic for **c**ontrol and **d**elegation, respectively. The following lemma is useful in the proof of Theorem 1.

Lemma A1. *Assume that* $\underline{c}_1 \le a \le b \le \bar{c}_1$. *Then, we have*

$$\int_a^b F_2(k_2^{-1}(w-c_1))\,dc_1$$
$$= \begin{cases} 0 & \text{if } w \le a+\underline{c}_2, \\ b-a & \text{if } w \ge b+k_2(\bar{c}_2), \\ (w-a-\min(k_2^{-1}(w-a),\bar{c}_2))F_2(\min(k_2^{-1}(w-a),\bar{c}_2)) & \\ \quad -(w-b-\max(k_2^{-1}(w-b),\underline{c}_2))F_2(\max(k_2^{-1}(w-b),\underline{c}_2)) & \\ \qquad \text{otherwise}. & \end{cases}$$

Proof of Lemma A1. The proof of this lemma is through algebraic comparisons and elementary calculus. We first rewrite the left-hand side (LHS) as a double integral, and then change the order of integration. The details of the calculations are provided in the online appendix. □

Proof of Theorem 1. (i) In comparing control and delegation, it is practical to rewrite problem $\mathbf{P_c}$ as

$$\mathbf{P}'_{\mathbf{c}}: \quad \Pi_M^c := \max_{w \le \bar{w}} \; \{F_1(w_1^*(w))F_2(w-w_1^*(w)) \cdot [R(Q^*(w)) - wQ^*(w) - \underline{\pi}] + \underline{\pi}\}$$
$$\text{s.t.} \quad w_1^*(w) \in \underset{\substack{\underline{c}_1 \le w_1 \le \bar{c}_1 \\ \underline{c}_2 \le w - w_1 \le \bar{c}_2}}{\arg\max} \; F_1(w_1)F_2(w-w_1). \quad (2)$$

A direct comparison of problems $\mathbf{P}_\mathbf{c}'$ and $\mathbf{P}_\mathbf{d}$ yields that to show that M's expected profit is greater under control, it is sufficient to prove that $F_1(w_1^*(w))F_2(w-w_1^*(w)) \geq E_{c_1}[F_2(k_2^{-1}(w-c_1))]$ for every $\underline{c}_1+\underline{c}_2 \leq w \leq \min(\bar{c}_1+k_2(\bar{c}_2), \bar{w})$. First, consider the case where M knows c_1. In this case, $w_1^*(w)=c_1$ and $F_1(w_1^*(w))=1$. Therefore, the LHS of the inequality reduces to $F_2(w-c_1)$. Since M knows c_1, the right-hand side (RHS) is $F_2(k_2^{-1}(w-c_1))$. Since $k_2^{-1}(w-c_1) \leq w-c_1$, the inequality is always satisfied, and therefore M's expected profit is lower with delegation than with control. Moreover, the inequality is strict as long as $w>c_1$, which is the case since $\bar{w}>c_1+\underline{c}_2$. Now, assuming that M has uncertainty regarding both c_1 and c_2, observe that $(\min(w-\min(k_2^{-1}(w-\underline{c}_1),\bar{c}_2),\bar{c}_1), \min(k_2^{-1}(w-\underline{c}_1),\bar{c}_2))$ is in the feasible set of the optimization problem (2). Thus, by principle of optimality, we have

$$\begin{aligned} &F_1(w_1^*(w))F_2\big(w-w_1^*(w)\big)\\ &\quad\geq F_1\big(\min(w-\min(k_2^{-1}(w-\underline{c}_1),\bar{c}_2),\bar{c}_1)\big)\\ &\qquad\cdot F_2\big(\min(k_2^{-1}(w-\underline{c}_1),\bar{c}_2)\big). \end{aligned}$$

Therefore, using this inequality, it is sufficient to show that

$$\begin{aligned} &F_1\big(\min(w-\min(k_2^{-1}(w-\underline{c}_1),\bar{c}_2),\bar{c}_1)\big)F_2\big(\min(k_2^{-1}(w-\underline{c}_1),\bar{c}_2)\big)\\ &\quad-E_{c_1}\big[F_2(k_2^{-1}(w-c_1))\big]\geq 0, \end{aligned} \tag{3}$$

for every $\underline{c}_1+\underline{c}_2 \leq w \leq \min(\bar{c}_1+k_2(\bar{c}_2),\bar{w})$ and F_1 with a $\underline{c}_1$-unimodal distribution f_1.

To prove (3), we solve the following generalized moment bound problem and show the value of this problem is less than zero. Let $\Im_1$ be the set of distributions with $\underline{c}_1$-unimodal density. Consider the following problem:

$$\begin{aligned} \mathbf{P}_{\mathbf{d.P}}:\quad &\max_{F_1\in\Im_1}\ E_{c_1}\big[F_2(k_2^{-1}(w-c_1))\\ &\qquad-\mathbf{1}_{\{c_1\leq\min(w-\min(k_2^{-1}(w-\underline{c}_1),\bar{c}_2),\bar{c}_1)\}}\\ &\qquad\cdot F_2\big(\min(k_2^{-1}(w-\underline{c}_1),\bar{c}_2)\big)\big]\\ &\text{s.t.}\quad \int_{\underline{c}_1}^{\bar{c}_1} f_1(c_1)\,dc_1=1. \end{aligned}$$

where $\mathbf{1}_{\{\cdot\}}$ is the indicator function. We can write the dual of $\mathbf{P}_{\mathbf{d.P}}$ as follows (see Popescu 2005, p. 640):

$$\begin{aligned} \mathbf{P}_{\mathbf{d.D}}:\quad &\min_{y\in\mathbb{R}}\ y\\ &\text{s.t.}\quad y\int_{\underline{c}_1}^{t} dc_1 \geq \int_{\underline{c}_1}^{t}\left(\begin{array}{c} F_2(k_2^{-1}(w-c_1))\\ -\mathbf{1}_{\{c_1\leq\min(w-\min(k_2^{-1}(w-\underline{c}_1),\bar{c}_2),\bar{c}_1)\}}\\ \cdot F_2(\min(k_2^{-1}(w-\underline{c}_1),\bar{c}_2)) \end{array}\right)dc_1\\ &\qquad\qquad\forall\, t\in(\underline{c}_1,\bar{c}_1]. \end{aligned}$$

Define, for any $t\in(\underline{c}_1,\bar{c}_1]$,

$$D(t):=\int_{\underline{c}_1}^{t}\big(F_2(k_2^{-1}(w-c_1))\big)\,dc_1 \quad\text{and}$$

$$\begin{aligned} C(t):&=\int_{\underline{c}_1}^{t}\mathbf{1}_{\{c_1\leq\min(w-\min(k_2^{-1}(w-\underline{c}_1),\bar{c}_2),\bar{c}_1)\}}\\ &\qquad\cdot F_2\big(\min(k_2^{-1}(w-\underline{c}_1),\bar{c}_2)\big)\,dc_1\\ &=F_2\big(\min(k_2^{-1}(w-\underline{c}_1),\bar{c}_2)\big)\\ &\qquad\cdot\big(\min(t,w-\min(k_2^{-1}(w-\underline{c}_1),\bar{c}_2))-\underline{c}_1\big). \end{aligned}$$

By the weak duality theorem, it is sufficient to show that the value of problem $\mathbf{P}_{\mathbf{d.D}}$ is less than zero to conclude that the value of problem $\mathbf{P}_{\mathbf{d.P}}$ is less than zero as well. Thus, we need to prove that $D(t)-C(t)\leq 0$, $\forall\, t\in(\underline{c}_1,\bar{c}_1]$. To prove this, we need to consider four cases.

Case 1: $t\leq w-k_2(\bar{c}_2)$. By Lemma A1, we have $D(t)=t-\underline{c}_1$. Because $\underline{c}_1<t$ and $k_2(\cdot)$ is a strictly increasing function, we conclude that $\bar{c}_2<k_2^{-1}(w-\underline{c}_1)\leq w-\underline{c}_1<w-t$. Hence, we get $C(t)=F_2(\bar{c}_2)(t-\underline{c}_1)=(t-\underline{c}_1)$, which results in $D(t)-C(t)=0$.

Case 2: $w-k_2(\bar{c}_2)\leq t\leq w-\min(k_2^{-1}(w-\underline{c}_1),\bar{c}_2)$. By Lemma A1 and the fact that $t\leq w-\min(k_2^{-1}(w-\underline{c}_1),\bar{c}_2)\leq w-\underline{c}_2$, we find that

$$\begin{aligned} D(t)&=\big(w-\underline{c}_1-\min(k_2^{-1}(w-\underline{c}_1),\bar{c}_2)\big)F_2\big(\min(k_2^{-1}(w-\underline{c}_1),\bar{c}_2)\big)\\ &\quad-\big(w-t-k_2^{-1}(w-t)\big)F_2\big(k_2^{-1}(w-t)\big),\\ C(t)&=F_2\big(\min(k_2^{-1}(w-\underline{c}_1),\bar{c}_2)\big)(t-\underline{c}_1). \end{aligned}$$

We use the change of variables (i.e., $u(t)=k_2^{-1}(w-t)$) and the chain rule to find that

$$\begin{aligned} \frac{\partial(D(t)-C(t))}{\partial t}&=\big[F_2(\min(k_2^{-1}(w-\underline{c}_1),\bar{c}_2))-F_2(k_2^{-1}(w-t))\big]\\ &\quad\cdot\big[1+h_2'(k_2^{-1}(w-t))\big]\frac{\partial(k_2^{-1}(w-t))}{\partial t}, \end{aligned}$$

where the first term is positive, the second term is positive (because $h_2(\cdot)$ is increasing), and the last term is negative (because $k_2^{-1}(\cdot)$ is increasing). Hence, we find that $D(t)-C(t)$ is decreasing for $w-k_2(\bar{c}_2)<t\leq w-\min(k_2^{-1}(w-\underline{c}_1),\bar{c}_2)$. Since $D(w-k_2(\bar{c}_2))-C(w-k_2(\bar{c}_2))=0$ by Case 1, we conclude that $D(t)-C(t)\leq 0$.

Case 3: $w-\min(k_2^{-1}(w-\underline{c}_1),\bar{c}_2)\leq t\leq w-\underline{c}_2$. Trivial algebraic comparison yields that

$$C(t)=F_2\big(\min(k_2^{-1}(w-\underline{c}_1),\bar{c}_2)\big)\big(w-\min(k_2^{-1}(w-\underline{c}_1),\bar{c}_2)-\underline{c}_1\big).$$

Because $D(t)$ is increasing in t (by definition) and $C(t)$ is constant, we conclude that $D(t)-C(t)$ is increasing in t over this range. Finally, observing that $D(w-\underline{c}_2)-C(w-\underline{c}_2)=0$ by Case 4, we conclude that $D(t)-C(t)\leq 0$.

Case 4: $w-\underline{c}_2\leq t$. Because $k_2^{-1}(w-t)\leq\underline{c}_2$, it is trivial to show that

$$\begin{aligned} D(t)=C(t)&=F_2\big(\min(k_2^{-1}(w-\underline{c}_1),\bar{c}_2)\big)\\ &\quad\cdot\big(w-\min(k_2^{-1}(w-\underline{c}_1),\bar{c}_2)-\underline{c}_1\big). \end{aligned}$$

Hence, we conclude that $D(t)-C(t)=0$.

Since $D(t)-C(t)\leq 0$ in all four cases, we conclude that the optimal value of $\mathbf{P}_{\mathbf{d.P}}$ is negative, which completes the proof of the first part of Theorem 1(i).

We can prove the second part of Theorem 1(i) using $c_i\sim U[\underline{c},\bar{c}]$ for high enough $\bar{w}$. The details of the analysis are provided in the online appendix.

(ii) Define $\Psi_1:=\{F_1 \mid f_1$ is a unimodal probability density function on the set $[\underline{c}_1,\bar{c}_1]$ with mode $m_1\geq\bar{w}-\underline{c}_2\}$ and $W_1:=\{w_1 \mid \max(\underline{c}_1,w-\bar{c}_2)\leq w_1\leq\min(\bar{c}_1,w-\underline{c}_2)\}$. Similar to (i), a direct comparison of problems $\mathbf{P}_\mathbf{c}'$ and $\mathbf{P}_\mathbf{d}$ yields that to show that M's expected profit is greater under delegation for every $F_1\in\Psi_1$, it is sufficient to prove that

$$\begin{aligned} &\max_{F_1\in\Psi_1}\left\{\max_{w_1\in W_1}F_1(w_1)F_2(w-w_1)-E_{c_1}[F_2(k_2^{-1}(w-c_1))]\right\}\\ &=\max_{w_1\in W_1}\left\{\max_{F_1\in\Psi_1}F_1(w_1)F_2(w-w_1)-E_{c_1}[F_2(k_2^{-1}(w-c_1))]\right\}\leq 0, \end{aligned} \tag{4}$$

for every $\underline{c}_1 + \underline{c}_2 \le w \le \min(\bar{c}_1 + k_2(\bar{c}_2), \bar{w}) \le m_1 + \underline{c}_2$. The dual of the inner maximization problem can be written as follows (see Popescu 2005, p. 640):

$$\mathbf{P}'_{\mathbf{c.D}}\colon \quad \min_{y\in\mathbb{R}} \; y$$

$$\text{s.t.} \quad y\int_t^{m_1} dc_1 \ge \int_t^{m_1} \big(F_2(w-w_1)\mathbf{1}_{\{c_1\le w_1\}} - F_2(k_2^{-1}(w-c_1))\big)\,dc_1, \quad \forall t\in[\underline{c}_1, m_1], \tag{5}$$

$$y\int_{m_1}^{t} dc_1 \ge \int_{m_1}^{t} \big(F_2(w-w_1)\mathbf{1}_{\{c_1\le w_1\}} - F_2(k_2^{-1}(w-c_1))\big)\,dc_1, \quad \forall t\in[m_1, \bar{c}_1], \tag{6}$$

We claim that the RHS of both constraints are negative for all $w_1 \in W_1$, which ensures that the objective function of $\mathbf{P}'_{\mathbf{c.D}}$ is negative. Applying the weak duality theorem, we conclude that inequality (4) holds, which completes the proof of part (i).

To prove the claim that the RHS of (5) is less than zero, we start by observing that

$$A(w_1) := \int_t^{m_1} F_2(w-w_1)\mathbf{1}_{\{c_1\le w_1\}}\,dc_1 = F_2(w-w_1)\big(\min(m_1, w_1) - \min(t, w_1)\big).$$

There are two cases to consider:

Case 1: $w - t \le \underline{c}_2$. First note that $A(w_1) = 0$ for $w_1 \le t + \underline{c}_2$. This is trivially true if $w_1 \le t$ (since $\mathbf{1}_{\{c_1\le w_1\}} = 0$ for all values of c_1); otherwise, we use the inequality $w - w_1 < w - t \le \underline{c}_2$. Now that we prove $A(w_1) = 0$, we turn our attention to the second term of (5). Because $w - t \le \underline{c}_2$, by Lemma A1, we have $\int_t^{m_1} F_2(k_2^{-1}(w-c_1))\,dc_1 = 0$. Thus, we conclude that the RHS is equal to zero for any $w_1 \in W_1$ when $w - t \le \underline{c}_2$.

Case 2: $w - t > \underline{c}_2$. Consider the maximum value of $A(w_1)$ over the set $w_1 \in W_1$. First, observe that $A(w_1) = 0$ for $w_1 \le t$ and $A(w_1)$ is decreasing for $w_1 \ge m_1$. For $t < w_1 \le m_1$, we have $A'(w_1) = f_2(w - w_1)(h_2(w - w_1) - w_1 + t)$. Because the first term of this derivative is positive and the second term is decreasing in w_1, we conclude that the derivative is either always positive, always negative, or positive up to a threshold w_1 and then becomes negative; that is, $A(w_1)$ is a unimodal function. $A(w_1)$ attains its maximum at $w - k_2^{-1}(w-t)$. We further divide Case 2 into two subcases based on the values $k_2^{-1}(w-t)$ can take:

Case 2.1: $k_2^{-1}(w-t) < \bar{c}_2$. In this case, we have $w - \bar{c}_2 \le w - k_2^{-1}(w-t) \le w - \underline{c}_2$. Thus, the maximum of $A(w_1)$ for all $w_1 \in W_1$ is equal to $F_2(k_2^{-1}(w-t))(w - t - k_2^{-1}(w-t))$. By Lemma A1, this term is equal to $\int_t^{m_1} F_2(k_2^{-1}(w-c_1))\,dc_1$ because $\max(k_2^{-1}(w-m_1), \underline{c}_2) = \underline{c}_2$ by the definition of W_1. Thus, we conclude that the RHS is negative for any $w_1 \in W_1$.

Case 2.2: $k_2^{-1}(w-t) \ge \bar{c}_2$. Note that $w - k_2^{-1}(w-t) \le w - \bar{c}_2$. Thus, the maximum of $A(w_1)$ over the set $w_1 \in W_1$ is attained at the lower bound of the set W_1, $\max(\underline{c}_1, w - \bar{c}_2)$. Using the bounds on the parameters, we can show that $\max(\underline{c}_1, w - \bar{c}_2) = w - \bar{c}_2$: $m_1 \ge w - \bar{c}_2 \ge w - k_2(\bar{c}_2) \ge t \ge \underline{c}_1$, where the first inequality follows by definition of $k_2(\bar{c}_2)$, the second one follows by the condition of Case 2.2, and the last one follows by the condition of (5).

Since $A(w - \bar{c}_2) = w - \bar{c}_2 - t$, which is once again equal to $\int_t^{m_1} F_2(k_2^{-1}(w-c_1))\,dc_1$ by Lemma A1, we complete the proof that the RHS of (5) is negative. Using the same techniques, it is easy to show that the RHS of (6) is less than zero. This completes the proof of the claim and the proof of the first part of Theorem 1(ii).

We can prove the second part of Theorem 1(ii) using triangular distribution. The details of the analysis are provided in the online appendix. □

Proof of Proposition 1. Let each supplier's cost be a binary distribution: c_i is equal to $\underline{c}_i$ with probability p_i, or equal to $\bar{c}_i$ with probability $1 - p_i$, for $i \in \{1, 2\}$. To eliminate trivial cases, assume that $0 < p_i < 1$. We make two additional assumptions:

$$\frac{\bar{c}_2 - \underline{c}_2}{\bar{c}_1 - \underline{c}_1} \le 1 - p_2, \tag{7}$$

$$\bar{w} \ge T_c := \underline{c}_1 + \frac{\bar{c}_1 - \underline{c}_1}{1 - p_1 p_2} + \underline{c}_2 + \frac{\bar{c}_2 - \underline{c}_2}{1 - p_1 p_2}. \tag{8}$$

The first assumption guarantees that the dispersion in the tier 2 supplier's cost is relatively lower than the dispersion in the tier 1 supplier's cost, and the second assumption guarantees that $\bar{w}$ is sufficiently high.

Analysis of quantity discount contracts: When firms use simple quantity discount contracts, M has a separating equilibrium and four pooling equilibria under the control scenario. M's optimal contract for the separating equilibrium is to offer $w_i^L = \underline{c}_i$ and $w_i^H = \bar{c}_i$ for $i \in \{1, 2\}$; her profit is equal to $p_1 p_2 \Pi(\underline{c}_1 + \underline{c}_2) + (1 - p_1 p_2)\Pi(T_c)$, where $\Pi(w) := R(Q^*(w)) - wQ^*(w)$. The four pooling equilibria are as follows: M can offer $\underline{c}_i$ to both suppliers, she can offer $\underline{c}_1$ to the tier 1 supplier and $\bar{c}_2$ to the tier 2 supplier, she can offer $\bar{c}_1$ to the tier 1 supplier and $\underline{c}_2$ to the tier 2 supplier, or she can offer $\bar{c}_i$ to both suppliers. Note that, when M offers $\bar{c}_i$ to supplier i, the supplier accepts the contract. However, when M offers $\underline{c}_i$ to supplier i, the supplier accepts the contract only if his cost is low; i.e., with probability p_i. M's optimal profit under control can be expressed as

$$\max\big\{p_1 p_2 \Pi(\underline{c}_1 + \underline{c}_2) + (1 - p_1 p_2)\Pi(T_c),\; p_1 p_2 \Pi(\underline{c}_1 + \underline{c}_2) + (1 - p_1 p_2)\Pi(\bar{w}),\; p_1 \Pi(\underline{c}_1 + \bar{c}_2) + (1 - p_1)\underline{\pi},\; p_2 \Pi(\bar{c}_1 + \underline{c}_2) + (1 - p_2)\underline{\pi},\; \Pi(\bar{c}_1 + \bar{c}_2)\big\}. \tag{9}$$

It is straightforward to verify that M's respective profits under these separating and pooling equilibria are equal to their counterparts using arbitrarily complex contracts. Because M cannot achieve higher profits than arbitrarily complex contracts with any other contract (see, for example, Mookherjee 2006), we conclude that control is always optimal under quantity discount contracts.

Next, we characterize conditions under which control is *strictly* better than delegation. To do so, we first characterize S1's profit under delegation. We start with solving for S1's problem. Given the contract $\{w_1^k, Q_1^k\}_{k\in\{L,H\}}$ offered by

M and S1's cost c_1, S1's optimal strategy can be expressed as follows:

Case 1.

$$c_1 + \frac{\bar{c}_2 - p_2 \underline{c}_2}{1-p_2} \le w_1^L \le w_1^H, \qquad \text{S1 offers } w_2^L = w_2^H = \bar{c}_2,\ Q_2^L = Q_2^H = Q_1^L.$$

Case 2.

$$c_1 + \underline{c}_2 \le w_1^L < c_1 + \frac{\bar{c}_2 - p_2 \underline{c}_2}{1-p_2} \le w_1^H, \qquad \text{S1 offers } w_2^L = \underline{c}_2,\ w_2^H = \bar{c}_2,\ Q_2^k = Q_1^k \quad \forall k \in \{L, H\}.$$

Case 3.

$$w_1^L < c_1 + \underline{c}_2 < c_1 + \frac{\bar{c}_2 - p_2 \underline{c}_2}{1-p_2} \le w_1^H, \qquad \text{S1 offers } w_2^L = w_2^H = \bar{c}_2,\ Q_2^L = Q_2^H = Q_1^H.$$

Case 4.

$$c_1 + \underline{c}_2 \le w_1^L \le w_1^H < c_1 + \frac{\bar{c}_2 - p_2 \underline{c}_2}{1-p_2}, \qquad \text{S1 offers } w_2^L = w_2^H = \underline{c}_2,\ Q_2^L = Q_2^H = Q_1^L.$$

Case 5.

$$w_1^L < c_1 + \underline{c}_2 \le w_1^H < c_1 + \frac{\bar{c}_2 - p_2 \underline{c}_2}{1-p_2}, \qquad \text{S1 offers } w_2^L = w_2^H = \underline{c}_2,\ Q_2^L = Q_2^H = Q_1^H.$$

Case 6.

$$w_1^L \le w_1^H < c_1 + \underline{c}_2, \quad \text{S1 offers no contract.}$$

Given the solution to S1's problem and assuming $\bar{w} > T_2$, M's optimal profit under delegation can be calculated by evaluating the maximum of the profits of seven cases as shown in the RHS of inequalities (10)–(16), where $T_1 := \underline{c}_1 + (\bar{c}_2 - p_2 \underline{c}_2)/(1-p_2)$ and $T_2 := \bar{c}_1 + (\bar{c}_2 - p_2 \underline{c}_2)/(1-p_2)$, and by (7), $\underline{c}_1 + \bar{c}_2 < T_1 < \bar{c}_1 + \underline{c}_2 < \bar{c}_1 + \bar{c}_2 < T_c < T_2$.

Using (9), control is strictly optimal under quantity discount contracts if the following inequalities hold:

$$p_1 p_2 \Pi(\underline{c}_1 + \underline{c}_2) + (1 - p_1 p_2)\Pi(T_c) > \Pi(T_2), \tag{10}$$

$$\Pi(\bar{c}_1 + \bar{c}_2) > \Big((p_1 + (1-p_1)p_2)\Pi(\bar{c}_1 + \underline{c}_2) + (1-p_1)(1-p_2) \cdot \Pi\Big(T_2 + \frac{(p_1 + (1-p_1)p_2)(T_2 - (\bar{c}_1 + \underline{c}_2))}{(1-p_1)(1-p_2)}\Big)\Big), \tag{11}$$

$$\Pi(\bar{c}_1 + \bar{c}_2) > p_1 \Pi(T_1) + (1-p_1)\Pi\Big(T_2 + \frac{p_1(T_2 - T_1)}{1-p_1}\Big), \tag{12}$$

$$\Pi(\bar{c}_1 + \bar{c}_2) > p_1 p_2 \Pi(\underline{c}_1 + \underline{c}_2) + (1 - p_1 p_2)\Pi\Big(T_2 + \frac{p_1 p_2 (T_2 - \underline{c}_1 - \underline{c}_2)}{1 - p_1 p_2}\Big), \tag{13}$$

$$p_1 p_2 \Pi(\underline{c}_1 + \underline{c}_2) + (1 - p_1 p_2)\Pi(T_c) > \Big(p_1 \Pi(T_1) + (1-p_1)p_2 \Pi\Big(\bar{c}_1 + \underline{c}_2 + \frac{p_1(\bar{c}_1 + \underline{c}_2 - T_1)}{(1-p_1)p_2}\Big) + (1-p_1)(1-p_2)\underline{\pi}\Big), \tag{14}$$

$$p_1 p_2 \Pi(\underline{c}_1 + \underline{c}_2) + (1 - p_1 p_2)\Pi(T_c) > \Big(p_1 p_2 \Pi(\underline{c}_1 + \underline{c}_2) + (1-p_1)(1-p_2)\underline{\pi} + (p_1(1-p_2) + p_2(1-p_1))\Pi\Big(\bar{c}_1 + \underline{c}_2 + \frac{p_1 p_2 (\bar{c}_1 - \underline{c}_1)}{(p_1(1-p_2) + p_2(1-p_1))}\Big)\Big), \tag{15}$$

$$p_1 \Pi(\underline{c}_1 + \bar{c}_2) + (1-p_1)\underline{\pi} > \Big(p_1 p_2 \Pi(\underline{c}_1 + \underline{c}_2) + p_1(1-p_2) \cdot \Pi\Big(T_1 + \frac{p_1 p_2 (T_1 - \underline{c}_1 - \underline{c}_2)}{p_1(1-p_2)}\Big) + (1-p_1)\underline{\pi}\Big). \tag{16}$$

Now, observe that (10) holds since $\underline{c}_1 + \underline{c}_2 < T_c < T_2$ and $\Pi(w)$ is strictly decreasing. Using the fact that $\Pi(w)$ is also a strictly concave function, we have the following:

$$\begin{aligned}
&\Big((p_1 + (1-p_1)p_2)\Pi(\bar{c}_1 + \underline{c}_2) + (1-p_1)(1-p_2) \cdot \Pi\Big(T_2 + \frac{(p_1 + (1-p_1)p_2)(T_2 - (\bar{c}_1 + \underline{c}_2))}{(1-p_1)(1-p_2)}\Big)\Big)\\
&< \Pi\Big((p_1 + (1-p_1)p_2)(\bar{c}_1 + \underline{c}_2) + (1-p_1)(1-p_2) \cdot \Big(T_2 + \frac{(p_1 + (1-p_1)p_2)(T_2 - (\bar{c}_1 + \underline{c}_2))}{(1-p_1)(1-p_2)}\Big)\Big)\\
&= \Pi(T_2) < \Pi(\bar{c}_1 + \bar{c}_2),
\end{aligned}$$

where the last inequality holds since $\bar{c}_1 + \bar{c}_2 < T_2$ and $\Pi(w)$ is strictly decreasing in w, implying inequality (11) holds. Using similar arguments, one can show that inequalities (12) and (13) also hold. To show inequality (14) holds, observe that if

$$\begin{aligned}
\bar{w} &> \{(1 - p_1 p_2)T_c - [p_1(1-p_2)T_1 + (1-p_1)p_2[\bar{c}_1 + \underline{c}_2 + p_1(\bar{c}_1 + \underline{c}_2 - T_1)/((1-p_1)p_2)]]\} \cdot ((1-p_1)(1-p_2))^{-1}\\
&= T_2 + \frac{p_1(\bar{c}_2 - \underline{c}_2)}{(1-p_1)(1-p_2)^2},
\end{aligned} \tag{17}$$

then

$$\begin{aligned}
\Pi(T_c) &> \Pi\big([p_1(1-p_2)T_1 + (1-p_1)p_2[\bar{c}_1 + \underline{c}_2 + p_1(\bar{c}_1 + \underline{c}_2 - T_1)/((1-p_1)p_2)] + (1-p_1)(1-p_2)\bar{w}] \cdot (1-p_1p_2)^{-1}\big)\\
&> \frac{p_1(1-p_2)}{(1-p_1p_2)}\Pi(T_1) + \frac{(1-p_1)p_2}{(1-p_1p_2)}\Pi\Big(\bar{c}_1 + \underline{c}_2 + \frac{p_1(\bar{c}_1 + \underline{c}_2 - T_1)}{(1-p_1)p_2}\Big) + \frac{(1-p_1)(1-p_2)}{(1-p_1p_2)}\Pi(\bar{w}).
\end{aligned}$$

Multiplying both sides with $1 - p_1 p_2$ and adding $p_1 p_2 \Pi(\underline{c}_1 + \underline{c}_2)$ and $p_1 p_2 \Pi(T_1)$ to the LHS and RHS of this inequality result in (14). Using similar arguments, we can show that (15) holds if

$$\bar{w} > \big[(1 - p_1 p_2)T_c - \big[(p_1(1-p_2) + p_2(1-p_1)) \cdot \big[\bar{c}_1 + \underline{c}_2 + p_1 p_2(\bar{c}_1 + \underline{c}_2 - \underline{c}_1 - \underline{c}_2)/\big(p_1(1-p_2) + p_2(1-p_1)\big)\big]\big]\big] \cdot ((1-p_1)(1-p_2))^{-1}. \tag{18}$$

Comparing the two bounds on $\bar{w}$ in (17) and (18), it is straightforward to see that the bound in (17), which is greater than T_2, is the larger of the two. That is, under the condition (17), both (14) and (15) hold.

Finally, inequality (16) also holds since

$$\begin{aligned}&\frac{p_1p_2}{p_1}\Pi(\underline{c}_1+\underline{c}_2)+\frac{p_1(1-p_2)}{p_1}\Pi\left(T_1+\frac{p_1p_2(T_1-\underline{c}_1-\underline{c}_2)}{p_1(1-p_2)}\right)\\&<\Pi\left(\frac{p_1p_2(\underline{c}_1+\underline{c}_2)+p_1(1-p_2)(T_1+p_1p_2(T_1-\underline{c}_1-\underline{c}_2)/(p_1(1-p_2)))}{p_1}\right)\\&=\Pi(T_1)<\Pi(\underline{c}_1+\bar{c}_2),\end{aligned}$$

because $\underline{c}_1+\bar{c}_2<T_1$. Combining all of the assumptions and conditions, we conclude that control is strictly optimal under quantity discount contracts if (7) and (17) hold.

Analysis of price-only contracts: Under price-only contracts, both control and delegation can be optimal. Next, we characterize the conditions for strict optimality of delegation. M's optimal profit under control is

$$\begin{aligned}\max\{&p_1p_2\Pi(\underline{c}_1+\underline{c}_2)+(1-p_1p_2)\underline{\pi},\,p_1\Pi(\underline{c}_1+\bar{c}_2)+(1-p_1)\underline{\pi},\\&p_2\Pi(\bar{c}_1+\underline{c}_2)+(1-p_2)\underline{\pi},\,\Pi(\bar{c}_1+\bar{c}_2)\}.\end{aligned}\quad(19)$$

Under delegation, we first solve for S1's problem given M's price w_1 and S1's cost c_1. S1 offers $\bar{c}_2$ if and only if (i) offering $\underline{c}_2$ yields lower profits and (ii) offering $\bar{c}_2$ yields positive profits. The former is true if $(w_1-c_1-\bar{c}_2)Q^*(w_1)\geq(w_1-c_1-\underline{c}_2)p_2Q^*(w_1)$; i.e., if $w_1\geq c_1+(\bar{c}_2-p_2\underline{c}_2)/(1-p_2)$. Since $\bar{c}_2\leq(\bar{c}_2-p_2\underline{c}_2)/(1-p_2)$, this condition also ensures that S1 has nonnegative profits. If $w_1<c_1+(\bar{c}_2-p_2\underline{c}_2)/(1-p_2)$, S1 offers $\underline{c}_2$, as long as offering so yields positive profits, i.e., $w_1\geq c_1+\underline{c}_2$.

Given the solution to S1's problem and under assumption (7), M's profit under delegation is

$$\begin{aligned}\max\{&p_1p_2\Pi(\underline{c}_1+\underline{c}_2)+(1-p_1p_2)\underline{\pi},\,p_1\Pi(T_1)+(1-p_1)\underline{\pi},\\&(p_1+(1-p_1)p_2)\Pi(\bar{c}_1+\underline{c}_2)+(1-p_1)(1-p_2)\underline{\pi},\,\Pi(T_2)\}.\end{aligned}\quad(20)$$

Comparing M's optimal profits in (19) and (20), we conclude that delegation is strictly optimal under the price-only contract if the following inequalities hold:

$$\begin{aligned}&(p_1+(1-p_1)p_2)\Pi(\bar{c}_1+\underline{c}_2)+(1-p_1)(1-p_2)\underline{\pi}\\&\quad>p_1p_2\Pi(\underline{c}_1+\underline{c}_2)+(1-p_1p_2)\underline{\pi},\end{aligned}\quad(21)$$

$$\begin{aligned}&(p_1+(1-p_1)p_2)\Pi(\bar{c}_1+\underline{c}_2)+(1-p_1)(1-p_2)\underline{\pi}\\&\quad>p_1\Pi(\underline{c}_1+\bar{c}_2)+(1-p_1)\underline{\pi},\end{aligned}\quad(22)$$

$$\begin{aligned}&(p_1+(1-p_1)p_2)\Pi(\bar{c}_1+\underline{c}_2)+(1-p_1)(1-p_2)\underline{\pi}\\&\quad>p_2\Pi(\bar{c}_1+\underline{c}_2)+(1-p_2)\underline{\pi},\end{aligned}\quad(23)$$

$$(p_1+(1-p_1)p_2)\Pi(\bar{c}_1+\underline{c}_2)>\Pi(\bar{c}_1+\bar{c}_2).\quad(24)$$

Because assumption (8) holds, $\bar{c}_1+\underline{c}_2<\bar{w}$, which, together with the fact that $\Pi(w)$ is strictly decreasing in w, implies that (23) holds. To show that (22) holds, we first note that the function $\Pi(w)$ is strictly concave in w using a trivial application of the envelope theorem. Hence, if

$$\begin{aligned}\bar{w}&>\underline{c}_1+\underline{c}_2+\frac{(\bar{c}_1-\underline{c}_1)(p_1+(1-p_1)p_2)-(\bar{c}_2-\underline{c}_2)p_1}{(1-p_1)p_2}\\&=\frac{(\bar{c}_1+\underline{c}_2)(p_1+(1-p_1)p_2)-(\underline{c}_1+\bar{c}_2)p_1}{(1-p_1)p_2},\end{aligned}\quad(25)$$

then $\bar{c}_1+\underline{c}_2<(p_1(\underline{c}_1+\bar{c}_2)+(1-p_1)p_2\bar{w})/(p_1+(1-p_1)p_2)$, which implies $\Pi((p_1(\underline{c}_1+\bar{c}_2)+(1-p_1)p_2\bar{w})/(p_1+(1-p_1)p_2))<\Pi(\bar{c}_1+\underline{c}_2)$. Using the fact that $\Pi(\cdot)$ is a strictly concave function, we conclude that $p_1/(p_1+(1-p_1)p_2)\Pi(\underline{c}_1+\bar{c}_2)+((1-p_1)p_2)/(p_1+(1-p_1)p_2)\Pi(\bar{w})<\Pi(\bar{c}_1+\underline{c}_2)$, which, in turn, implies that (22) holds.

Using a similar argument, we can show that (21) holds if $\bar{w}>\underline{c}_1+\underline{c}_2+((\bar{c}_1-\underline{c}_1)(p_1+(1-p_1)p_2))/(p_1(1-p_2)+(1-p_1)p_2)$. Using assumption (7), we can show that this lower bound on $\bar{w}$ is lower than the one in (25). That is, under the condition (25), both (21) and (22) hold.

Combining these conditions with the assumptions, we conclude that delegation is strictly optimal under price-only contracts if (7), (8), (24), and (25) hold.

Comparison of price-only and quantity discount contracts: Using the analysis above, we conclude that delegation is strictly optimal under price-only contracts, whereas control is strictly optimal under quantity discount contracts if (7), (17) (which guarantees that (8) is satisfied), (24), and (25) hold. □

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