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Sourcing for Supplier Effort and Competition: Design of the Supply Base and Pricing Mechanism

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We study a buyer's sourcing strategy along two dimensions: the supply base design and the pricing mechanism, considering supplier competition and cost-reduction effort. The supply base design concerns the number of suppliers (one or two) included in the supply base and the capacity to be invested in each supplier. The pricing mechanism determines the timing of the price decisions, with the buyer making price commitments before suppliers exert cost-reduction efforts that may be renegotiated afterward. We find that symmetric capacity investment in suppliers and low price commitments (more likely to be renegotiated) are effective at fostering supplier competition, whereas asymmetric investment and high price commitments (less likely to be renegotiated) are better at motivating supplier effort. A *complementary* relationship exists between the supply base design and pricing mechanism: A more symmetric supply base should be combined with lower price commitments, leading to more renegotiation opportunities. This results in three possible sourcing structures: *sole sourcing* (investing capacity in a single supplier and forming price with ex ante commitments), *symmetric dual sourcing* (investing equal capacity in both suppliers and forming price with ex post negotiations), and *asymmetric dual sourcing* (investing positive but unequal capacities in two (ex ante identical) suppliers and forming price using both ex ante commitments and ex post (re)negotiations). We characterize the conditions for each structure and identify a strategic role of capacity investment.

Key words: sourcing; supply base; supplier competition; supplier effort; commitment; renegotiation
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1. Introduction

Manufacturers increasingly rely on suppliers to create value, reduce costs, and improve products or services. In the auto industry, most original equipment manufacturers (OEMs) create only 30%–35% of value internally (Maurer et al. 2004). As OEMs give suppliers more design and production responsibilities, suppliers' improvement and innovation efforts become a major source for OEMs to enhance the quality and functionality of their products while reducing manufacturing costs (Nelson et al. 2001). In this paper, we consider a supplier's process improvement effort to reduce production costs. Process improvements at assembly plants, especially the adoption of lean production practices, were considered as the largest factor that contributed to the productivity growth in the U.S. auto industry from 1987 to 2002 (Baily et al. 2005). An example of such improvement was by Trim Masters, a car seat supplier, that redesigned the assembly line to have work done on the inside of the line. This allowed parts to be automatically delivered on the outside of the line, significantly reducing labor costs.[1] In the electronics industry, a major opportunity of cost reduction lies in process improvements to reduce contamination of dust at wafer fabs to increase yield (see, e.g., West et al. 1997). Achieving such improvements absorbs considerable engineering and management resources for activities such as monitoring, analysis, experiments, and implementation. In addition, these activities may interrupt the regular production process, yet the redesigned process may not work as intended. Thus, motivating suppliers to undertake such efforts is not always easy.

To induce supplier effort, many manufacturers have reduced their supply base (Duffy 2005). A small supply base allows an OEM to build deeper trust and foster close supplier relationships, thereby encouraging suppliers to dedicate more resources to improve their performance (Dyer 2000, Liker and Choi 2004). For example, in 2005, Ford overhauled its supply system by offering larger contracts to a smaller group of suppliers to motivate suppliers to provide it the best technology (McCracken 2005). In 2006, Airbus trimmed its supply base, "in hoping to forge durable relationships so contractors can make long-term investment plans to improve the quality of their products and increase efficiency" (Michaels 2006).

Besides supply base reduction, early price commitments may also help to incentivize suppliers.

[1] Based on the author's communication with Jeff Liker (http://www-personal.umich.edu/~liker/) in August 2011.

By committing to a price before the supplier exerts cost-reduction effort, the OEM (buyer) allows the supplier to retain the margin achieved with his effort. This contrasts with the strategy of (re)negotiating price based on the cost outcome of the effort. The latter strategy may hold up supplier effort when the supplier is in a weak bargaining position relative to the buyer (McMillan 1990): Because a supplier's effort cost is already sunk at the time of price decision, the buyer would extract all returns of the supplier's effort by demanding a low price. Expecting this result, the supplier would be reluctant to exert effort up front.

Although a small supply base and price commitment may be advantageous at motivating supplier effort, forming a large supply base and engaging suppliers in competition can also deliver benefits. Two key reasons provide this opportunity: First, supplier competition allows the buyer to maintain an upper hand on pricing, which is important when it is difficult to estimate a supplier's cost. In the automotive industry, suppliers do not merely provide small parts but increasingly serve as integrators for complex assembled systems. The integrated systems are much harder for OEMs to price and evaluate than are simple parts (Maurer et al. 2004). In such cases, supplier competition helps the buyer to form reasonable expectations of supplier cost, thereby extracting a lower price (Duffy 2005, McMillan 1990).

Second, supplier competition allows flexibility of supplier selection, mitigating supplier performance risks. A supplier's cost performance may vary because of changes in the internal or external environment, such as variations in the management, financial status, logistics, or subsuppliers. The uncertainty of supplier capability may also be caused by the uncertain outcome of innovation and process improvement (Choi and Krause 2006, Carrillo and Gaimon 2004). With multiple competing suppliers in the supply base, a buyer can respond to supplier performance changes by adjusting her business allocation among suppliers (Duffy 2005). For example, both Toyota and Cisco maintain more suppliers than they need in their supplier networks so that they can "keep the resulting higher costs in check by monitoring and benchmarking suppliers against each other" (Chopra and Sodhi 2004, p. 58).

In this paper, we study a buyer's sourcing strategy consisting of the supply base design and pricing mechanism, considering supplier cost-reduction effort and supplier competition. The supply base design concerns the number of suppliers and the buyer's investment in supplier capacity. To reveal the economic trade-off sharply, we limit our analysis to two ex ante identical suppliers. A buyer may invest in assets that are located within her suppliers but dedicated for the buyer's use. The investment is made to improve the suppliers' delivery capability and enhance the buyer's relationship with them; examples from the automotive industry include Toyota (CAPS 2005), Hyundai (Hahn et al. 1989), and Chrysler (Dyer 2000, Table 5.1). The investment may also be made by the buyer concerned with extra costs charged by a supplier for such investment and suppliers' lack of financial clout to make such purchases (*AutoBeat Daily* 2002). In the electronics industry, an OEM often invests in work stations, testing equipment, tooling, or other intellectual properties used by suppliers.[2] Apple invested billions of dollars in its suppliers, especially those of displays, to expand their production capacity and secure the product availability (Kovar 1999, Jakhanwal 2011, Satariano and Burrows 2011). The buyer investing in suppliers does not necessarily exclude supplier competition. The buyer can collaborate with a few suppliers yet still impose competition between suppliers. Such a situation may be called a performance-based partnership (Mair 2000) or durable arms-length relationship (Dyer et al. 1998). For instance, Toyota invested in its auto seats supplier Trim Masters to introduce competition to its other supplier Johnson Controls (Liker 2004, p. 217). Investing heavily in its display suppliers, Apple also pitted the suppliers against each other by putting its business up for bid each time it readied a factory order (Carson 2007).

The pricing mechanism determines the timing of the price decision. The buyer can commit to a price *before* the supplier exerts cost-reduction effort or negotiate the price *after* the cost reduction occurs. The former is termed "ex ante commitment" and the latter is termed "ex post negotiation." The two mechanisms may be blended together with the buyer committing up front to a price that can be renegotiated afterward based on the supplier cost outcome. The renegotiation brings two benefits: First, it improves voluntary participation of the supplier. Without it, a supplier would likely quit if his actual cost turns out to be too high for him to make a profit based on the committed price. The supplier may legally disassociate himself without penalty under the protection of limited liability that limits the loss for him to bear. Contracts with limited liability clauses are common in practice, particularly when information about risk is incomplete or equity considerations mandate risk spreading and the guarantee of certain levels of "well-being" for each party to survive (Sappington 1983, Stole 1994). Even without formal limited liability clauses, it may be difficult to enforce a party to continue with a loss-making contract. The party at loss will press for renegotiation, and the other party often has to concede for

[2] Based on the author's communication with Mark Zetter (http://www.ventureoutsource.com/electronics-global-network/profile/mark-zetter) in August 2011.

fear of disrupting the supply chain and risking the distressed partner's failure (McCracken and Glader 2007). Recent years have witnessed several cases in which auto suppliers cut off the supply in disputes over the prices that required them to sell parts at a loss and eventually had the buyer raise the price (McCracken and Glader 2007, McCracken 2006). Second, renegotiation can improve the quantity allocation efficiency when the buyer sources from multiple suppliers. The buyer can adjust the quantity allocation between suppliers in response to their cost outcomes, thereby improving system efficiency and enhancing the profits of all parties.

In practice, firms adopt different supply base and pricing strategies. Typically, Japanese manufacturers tend to use sole sourcing (or a small supply base) and commit to target prices with suppliers. In contrast to their Japanese peers, American manufacturers traditionally prefer to form a large supply base and engage suppliers in fierce competition, and they often renegotiate prices with suppliers (McMillan 1990). Thus, the sourcing decisions facing firms are not trivial, and it is important to identify and understand the underlying factors that drive different choices.

This paper addresses the following research question: How should a buyer design her sourcing strategy, including the supply base and the pricing mechanism, to leverage supplier competition and effort? We break this broad question into three subquestions. These are stated below accompanied by a brief summary of our research findings related to each of the subquestions:

(1) *How do the supply base design and pricing mechanism affect supplier competition and efforts*? We find that supplier symmetry in capacity and use of ex post negotiations foster supplier competition, whereas supplier asymmetry and use of ex ante commitments motivate supplier effort. Therefore, the buyer must carefully design the capacity investment and price commitment for each supplier, which determine the supplier (a)symmetry level and likelihood of renegotiations, to trade off the benefits of supplier competition and effort.

(2) *What is the relationship between the supply base and pricing mechanism designs*? We find that greater supplier asymmetry in capacity should be accompanied with higher price commitments that lead to less chance of renegotiation, whereas greater supplier symmetry should be combined with lower price commitments that are more likely to be renegotiated. Hence, the supply base design and pricing mechanism are strategic complements. This leads to the identification of three sourcing strategies: (i) *Sole sourcing*: The buyer invests in a single supplier and commits to a price so high that it will never be renegotiated, to maximize the benefit of supplier effort. (ii) *Symmetric dual sourcing*: The buyer invests equal capacities in both suppliers and commits to a price so low that it will always be renegotiated, to maximize the benefit of supplier competition. (iii) *Asymmetric dual sourcing*: The buyer invests positive but unequal capacities in the suppliers and commits to a price that may or may not be renegotiated depending on the supplier cost outcome, to balance the two benefits. Note that asymmetric dual sourcing can be optimal even though the suppliers are ex ante identical.

(3) *How does the choice of the sourcing strategy depend on the environment*? We find that sole sourcing is preferred when supplier effort is cheap or supplier cost uncertainty is low; symmetric dual sourcing is preferred when supplier effort is expensive or supplier cost uncertainty is high; and asymmetric dual sourcing, which emerges only when demand is uncertain, is located in between. In addition, we find that greater demand uncertainty may increase the preference for sole sourcing and meanwhile *reduce* the total investment of supplier capacity. This occurs because of the strategic role played by capacity investment in maintaining supplier competition.

The rest of this paper is organized as follows. We position our work against the literature in §2. Then we present the model in §3, followed by the analysis in §4. Section 5 establishes the results about the structure and choice of the optimal sourcing strategy. We consider some model extensions in §6 and summarize our conclusions in §7.

2. Literature Review

The supply chain management literature has considered supplier effort and studied incentive structures to induce desirable supplier behavior. Different incentive instruments have been examined in this literature, including the contract design, pricing mechanism, and the buyer's resource investment in the supplier. The papers on contract design usually assume that the supplier effort or the capability achieved from the effort is observable, thus considering contract terms tied to the effort (Roels et al. 2010) or to the realized capability (Kim et al. 2007, Corbett et al. 2005, Plambeck and Taylor 2006). In our model, neither a supplier's cost-reduction effort nor the realized cost is observable, which limits the buyer's instruments in contract design. Thus, instead of focusing on contract design, we adopt simple contracts independent of supplier effort and cost outcome but investigate the influence of the supply base design and the pricing mechanism. Some papers focus on the effect of the pricing mechanism on supplier effort, comparing ex ante and ex post decisions (see, e.g., Van Mieghem 1999, Bernstein and Kök 2009, Kim and Netessine 2013). Our work differs from these papers in that we consider supplier competition and reveal the relationship between the pricing mechanism and the supply base design. In addition, our pricing mechanism accommodates both ex ante and ex post decisions, instead of limiting to exclusive choices as in these papers. Other papers consider the buyer investing resources in the supplier and analyze the influence of such investment on the supplier's improvement effort (see, e.g., Iyer et al. 2005, Zhu et al. 2007). We consider the buyer's investment in two suppliers, which shapes supplier competition while affecting supplier effort.

Unlike the supply chain management literature, the auction literature has a focus on supplier competition but not supplier effort. Most papers in the auction literature assume an exogenous supply base. The papers that study supply base design have considered the trade-off between the value of supplier competition and other factors such as supplier qualification costs (Riordan 1996), supplier diversification (Wan and Beil 2009), inefficiency of purchasing from higher-cost suppliers (Klotz and Chatterjee 1995, Lewis and Yildirim 2002), and production diseconomy (Tunca and Wu 2009). Supply base design is also an important decision for a buyer facing supply risks. Papers in this stream have considered the fixed costs associated with each supplier (Agrawal and Nahmias 1997) and investment in supplier reliability improvement (Wang et al. 2010) along with supply reliability concerns, assuming nonstrategic suppliers. In our paper, the supply base design trades off the benefit from supplier competition against that from supplier effort. Our supply base design concerns the competition between concurrently existing suppliers, whereas Li and Debo (2009a, b) study whether to introduce future competition for the incumbent supplier.

A stream of papers in the procurement literature considers both supplier competition and effort. This literature can be divided into two groups. In one group, the suppliers acquire private information and compete (bid) *before* the winner exerts effort. Laffont and Tirole (1993) provide a comprehensive study of this type of model. In the other group, a supplier acquires private information after exerting effort. Because the uncertainty of supplier type is not resolved until after the effort is made, suppliers compete *after* they exert effort. In the first group, the incentive of supplier effort depends only on the contract design but not on supplier competition (Laffont and Tirole 1987), whereas in the second group, supplier competition affects a supplier's upfront effort. Our model falls into the second group, which is reviewed next.

When suppliers make an investment in anticipation of future competition, the investment decision depends on the procurement mechanism used by the buyer to allocate demand and negotiate contracts with competing suppliers. Depending on the timing of actions, there are again two types of model settings: sequential move and simultaneous move. In a sequential move game, the buyer announces (commits to) a procurement mechanism *before* suppliers make investment. In this case, the first-best solution can be implemented with an appropriate design of the procurement mechanism if no information asymmetry exists prior to supplier investment. The optimal mechanism, though not difficult to find, is typically complex or not practical. Some papers thus focus on the performance of simpler intuitive mechanisms (Cachon and Zhang 2007), standard auction formats (Li and Gupta 2007), or variations of standard formats (Bag 1997).

In a simultaneous move game, the procurement mechanism is announced *after* suppliers exert effort (the buyer's choice of the procurement mechanism is simultaneous with suppliers' effort decisions because supplier effort is unobservable by the buyer). This setting is appropriate if the parties cannot reach a formal agreement on a complex procurement mechanism, because of the high cost of writing court-enforcible complete contracts, long before the uncertainty about supplier efficiency is resolved. Our model is a simultaneous move game. Existing papers based on such a setting include Piccione and Tan (1996), Dasgupta (1990), and Li et al. (2006). All these papers assume that the supply base is exogenously given. We differ by considering supply base design as an endogenous decision. This decision influences supplier investment in cost reduction and shapes the follow-up procurement mechanism chosen by the buyer.

To summarize, the existing literature has studied either supply base design or the pricing mechanism, concerned with supplier competition or supplier effort. We contribute to the literature by considering *both* supplier competition and effort as driving forces in the *joint* design of the supply base and pricing mechanism.

3. Model

A downstream firm (the "buyer") sources an essential input to her product from external suppliers. Each unit of the product requires a unit of the input from the supplier(s) and generates revenue r when sold on the market. The demand of the product, X, is random with a probability distribution $G(\cdot)$ and a density $g(\cdot)$. Let μ_d and σ_d be the mean and standard deviation of the demand.

The buyer may use two upstream firms, supplier 1 and supplier 2, as her suppliers. The buyer invests in assets used by suppliers that enhance their delivery capability. To emphasize the impact of the buyer's investment on supply base performance, we strengthen the relationship by assuming that the buyer's investment fully determines a supplier's production capacity. Investing one unit of capacity costs the buyer k. Aside from the capacity and purchasing costs, all other costs of the buyer are normalized to zero. Define $S(K) \equiv \mathbb{E}[\min(X, K)]$ as the expected demand covered by supplier capacity K. Denote by $\mathbf{K} \equiv (K_1, K_2)$ the suppliers' capacity profile and $\bar{K} \equiv K_1 + K_2$ the total capacity of suppliers.

Each supplier can exert effort to reduce his production cost.[3] The effort is observable neither by the buyer nor by the other supplier. The disutility of supplier effort e is characterized by an increasing convex function $\varphi(e)$. We assume that $\varphi(e) = ae^2$ in the analysis, where a measures the challenge of cost reduction. The realization of a supplier's production cost is uncertain because of variations in the supplier's internal and external environments or uncertain outcome of effort; the realized cost γ_i of supplier i is a random cost c_i reduced by his effort e_i: $\gamma_i = c_i - e_i$.[4]

The random cost c_i follows a uniform distribution between $\underline{c}$ and $\bar{c}$; its cumulative probability is $F(c_i) = (c_i - \underline{c})/\Delta$ and density is $f(c_i) = 1/\Delta$, where $\Delta \equiv \bar{c} - \underline{c}$ measures the cost uncertainty. The random cost is realized *after* supplier effort is exerted and is called the supplier's *type*. The type is a supplier's private information, although its distribution $F(\cdot)$ is common knowledge. We focus on the idiosyncratic sources of cost uncertainty (such as the uncertainty related to the management, logistics, lower-tier suppliers, or improvement outcome) rather than the common sources because the former sources are not easily accessible and allow cost uncertainty to be reduced by supplier competition. Thus, we assume that the supplier types c_1 and c_2 are independent of each other. In our model, the suppliers are ex ante identical, facing the same effort disutility function $\varphi(e)$ and cost distribution $F(\cdot)$ for given effort. This allows us to focus on the endogenous impact of the buyer's sourcing strategy on supplier performance.

We assume that the buyer has strong bargaining power relative to the suppliers. This is often the case in the automotive industry, where automakers are typically larger firms that hold greater stakes in the supply chain than the parts suppliers. It is also the case in the electronics industry, where OEMs such as Apple are the leaders of the supply chains (Satariano and Burrows 2011). In a strong bargaining position, the buyer offers the suppliers contracts that the latter may accept or reject. If a supplier rejects the buyer's offers, he earns the reservation profit, which is normalized to be zero.

The sequence of events is organized in four stages: (1) commitment, (2) cost realization, (3) renegotiation, and (4) contract execution. In the commitment stage (1), the buyer invests capacity and commits a price to each supplier (a supplier is excluded from the supply base if he receives zero capacity investment). Then, in the cost realization stage (2), suppliers exert cost-reduction efforts e_i, leading to production costs $\gamma_i = c_i - e_i$, $i = 1, 2$, where c_i is drawn from the distribution $F(\cdot)$. This is followed by the renegotiation stage (3), in which the buyer offers suppliers new contracts, though each supplier has the right to retain his contract received earlier in the commitment stage. Finally, in the contract execution stage (4), the market demand is realized and the contracts are executed. As shown in this process, a supplier's contract is determined via stages (1) and (3), the commitment and renegotiation, which occur before and after the supplier exerts effort and realizes his cost, respectively. Below we explain these two stages (1) and (3) in more detail.

In the commitment stage, the buyer offers each supplier i a unit price p_i^0 along with capacity investment K_i, $i = 1, 2$. Let $p_1^0 \le p_2^0$ (otherwise swap the supplier labels) and $\mathbf{p}^0 \equiv (p_1^0, p_2^0)$. Based on the committed prices, the buyer will source all quantity up to K_1 from supplier 1, with only the demand beyond K_1 allocated to supplier 2; in other words, supplier 1 is granted the quantity priority. This allocation implies that for given cost realizations γ_i, supplier 1 expects profit $\pi_1^0(\gamma_1) \equiv (p_1^0 - \gamma_1)S(K_1)$ and supplier 2 expects $\pi_2^0(\gamma_2) \equiv (p_2^0 - \gamma_2)(S(\bar{K}) - S(K_1))$. Note two possible consequences of the commitments: (1) If a supplier's cost realization γ_i turns out higher than the committed price p_i^0, then his profit $\pi_i^0(\gamma_i)$ is negative. In this case, the supplier will quit unless a new contract is offered to generate positive profits and hence ensure voluntary participation (Stole 1994). (2) If γ_1 is greater than γ_2, then the quantity allocation with priority to supplier 1 is not efficient; in this case, the buyer could offer new contracts to the suppliers, with a different allocation rule, that result in better profits for all parties. The renegotiation stage provides the buyer with the opportunity to amend both situations.

In the renegotiation stage, the buyer offers new contracts to suppliers, with a supplier's right to keep the committed contract, to ensure voluntary supplier participation and enhance quantity allocation efficiency. Because the supplier costs are private information, renegotiation is implemented via an incentive compatible direct mechanism; it is without

[3] Although a buyer can also invest in resources, such as engineering support or training programs, to help improve a supplier's efficiency, in this paper we focus on the effort initiated by a supplier because the improvement pertains to the activities performed by the supplier and thus requires great commitment on the part of the supplier (Handfield et al. 2000).

[4] Such an additive form of cost reduction allows tractable analysis. See similar assumptions used by Kim et al. (2007) and Dasgupta (1990).

loss of generality to restrict to such mechanisms based on the revelation principle (Myerson 1981). In a direct mechanism, the buyer offers each supplier i a menu of contracts parameterized by the suppliers' cost profile $\boldsymbol{\gamma}$: $(p_i(\boldsymbol{\gamma}), w_i(\boldsymbol{\gamma}))$, where p_i is the price and w_i the probability for supplier i to be selected as the winner (receiving quantity priority). Suppliers report their costs after the contract menus are announced. Then given the reported cost profile $\hat{\boldsymbol{\gamma}} \equiv (\hat{\gamma}_1, \hat{\gamma}_2)$, each supplier i is awarded the contract $(p_i(\hat{\boldsymbol{\gamma}}), w_i(\hat{\boldsymbol{\gamma}}))$. The mechanism is incentive compatible if it is in the interest of a supplier to report his true cost.

4. Analysis

The analysis is conducted backward in two stages. In the second-stage analysis (§4.1), we characterize the equilibrium between the buyer's renegotiation mechanism (contract menus) and suppliers' efforts for given capacity and price commitments. Then, based on this equilibrium outcome, in the first-stage analysis (§4.2) we analyze the buyer's capacity investment and price commitment decisions. The consideration of price commitments p_i^0 is limited to those that will not surpass the highest possible supplier costs $\bar{c} - e_i$ in the outcome, $i = 1, 2$, without loss of generality.[5] Let $-i$ denote the other supplier as opposed to supplier i.

4.1. Second-Stage Analysis

Because a supplier's effort decision is unobservable when the buyer decides the renegotiation mechanism, both decisions occur simultaneously. In equilibrium, each supplier's effort is his best response to the other supplier's effort and the buyer's renegotiation mechanism, and the latter is the buyer's best response to the suppliers' effort profile. The analysis of the equilibrium is performed in two steps. In §4.1.1, we analyze the renegotiation mechanism as the buyer's best response to supplier effort profile $\mathbf{e}$. Then, in §4.1.2, we derive the equilibrium of supplier efforts based on the buyer's best-response renegotiation mechanism.

4.1.1. Best-Response Renegotiation Mechanism. Recall that the buyer offers a contract menu $(p_i(\boldsymbol{\gamma}), w_i(\boldsymbol{\gamma}))$ to each supplier $i = 1, 2$ in the renegotiation. The buyer designs the contract menus to maximize her profit, subject to three constraints: (1) Incentive compatibility: A supplier optimizes his expected profit by reporting his true cost. (2) Individual rationality: A supplier receives nonnegative profits from the contract offers (because a supplier has the right to reject the contracts and walk away). (3) Profit enhancement: A supplier receives at least the same expected profit from the contract offers as from the commitment (because a supplier has the right to reject the new offer and keep the committed contract). The first two constraints are standard in mechanism design. The third constraint is unique to our setting and exists because of the presence of commitments. The buyer may offer the same contract as in the commitment to some supplier types. For those types, we say that the contract is *not* renegotiated.

Define $J(\gamma, e, c) \equiv \gamma + (F(\gamma + e) - F(c))/f(\gamma + e)$ for some $c \in [\underline{c}, \bar{c}]$; call it the virtual cost of a supplier with effort e and realized cost γ, when the supplier type is drawn from the truncated uniform distribution on $[c, \bar{c}]$. The virtual cost is increasing in γ and can be interpreted as the true cost γ inflated by information rent (when viewed ex ante). We assume that the buyer's revenue is large enough to cover the capacity cost and the highest possible virtual cost of a supplier: $r > k + J(\bar{c}, 0, \underline{c})$. This assumption implies that it is always profitable for the buyer to source from a supplier to satisfy demand, even if the supplier has the lowest possible efficiency; therefore, no supplier cutoff needs to be considered.

Let $\pi_i(\gamma_i) = (p_i - \gamma_i) q_i(\gamma_i)$ be the expected profit of supplier i with actual cost γ_i from the renegotiation, where $q_i(\gamma_i) = \mathbb{E}_{\gamma_{-i}}[w_i(\boldsymbol{\gamma}) S(K_i) + w_{-i}(\boldsymbol{\gamma})(S(\bar{K}) - S(K_{-i}))]$ is the expected quantity provided by supplier i based on the quantity allocation rule specified by $w_i(\boldsymbol{\gamma})$, $i = 1, 2$. (Recall that $\pi_i^0(\gamma_i)$ is the expected profit of supplier i based on the ex ante commitments.) Lemma 1 presents the design of the renegotiation mechanism. All proofs are given in the appendix.

LEMMA 1. *Given capacity profile* $\mathbf{K}$ *and price commitments* $\mathbf{p}^0$, *the renegotiation mechanism in the best response to supplier efforts* $\mathbf{e}$ *is characterized in Table* 1, *where* $\hat{c} \in [\underline{c}, \bar{c}]$ *is uniquely defined by* $\pi_1^0(\hat{c} - e_1) = \pi_1(\hat{c} - e_1)$.

In the renegotiation, supplier 1 receives the same contract as in the commitment if his type is lower than a threshold $\hat{c}$ $(\gamma_1 \le \hat{c} - e_1)$; otherwise, he receives a new contract. Supplier 2 always receives a new contract. Supplier 2 always benefits from the renegotiation because he is committed to a secondary position in quantity allocation—he can ask for a higher price (by imitating a higher type) without risking his quantity and may even receive more quantity when the buyer changes the allocation rule. Supplier 1, however, must be more careful because he may lose the quantity priority from commitment by requesting a price increase. Thus, only when his cost is high $(\gamma_1 > \hat{c} - e_1)$, and hence the margin from the price commitment is low (it can be negative), will he renegotiate for a higher margin at the risk of losing his quantity priority. Otherwise (when $\gamma_1 \le \hat{c} - e_1$), it is more profitable for him to stay with the committed contract.

When $\gamma_1 > \hat{c} - e_1$, both suppliers renegotiate, competing for quantity priority. Because of information

[5] If p_i^0 leads to an effort outcome e_i such that $p_i^0 > \bar{c} - e_i$, the buyer could always improve her profit by reducing p_i^0 without affecting e_i.

Table 1 **Best-Response Renegotiation Mechanism**

	Supplier costs		
		$\gamma_1 > \hat{c} - e_1$	
Contract offers	$\gamma_1 \le \hat{c} - e_1$	$J(\gamma_1, e_1, \hat{c}) \le J(\gamma_2, e_2, \underline{c})$	$J(\gamma_1, e_1, \hat{c}) > J(\gamma_2, e_2, \underline{c})$
$w_1(\boldsymbol{\gamma}), w_2(\boldsymbol{\gamma})$	1, 0	1, 0	0, 1
$p_1(\boldsymbol{\gamma})$	p_1^0	$\gamma_1 + \frac{1}{q_1(\gamma_1)} \int_{\gamma_1}^{\hat{c}-e_1} q_1(\rho)\mathrm{d}\rho$	
$p_2(\boldsymbol{\gamma})$	$\gamma_2 + \frac{1}{q_2(\gamma_2)} \int_{\gamma_2}^{\bar{c}-e_2} q_2(\rho)\mathrm{d}\rho$		

asymmetry, the quantity allocation is determined by the comparison of suppliers' virtual costs (instead of true costs), $J(\gamma_1, e_1, \hat{c})$ and $J(\gamma_2, e_2, \underline{c})$, to take into account information rent. Note that the virtual cost of supplier 1, $J(\gamma_1, e_1, \hat{c})$, uses the truncated type distribution on $[\hat{c}, \bar{c}]$ but not the original distribution on $[\underline{c}, \bar{c}]$ as for supplier 2. The reason is that the buyer needs to screen only those types above $\hat{c}$ for supplier 1 in the contract menu design because all the types below $\hat{c}$ will be offered the same contract as in the commitment. Based on the quantity allocation rule, given $\hat{c}$ and $\mathbf{K}$ the expected quantity of a supplier i can be expressed as a function of $\mathbf{e} = (e_1, e_2)$; denote it by $\bar{q}_i(\mathbf{e}, \hat{c}, \mathbf{K})$ for later use. Note from Table 1 that p_1^0 does not affect the new contract offered to supplier 1 (though it affects through $\hat{c}$ whether a new contract will be offered). In addition, the contract menu is independent of p_2^0, which will always be renegotiated. This means p_2^0 (between p_1^0 and $\bar{c} - e_2$) has no impact on the buyer's profit.

The threshold type $\hat{c}$ is determined so that supplier 1 with type $\hat{c}$ is indifferent between the commitment and renegotiation, $\pi_1^0(\hat{c} - e_1) = \pi_1(\hat{c} - e_1)$; this leads to the price commitment with supplier 1 for given $\hat{c}$: $p_1^0(\hat{c}) = \pi_1(\hat{c} - e_1)/S(K_1) + \hat{c} - e_1$. We assume that for now there exists a one-to-one relationship between p_1^0 and $\hat{c}$, and p_1^0 is increasing in $\hat{c}$; this can be verified later based on the equilibrium outcome of efforts (see Lemma 7 in the appendix). In the analysis to follow, we will work with the decision variable $\hat{c}$ instead of p_1^0 for convenience. With $p_1^0(\hat{c})$ increasing, the higher the committed price, the less likely the renegotiation of supplier 1. Particularly, if $\hat{c} = \underline{c}$, then the suppliers' contracts will always be renegotiated, the price commitments having no effect at all. If $\hat{c} = \bar{c}$, then supplier 1's contract will never be renegotiated. In this case, the buyer faces only supplier 2 in renegotiation, which always results in the price $p_2(\boldsymbol{\gamma}) = \bar{c} - e_2$. This is equivalent to the buyer committing this price to supplier 2 with no renegotiation. Thus, with $\hat{c} = \bar{c}$, the contracts will be fully determined by price commitments, renegotiation having no effect at all. If $\underline{c} < \hat{c} < \bar{c}$, then supplier 1 may or may not renegotiate, depending on his cost realization, whereas supplier 2 will always renegotiate. Hence, based on the value of $\hat{c}$, our model is flexible enough to endogenously determine the timing of the price formation, before or after the supplier cost realization.

The contract menus in Table 1 are designed based on the anticipation of supplier effort e_i, or equivalently the cost distribution on the range $[\underline{c} - e_i, \bar{c} - e_i]$, $i = 1, 2$. To analyze a supplier's effort decision, we must examine the supplier's profit obtained from renegotiation for any given effort, which may result in costs outside the range. This entails analyzing the supplier response to the contract menu without restricting his cost distribution. We find that a supplier will report the cost $\underline{c} - e_i$ if his actual cost is lower than this level, quit if his cost is higher than $\bar{c} - e_i$, and report his true cost if it is in between (see Lemma 6 in the appendix). Given such responses, for a supplier with any cost realization γ_i, his expected profit from renegotiation (before subtracting the effort disutility) is well defined; denote it by $u_i(\gamma_i)$. Using $u_i(\gamma_i)$, we are ready to analyze a supplier's effort choice in §4.1.2.

4.1.2. Equilibrium Efforts. In this subsection, we analyze the equilibrium of supplier efforts given $\mathbf{K}$ and $\hat{c}$ (recall that p_2^0 has no impact and there exists a one-to-one relationship between $\hat{c}$ and p_1^0). Taking the contract menus (renegotiation mechanism) designed for supplier efforts $\mathbf{e} = (e_1, e_2)$, supplier i's expected profit as a function of his own effort $\hat{e}_i$ is $\hat{\Pi}_i(\hat{e}_i) \equiv \mathbb{E}_{c_i}[u_i(c_i - \hat{e}_i)] - \varphi(\hat{e}_i)$, if the other supplier chooses the effort e_{-i}. The supplier efforts e_1 and e_2 constitute an equilibrium if $\hat{\Pi}_i(\hat{e}_i)$ is maximized at $\hat{e}_i = e_i$ for both $i = 1, 2$.

Given that the renegotiation mechanism and supplier efforts are determined simultaneously, a pure strategy equilibrium of such decisions may not exist.[6] To ensure the existence of a pure strategy equilibrium,

[6] To see this, let the supplier type be a constant c (i.e., $\Delta = 0$). If a supplier exerts effort e in a pure strategy equilibrium, the buyer will always propose a price $p = c - e$, which leaves the supplier a total

we further assume that the supplier cost uncertainty Δ or marginal disutility of supplier effort a is sufficiently high: $a\Delta \geq \mu_d$. Under this assumption, the suppliers' equilibrium efforts are characterized in Lemma 2.

Lemma 2. *Given* $\mathbf{K}$ *and* $\hat{c}$, *the equilibrium of supplier efforts* $\mathbf{e} = (e_1, e_2)$ *is uniquely defined by* $ae_i = \bar{q}_i(\mathbf{e}, \hat{c}, \mathbf{K})$, $i = 1, 2$, *and satisfies* $e_1 + e_2 = S(\bar{K})/a$. *In equilibrium,* e_i *is increasing in* K_i *and decreasing in* K_{-i}, *and* e_1 *is increasing while* e_2 *decreasing in* $\hat{c}$.

Lemma 2 is intuitive. It shows that a supplier's cost-reduction effort is tied to the expected quantity provided by the supplier ($\bar{q}_i$); the greater the expected quantity, the higher the effort. Because the expected quantity is affected by the buyer's decisions of capacity investment and price commitment, Lemma 2 further reveals the impact of the two decisions on supplier efforts: A supplier will exert greater effort when he is equipped with a larger capacity or the opponent is equipped with a smaller capacity. In addition, committing a higher price (which leads to a greater $\hat{c}$) with supplier 1 increases supplier 1's effort, although it reduces supplier 2's.

4.2. First-Stage Analysis

Given the equilibrium outcome of supplier efforts and the renegotiation mechanism, we are ready to analyze the buyer's decisions on $\mathbf{K}$ and $\hat{c}$. Lemma 3 presents two important intermediate results.

Lemma 3. *The optimal solution has* $K_1 \geq K_2$ *and* $\hat{c} - e_1 = \underline{c} - e_2$.

Recall we assume that $p_1^0 \leq p_2^0$. According to Lemma 3, the supplier who is offered a lower price (thus granted quantity priority) in the commitment should also receive a larger capacity investment ($K_1 \geq K_2$).

In addition, Lemma 3 shows that the price commitment should be designed such that the two suppliers have the same lower bound costs, $\hat{c} - e_1 = \underline{c} - e_2$, when they compete in the renegotiation. Under such a condition, the rank of suppliers based on their virtual costs is consistent with the rank based on their true costs; i.e., $J(c_1, e_1, \hat{c}) \leq J(c_2, e_2, \underline{c})$ if and only if $c_1 - e_1 \leq c_2 - e_2$, leading to an efficient quantity allocation. Intuitively speaking, this condition makes the two suppliers comparable in costs when they compete; a price commitment that is too high or too low will cause disparity between the suppliers, weakening supplier competition and distorting the quantity allocation. Because $\hat{c} \geq \underline{c}$, this result suggests $e_1 \geq e_2$; i.e., supplier 1 (the one committed with a lower price and a larger capacity) will exert a greater effort, generating lower expected costs, than will supplier 2.

Hereafter, we restrict to $K_1 \geq K_2$. Define

$$A(\mathbf{K}) \equiv 2S(K_1) - S(\bar{K}) \quad \text{and} \qquad B(\mathbf{K}) \equiv S(K_1) + S(K_2) - S(\bar{K}), \tag{1}$$

where $A(\mathbf{K})$ is the expected quantity difference between supplier 1 as the winner, $S(K_1)$, and supplier 2 as the loser, $S(\bar{K}) - S(K_1)$; and $B(\mathbf{K})$ is the expected quantity difference for supplier i between when he is the winner, $S(K_i)$, and when he is the loser, $S(\bar{K}) - S(K_{-i})$. It is easy to show that for given total capacity $\bar{K}$, $A(\mathbf{K})$ increases and $B(\mathbf{K})$ decreases in the capacity difference $K_1 - K_2$ between the two suppliers.

Recall from Lemma 2 that the equilibrium of supplier efforts $\mathbf{e} = (e_1, e_2)$ depends on both $\mathbf{K}$ and $\hat{c}$. Now with relationship $\hat{c} = \underline{c} + e_1 - e_2$ from Lemma 3, the effort equilibrium can be written as a function of $\mathbf{K}$ only. This in turn defines $\hat{c}$ as a function of $\mathbf{K}$.

Lemma 4. *Given a supplier capacity profile* $\mathbf{K}$, *the supplier efforts are specified by*

$$e_1(\mathbf{K}) = \frac{S(\bar{K})}{2a} + \Delta\eta(\mathbf{K}) \quad \textit{and} \qquad e_2(\mathbf{K}) = \frac{S(\bar{K})}{2a} - \Delta\eta(\mathbf{K}), \tag{2}$$

and the optimal $\hat{c}$ *is* $\hat{c}(\mathbf{K}) \equiv \underline{c} + 2\Delta\eta(\mathbf{K})$, *where* $\eta(\mathbf{K}) \in [0, 1/2]$ *is uniquely defined by the higher root of*

$$A(\mathbf{K}) - (1 - 2\eta)^2 B(\mathbf{K}) = 2a\Delta\eta \tag{3}$$

and is increasing in $K_1 - K_2$ *for given* $\bar{K}$.

Following Lemma 4, $\hat{c}(\mathbf{K})$ is increasing in $K_1 - K_2$ (for given $\bar{K}$). Therefore, when suppliers become more asymmetric in their capacities ($K_1 - K_2$ larger), the price commitment with supplier 1 should increase at the same time to generate a lower probability of renegotiation with supplier 1 ($\hat{c}$ higher). Larger $K_1 - K_2$ and/or higher $\hat{c}$ lead to greater (lower) effort of the larger (smaller) supplier, reducing the competition between suppliers. This reveals a *complementary* relationship between the designs of supply base and pricing mechanism: They must be coordinated to drive supplier effort and competition in the same direction.

With both $\hat{c}$ and $\mathbf{e}$ defined as functions of $\mathbf{K}$, the corresponding price commitment p_1^0 is also defined (again, p_2^0 does not matter because it will always be renegotiated). We are now ready to analyze the

profit $-\varphi(e)$. Expecting the buyer's strategy, the supplier will not exert any effort, resulting in $e = 0$. Then, the best-response strategy for the buyer is to offer a price $p = c$. However, expecting such a price, the supplier will then exert positive effort e to maximize his total profit $e - \varphi(e)$. Thus, a pure strategy equilibrium does not exist under $\Delta = 0$.

buyer's profit based on $\mathbf{K}$, $\Pi(\mathbf{K})$. After transformation, $\Pi(\mathbf{K})$ can be written as

$$\Pi(\mathbf{K}) = \underbrace{\left(r - \bar{c} + \frac{S(\bar{K})}{2a}\right)S(\bar{K}) - k\bar{K}}_{\text{(1) profit if suppliers were combined}} + \underbrace{\frac{\Delta}{3}(1-2\eta(\mathbf{K}))^2(1+\eta(\mathbf{K}))B(\mathbf{K})}_{\text{(2) benefit of supplier symmetry}} + \underbrace{\Delta\eta(\mathbf{K})A(\mathbf{K})}_{\text{(3) benefit of supplier asymmetry}}. \quad (4)$$

The buyer's total profit can be decomposed in three terms. The first term depends only on the total capacity but not on capacity distribution between suppliers. This part can be regarded as the profit that the buyer would receive if the two suppliers were combined as one, keeping the same total capacity $\bar{K}$ and (average) cost-reduction effort $S(\bar{K})/(2a)$. With a single supplier, the buyer would pay a price according to the least efficient type $\bar{c}$ because of information asymmetry. The second term increases with supply symmetry in capacity (smaller $K_1 - K_2$ for given $\bar{K}$). It characterizes the *benefit of supplier competition*: Greater supplier symmetry (resulting in greater B and lower η) intensifies supplier competition, reducing information rent as well as mitigating supplier cost uncertainty. The third term increases with supplier asymmetry in capacity (larger $K_1 - K_2$ for given $\bar{K}$). It characterizes *the benefit of supplier effort*: Greater supplier asymmetry (resulting in greater A and η) makes the larger supplier (supplier 1) increase his effort and the smaller supplier (supplier 2) decrease his effort by the same amount. Such a change benefits the buyer because the effort of supplier 1, who provides a larger quantity in expectation, is more important than supplier 2's. The second term and third term may not always exist: If the buyer invests in equal capacities for the suppliers, $K_1 = K_2$, then $\eta(\mathbf{K}) = 0$ and there is no benefit of supplier asymmetry. If the buyer invests in only one supplier, $K_2 = 0$, then $B(\mathbf{K}) = 0$ and the benefit of supplier symmetry goes away.

5. Optimal Sourcing Strategies

The buyer designs the capacity profile $\mathbf{K}$ to maximize her profit characterized in Equation (4). When $K_2 = 0$ (supplier 1 is the sole supplier), the renegotiation always leads to a price equal to the upper bound cost $\bar{c} - e_1$, and the same profit can be achieved with the buyer committing such a price up front, which will never be renegotiated; i.e., $\hat{c} = \bar{c}$. When $K_1 = K_2 > 0$, $\hat{c}(\mathbf{K})$ can be greater than or equal to $\underline{c}$ (with $\eta(\mathbf{K})$ greater than or equal to 0), depending on K. The case with $K_1 = K_2$ and $\hat{c}(\mathbf{K}) > \underline{c}$ cannot be optimal because it leads to unequal margins of capacity investment in the two suppliers. Given these considerations, the optimal strategy can be classified in three types: S*ole sourcing* (S), in which the buyer invests capacity in a single supplier ($K_1 > 0$ and $K_2 = 0$) and fully commits the price without renegotiation ($\hat{c} = \bar{c}$); *symmetric dual sourcing* (sD), in which the buyer invests positive and equal capacities in the two suppliers ($K_1 = K_2 > 0$) and always renegotiates the contracts ($\hat{c} = \underline{c}$); and *asymmetric dual sourcing* (aD), in which the buyer invests positive but unequal capacities in the two suppliers ($K_1 > K_2 > 0$) and may or may not renegotiate with supplier 1 ($\underline{c} < \hat{c} < \bar{c}$) depending on the supplier's cost realization (while always renegotiating with supplier 2). Table 2 summarizes the three sourcing structures.

Table 2 Three Structures of the Sourcing Strategy

Sourcing structure	Capacity investment	Price commitment	Contract formation
S	$K_1 > 0, K_2 = 0$	$\hat{c} = \bar{c}$	Ex ante commitment only
aD	$K_1 > K_2 > 0$	$\hat{c} \in (\underline{c}, \bar{c})$	Ex ante commitment and ex post negotiation
sD	$K_1 = K_2 > 0$	$\hat{c} = \underline{c}$	Ex post negotiation only

Proposition 1 reveals the condition for each structure to emerge when demand uncertainty is small. It assumes $g(\cdot)/(1 - G(\cdot))^2$ increasing, which is satisfied by all distributions with an increasing failure rate.

Proposition 1. *Assume that* $g(\cdot)/(1 - G(\cdot))^2$ *is increasing. When* $\sigma_d \to 0$, *there exist* k_D *and* k_S, *both increasing in* a *and* Δ, *and* $k_D < k_S$ *if* r *is sufficiently large, such that*

(i) *for* $k \le k_D$ *and* $a\Delta \ge 2\mu_d$, *sD is optimal with* $K_1 = K_2 \to \mu_d$;

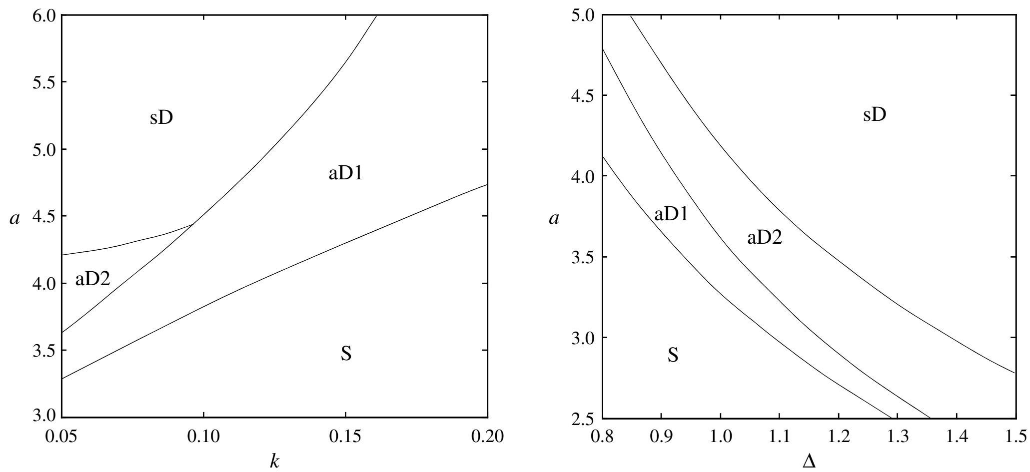
(ii) *for* $k \le k_D$ *and* $a\Delta < 2\mu_d$, *aD is optimal with* $K_1 > K_2 > 0$ *and* $K_1 \to \mu_d$, $K_2 \to \mu_d$;

(iii) *for* $k \in (k_D, \max(k_D, k_S))$, *aD is optimal with* $K_1 > K_2 > 0$ *and* $K_1 \to \mu_d$, $K_2 \to 0$;

(iv) *for* $k \ge \max(k_D, k_S)$, *S is optimal with* $K_1 \to \mu_d$ *and* $K_2 = 0$.

Based on Proposition 1, if demand is certain, then K_i reduces to either 0 or μ_d, $i = 1, 2$; that is, the buyer should invest capacity equal to μ_d in a single supplier or in each supplier. If demand is uncertain, however, the buyer may invest positive but unequal capacities in *both* suppliers, adopting the aD structure. Under aD, the two suppliers may be equipped with similar or disparate capacities, reducing to symmetric investment or sole investment when demand uncertainty goes to zero, as shown in (ii) and (iii) of Proposition 1; we call the former "aD2" and the latter "aD1" to differentiate these two aD structures. Hence, although the two suppliers are ex ante identical, the

Figure 1 The Optimal Sourcing Structure



Notes. $r = 5$; demand follows a uniform distribution on [1.5, 2.5]. For the left plot, $\underline{c} = 2$ and $\bar{c} = 3$. For the right plot, $k = 0.05$ and $(\underline{c} + \bar{c})/2 = 2.5$.

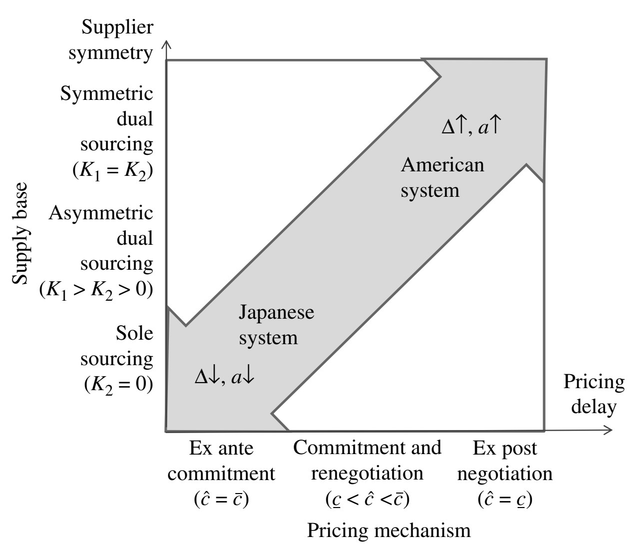
optimal interior solution is not necessarily symmetric. With aD, the buyer relies on the larger supplier for cost reduction and uses the small supplier to maintain some competition, thereby balancing the benefits of supplier effort and supplier competition. This balance can only be reached under demand uncertainty, when moderate capacity investment is possible with the demand fulfillment concern. The moderate capacity is high enough to foster intense supplier competition when distributed between suppliers yet not sufficient to deliver a supplier competition benefit that would dominate that of supplier effort.

The choice of the sourcing structure depends on the capacity cost k, effort disutility a, and supplier cost uncertainty Δ: The structure sD is optimal when k is small or a and Δ are large, S is preferred in the opposite situations, and aD is chosen for the circumstances in between. To explain, a small k allows the buyer to invest large capacity in both suppliers to foster supplier competition, and a large Δ implies substantial information rent and supplier cost uncertainty faced by the buyer, both enhancing the value of supplier competition and thus the benefit of supplier symmetry. On the other hand, a large a makes it difficult to induce supplier effort, reducing the benefit of supplier asymmetry. Therefore, sD is preferred with a small k or large a or Δ. Under the opposite conditions, the benefit of supplier asymmetry dominates, making S optimal. Indeed, when a or Δ is sufficiently small, S can be optimal even if $k = 0$ (because k_D and k_S can be negative); in other words, even if capacity is free, the buyer may invest in only one supplier to motivate supplier effort.

Though Proposition 1 is proved for small demand uncertainty σ_d, our numerical study shows that its qualitative insights hold in general situations where σ_d can be large. As an example, Figure 1 demonstrates the sourcing structure with varying k and a (the left plot) and varying Δ and a (the right plot) for significant demand uncertainty.

Based on the results above, Figure 2 illustrates the buyer's sourcing decisions in a two-dimensional space. The horizonal dimension is the pricing mechanism, determining the level of pricing delays. The vertical dimension is supplier base design, determining the level of supplier symmetry in capacity. Our results suggest that the buyer's optimal sourcing strategy should be located on the diagonal line, with more pricing delays combined with a more symmetric supply base. The position of the strategy depends on the supplier cost uncertainty Δ and disutility of supplier effort a. When Δ and a are low, the strategy leans toward the lower-left corner, combining ex ante commitments with sole sourcing. When Δ and a are high, the strategy leans toward the upper-right corner, combining ex post negotiations with symmetric dual

Figure 2 The Buyer's Sourcing Strategy



sourcing. In the intermediate situations, the strategy integrates ex ante commitments and ex post negotiations, adopting asymmetric dual sourcing.

Our results are consistent with empirical observations. Japanese automakers typically form close relationships with their suppliers by sharing knowledge and providing engineering support (Dyer 2000). A close supplier relationship reduces supplier cost uncertainty Δ because it allows the buyer to gain information about a supplier's cost structure and keep a supplier's performance variation under control. It also lowers the cost of supplier improvement a because of the support provided by the buyer. Along with establishing close relationships with suppliers, Japanese automakers often source from a single supplier (or a small number of suppliers) and commit target prices. Compared to their Japanese peers, U.S. automakers do not work as closely with their suppliers, causing higher uncertainty about supplier costs and more difficulty in supplier cost reduction. Meanwhile, they are more inclined to engage suppliers in competition by forming a large supply base and often (re)negotiate prices based on suppliers' achieved costs (McMillan 1990, Liker and Choi 2004).

With the understanding of the sourcing structures, we further investigate the impact of demand uncertainty on the structure choice.

Proposition 2. *For both normal and uniform demand distributions, when $\sigma_d \to 0$, with a or Δ sufficiently small and $a\Delta \geq 2\mu_d$ and r sufficiently low, increasing σ_d leads the sourcing structure to shift from sD to S along with total capacity reduction.*

When the revenue r is low with $a\Delta \geq 2\mu_d$, the sourcing structure is limited to the choice between sD and S, with the former requiring greater total capacity investment than does the latter (see Proposition 1). Then for relatively low a and Δ, Proposition 2 indicates that S becomes more favorable to sD as demand uncertainty increases (but remaining small). This is somewhat counterintuitive because one may think that a larger supply base, as a usual measure to counter demand uncertainty, would be more preferable for the buyer facing greater demand uncertainty. The intuition for this result comes from the negative effect that demand uncertainty has on supplier competition: Recall that when the two suppliers compete, the higher-cost supplier receives the demand flow over the lower-cost supplier's capacity. When the demand uncertainty σ_d increases, the expectation of such demand overflow increases, too. This results in a higher expected quantity for the higher-cost supplier, reducing the benefit of supplier competition. Expecting this, the buyer is less willing to invest in redundant capacity to maintain supplier competition, shifting away from sD toward S, when the market demand is more uncertain. The redundant capacity in dual sourcing to stimulate supplier competition may be called *strategic capacity*, and the capacity used to meet uncertain demand may be called *operational capacity*. Our result suggests that when investing in supply base capacity, the buyer should be concerned not only with operational capacity but also with strategic capacity. Although greater demand uncertainty typically calls for a greater buffer of operational capacity (when the service level is not too low), it may reduce the strategic capacity, resulting in *reduction* of the total capacity.

When the revenue r is high, the condition of Proposition 2 is not satisfied, and the result may differ. In this case, the buyer is more concerned about demand fulfillment. This increases the advantage of sD because it has more capacity than S. This advantage is further enhanced with a large supplier cost uncertainty Δ or supplier effort disutility a because the former improves the value of supplier competition, increasing the (return of) capacity investment in sD, and the latter dampens a supplier's incentive to exert effort, reducing the (return of) capacity investment in S. In our numerical study, we find that increasing the demand uncertainty σ_d up to a certain level increases the preference for sD over that for S, though the direction may change if σ_d increases further.

6. Extensions

In this section, we consider two extensions to verify the robustness of our insights. In §6.1, we allow the buyer to commit to a minimum order quantity. In §6.2, we extend the model to a multiperiod setting in which the buyer repeatedly sources from the suppliers.

6.1. Quantity Commitment

We have considered price commitments as the buyer's instrument to induce supplier effort. In this extension, we investigate the additional value of committing a minimum order quantity. Let the quantity commitment with supplier i be $Q_i \leq K_i$; that is, supplier i will always provide at least quantity Q_i, irrespective of the demand and cost realizations. The demand beyond the total committed quantity is allocated between the two suppliers in the same way as in the main model via a two-stage process: The supplier committed with a lower price initially receives the priority, but the priority may be overturned in the renegotiation. We assume that the cost reduction reached by a supplier cannot exceed $\underline{c}$ (i.e., the effort cost $\varphi(e)$ is infinitely large for $e > \underline{c}$); this assumption guarantees a supplier's final production cost to be positive and thus his total cost always increasing in the quantity.

Because a higher quantity commitment to a supplier increases the expected quantity provided by the supplier, it is not surprising that it motivates a greater supplier effort. This benefit, however, must be weighed against its cost caused by quantity inflexibility. Indeed, Lemma 5 shows that a quantity commitment may not overall benefit the buyer.

Lemma 5. (i) *The optimal* Q_2 *is zero.*
(ii) *When* $K_2 = Q_2 = 0$, *the optimal* Q_1 *is zero.*

Lemma 5(i) shows that the optimal quantity commitment to supplier 2 (the supplier exerting smaller effort) is always zero. Intuitively, this occurs because the purpose of quantity commitment is to induce supplier effort. Because supplier 1's effort is more valuable to the buyer than is supplier 2's, it is better for the buyer to concentrate the committed quantity with supplier 1 than to distribute it between the two suppliers. Lemma 5(ii) shows that the optimal quantity commitment is zero under sole sourcing. To explain, recall that a quantity commitment helps to motivate supplier effort by increasing the expected quantity for a supplier. Such quantity increase, however, comes from the obligation of the buyer to purchase the quantity even if it is not demanded by the market; it thus incurs costs without generating revenue for the buyer. Therefore, although a quantity commitment reduces the unit price with its positive effect on supplier cost-reduction effort, it leads to wasteful purchasing and hence higher total costs. This result is consistent with the one from Cachon and Lariviere (2001) that firm commitments are not useful for aligning incentives.

For small demand uncertainty, Proposition 3 strengthens Lemma 5 and shows that the optimal quantity commitment is zero for both suppliers even under dual sourcing ($K_2 > 0$). We observe in numerical experiments that the result holds in more general situations with significant demand uncertainty. Therefore, the buyer will not commit to a quantity with either supplier—although such a commitment may induce greater supplier effort, its inflexibility causes more total cost for the buyer. It is thus sufficient for the buyer to commit only to the capacity and price to manage supplier effort and competition.

Proposition 3. *When* $\sigma_d \to 0$, *the optimal strategy has* $Q_1 = Q_2 = 0$.

6.2. Multiperiod Sourcing

In our main model, we have assumed a one-period setting in which a supplier has no need to continue exerting cost-reduction effort after the contract is awarded. In this extension, we consider a multiperiod setting in which the buyer repeatedly sources from the supply base, and hence suppliers may exert effort in multiple periods to reduce their costs. Let the total number of periods be T and the time discount factor be $\alpha \in [0, 1]$. At the beginning of the horizon, the buyer invests in supplier capacity $\mathbf{K} = (K_1, K_2)$ and commits with each supplier i a price $p^0_{i,t}$ for each period $t = 1, 2, \ldots, T$. In each period, the players move as follows: First the suppliers exert efforts, which lead to their production costs based on the cumulative efforts up to date. Then the buyer offers each supplier a menu of contracts for renegotiation. Finally, the demand is realized and the selected contracts are executed.

For supplier i, denote by $e_{i,t}$ his effort in period t, and $\bar{e}_{i,t} \equiv \sum_{l=1}^{t} e_{i,l}$ the cumulative effort up to period t. His incremental cost of effort in period t is $\varphi(\bar{e}_{i,t}) - \varphi(\bar{e}_{i,t-1}) = (a/2)(\bar{e}^2_{i,t} - \bar{e}^2_{i,t-1})$. The realized production cost of supplier i in period t is $\gamma_{i,t} = c_{i,t} - \bar{e}_{i,t}$, where $c_{i,t}$ represents the random cost shock in period t. We assume that the cost shocks are independent and identical across periods. The assumption of independence across periods is reasonable when the duration of a period is long (see, e.g., Lewis and Yildirim 2002). Under this assumption, a supplier's responses in previous renegotiations do not affect the future renegotiation design; thereby the revelation principle continues to hold to allow tractable analysis. As in the single-period model, we further assume that the cost shocks are independent and identical between the two suppliers. Let $c_{i,t} \in [\underline{c}, \bar{c}]$ be drawn from an i.i.d. uniform distribution $F(\cdot)$, for $i = 1, 2$ and $t = 1, 2, \ldots, T$. Finally, let the demand in each period be drawn from an i.i.d. distribution $G(\cdot)$.

For a given capacity profile $\mathbf{K}$, we analyze the buyer's price commitments and the suppliers' effort paths $\mathscr{E}_i \equiv (e_{i,1}, e_{i,2}, \ldots, e_{i,T})$, $i = 1, 2$. Intuitively, a supplier benefits more from cost reduction that occurs earlier than later because the former allows him to enjoy lower costs for longer periods. Indeed, for a sufficiently large discount factor α, Proposition 4 shows that the suppliers exert positive efforts only in the first period, resulting in a constant average cost for each supplier throughout the horizon, and the buyer commits a constant price to each supplier. In other words, when the future matters a lot, the suppliers will make substantial effort to achieve cost reduction at the beginning, expecting the benefits to come over the entire horizon, and then compete repeatedly based on their cost realizations in each period. And the buyer will structure the price commitments to generate a stable profit flow for all parties.[7] This echoes a result in Bernstein and Kök (2009) that suppliers invest in cost-reduction only in the first period under the cost-contingent pricing mechanism,

[7] If the time discount factor is small, then suppliers are more myopic (and conservative) in cost reduction, and the buyer may use price commitments to induce continual effort of suppliers.

when demand is relatively flat over the product life cycle.

Proposition 4. *Given a capacity profile* $\mathbf{K}$ *and sufficiently large* α, (i) $\mathscr{E}_{1,T} = (e_1, 0, \ldots, 0)$ *and* $\mathscr{E}_{2,T} = (e_2, 0, \ldots, 0)$ *constitute an equilibrium of supplier efforts, where* $e_1 = ((1-\alpha^T)/(1-\alpha))S(\bar{K})/(2a) + \Delta\hat{\eta}(\mathbf{K})$ *and* $e_2 = ((1-\alpha^T)/(1-\alpha))S(\bar{K})/(2a) - \Delta\hat{\eta}(\mathbf{K})$, *with* $\hat{\eta}(\mathbf{K}) \geq 0$ *uniquely defined by the higher root of*

$$2a\Delta\hat{\eta} = \frac{1-\alpha^T}{1-\alpha}(A(\mathbf{K}) - (1-2\hat{\eta})^2 B(\mathbf{K}));$$

(ii) *the price commitments are equal across periods and are designed so that in each period* t, *supplier* 2 *will always renegotiate, and supplier* 1 *will renegotiate if and only if* $c_{1,t} \geq \underline{c} + 2\Delta\hat{\eta}(\mathbf{K})$.

With the above structure, the multiperiod sourcing problem can be essentially reduced to a single-period problem as considered in our main model (for α sufficiently large). All structural results about the sourcing strategy (as shown in Table 2 and Proposition 1) remain. Compared to the single-period setting, the presence of the future enhances the value of supplier effort for the buyer and increases suppliers' incentive to exert effort because the cost reduction achieved from the effort endures for the future periods. In the result, the buyer commits to a price that translates to a lower renegotiation probability, and favors more sole sourcing, as α or the number of periods increases.

7. Conclusion

A buying firm relying on suppliers for critical production activities has two levers to reduce supply-related costs: fostering supplier competition and motivating suppliers to invest in cost reduction. We study the buyer's sourcing strategy along two dimensions: the supply base design and pricing mechanism, that control these two levers. Our model of the sourcing strategy is novel and general, without restricting to dichotomous choices: The supply base design generalizes sole sourcing and dual sourcing with endogenous supplier capacity decisions, and the pricing mechanism integrates ex ante commitments and ex post negotiations with information asymmetry on supplier costs. This allows us to interpret different choices with one single framework and reveal structures that would not be possible under divided views. Below we summarize our contributions.

First, our work sheds light on how the buyer may take advantage of both supplier competition and cooperation, two forces that are generally considered as adversarial in sourcing. By creating some capacity asymmetry between suppliers intentionally, the buyer can balance the benefit of supplier competition and the gain from supplier cost reduction, thus reconciling these two forces. Though the literature (e.g., Dasgupta 1990) has considered symmetric sourcing solutions in a symmetric setting, our result suggests that one may not rule out asymmetric solutions in general. Second, we establish a complementary relationship between supply base design and pricing mechanism, two decisions that have been studied in isolation in the literature. We show that it is important to coordinate these two decisions to reinforce instead of balance out the advantages of each other. Third, we identify three sourcing structures and offer managerial guidance on the choice of the structure. The results reflect the different systems championed by Japanese and American firms in practice. Finally, we identify the role of strategic capacity, which stimulates supplier competition and may respond to demand uncertainty in a different direction than the operational (buffer) capacity.

We discuss the implications of some modeling assumptions. We allow renegotiation of contracts, which prevents a supplier walking away from ex post unprofitable contracts. If the buyer is able to commit not to renegotiate a fixed-price contract but the supplier is not allowed to walk away, then the result becomes trivial: The buyer should always use sole sourcing and commit to a price up front with the supplier. Without renegotiation, the buyer can extract all expected profits of the supply chain by designing the fixed price appropriately. This gives the ex ante commitment mechanism substantial advantage because without commitments (i.e., with ex post negotiations) the buyer will have to concede information rent. Under ex ante commitments (fixed-price contracts), dual sourcing is dominated by sole sourcing because the former no longer fosters supplier competition. Thus, it is in the presence of renegotiation that dual sourcing may be optimal.

We assume no side payment between the buyer and her suppliers. If the buyer can impose a fixed transfer upon a supplier, then the buyer can extract all profits of the supply chain. Thus, the values of supplier effort and supplier competition are measured by their effects on the supply chain profit only, the information rent not a concern any more (though it still affects the second-stage decision in a subgame perfect solution). As a result, both values of supplier effort and supplier competition shrink, but the trade-off between these two factors still governs the sourcing strategy design.

Our model considers the buyer investing in the capacity for a supplier. Shifting the capacity responsibility to suppliers will make ex post negotiations and dual sourcing less attractive because they may hold up not only suppliers' cost-reduction effort but also their own capacity investment.

Finally, we assume that a supplier's effort reduces his inherent cost additively. If cost reduction is fractional, the equilibrium of supplier efforts can still be identified, and we find numerically that the main insights hold qualitatively.

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Appendix. Proofs

Proof of Lemma 1. Define $x_i(\boldsymbol{\gamma}) \equiv w_i(\boldsymbol{\gamma})S(K_i) + w_{-i}(\boldsymbol{\gamma})(S(\bar{K}) - S(K_{-i}))$ as the expected quantity provided by supplier i given suppliers' cost profile $\boldsymbol{\gamma}$. Recall $q_i(\gamma_i) = \mathbb{E}_{\gamma_{-i}}[x_i(\boldsymbol{\gamma})]$. The mechanism is incentive compatible if and only if $\pi_i(\gamma_i) = \int_{\gamma_i}^{\bar{c}-e_i} q_i(\rho)d\rho$ and $q_i(\gamma_i)$ is decreasing in γ_i. Thus, $\pi_i(\gamma_i)$ is decreasing and convex in γ_i. Comparing the derivatives, it can be shown that $\pi_2(\gamma_2) \geq \pi_2^0(\gamma_2)$ for all γ_2, and that there exists $\hat{c} \in [\underline{c}, \bar{c}]$, defined by $\pi_1(\hat{c}-e_1) = \pi_1^0(\hat{c}-e_1)$, such that $\pi_1(\gamma_1) > \pi_1^0(\gamma_1)$ if and only if $\gamma_1 > \hat{c} - e_1$. Therefore, for $\gamma_1 \leq \hat{c} - e_1$, the same contract as committed will be assigned to supplier 1, with $w_1(\boldsymbol{\gamma}) = 1$, $w_2(\boldsymbol{\gamma}) = 0$, and $p_1(\boldsymbol{\gamma}) = p_1^0$, which results in $x_1(\boldsymbol{\gamma}) = S(K_1)$ and $x_2(\boldsymbol{\gamma}) = S(\bar{K}) - S(K_1)$.

The ex ante profit of supplier 1 is

$$
\begin{aligned}
\bar{\pi}_1 &= \int_{\underline{c}}^{\hat{c}} S(K_1)(p_1^0 - c_1 + e_1) f(c_1)\, dc_1 \\
&\quad + \int_{\hat{c}}^{\bar{c}} \int_{c_1}^{\bar{c}} q_1(\rho - e_1)\, d\rho f(c_1)\, dc_1 \\
&= S(K_1)\left(p_1^0 - \frac{\hat{c} + \underline{c}}{2} + e_1\right) F(\hat{c}) \\
&\quad + \int_{\hat{c}}^{\bar{c}} q_1(c_1 - e_1)(F(c_1) - F(\hat{c}))\, dc_1,
\end{aligned}
$$

where the second equality is obtained from changing the order of integrations. Similarly, the ex ante profit of supplier 2 is $\bar{\pi}_2 = \int_{\underline{c}}^{\bar{c}} q_2(c_2 - e_2) F(c_2)\, dc_2$. The expected profit of the buyer is equal to the total profit of the supply chain minus the suppliers' profits,

$$
\begin{aligned}
U = rS(\bar{K}) - \int_{\underline{c}}^{\bar{c}} \int_{\underline{c}}^{\bar{c}} &\left[\sum_{i=1,2} (c_i - e_i) x_i(c_1 - e_1, c_2 - e_2)\right] \\
&\cdot f(c_2) f(c_1)\, dc_2\, dc_1 - \bar{\pi}_1 - \bar{\pi}_2,
\end{aligned}
$$

which can be transformed to

$$
\begin{aligned}
U &= rS(\bar{K}) - p_1^0 S(K_1) F(\hat{c}) - (S(\bar{K}) - S(K_1))(\bar{c} - e_2) F(\hat{c}) \\
&\quad - \int_{\hat{c}-e_1}^{\bar{c}-e_1} \int_{\underline{c}-e_2}^{\bar{c}-e_2} [(J(\gamma_1, e_1, \hat{c}) - J(\gamma_2, e_2, \underline{c})) B(\mathbf{K}) w_1(\boldsymbol{\gamma}) \\
&\qquad + J(\gamma_1, e_1, \hat{c})(S(\bar{K}) - S(K_2)) \\
&\qquad + J(\gamma_2, e_2, \underline{c}) S(K_2)] \\
&\qquad \cdot f(\gamma_2 + e_2) f(\gamma_1 + e_1)\, d\gamma_2\, d\gamma_1,
\end{aligned}
$$

with $w_2(\boldsymbol{\gamma}) = 1 - w_1(\boldsymbol{\gamma})$. Therefore, in the optimal design for $\gamma_1 > \hat{c} - e_1$, $w_1(\boldsymbol{\gamma}) = 1$ if $J(\gamma_1, e_1, \hat{c}) \leq J(\gamma_2, e_2, \underline{c})$, otherwise $w_1(\boldsymbol{\gamma}) = 0$. Then the specification of $q_i(\gamma_i)$ follows. Based on $(p_i - \gamma_i) q_i(\gamma_i) = \int_{\gamma_i}^{\bar{c}-e_i} q_i(\rho)\, d\rho$, p_i is then defined. □

Lemma 6. *Under the renegotiation mechanism specified in Lemma 1, supplier i will report cost $\underline{c}_i - e_i$ if his actual cost is below this level, quit if his actual cost is above $\bar{c}_i - e_i$, and report truthfully otherwise.*

Proof. The result with $\gamma_i \in [\underline{c}_i - e_i, \bar{c}_i - e_i]$ follows incentive compatibility of the mechanism. If $\gamma_i < \underline{c}_i - e_i$, by reporting $\hat{\gamma}_i \in [\underline{c}_i - e_i, \bar{c}_i + e_i]$, supplier i achieves a profit $\hat{u}_i(\hat{\gamma}_i \mid \gamma_i) = u_i(\hat{\gamma}_i) + (\hat{\gamma}_i - \gamma_i) q_i(\hat{\gamma}_i)$. Since $(\partial/\partial\hat{\gamma}_i)\hat{u}_i(\hat{\gamma}_i \mid \gamma_i) = (\hat{\gamma}_i - \gamma_i) q_i'(\hat{\gamma}_i) \leq 0$, $\hat{u}_i(\hat{\gamma}_i \mid \gamma_i)$ is maximized at $\hat{\gamma}_i = \underline{c}_i - e_i$. If $\gamma_i > \bar{c}_i - e_i$, with $(\partial/\partial\hat{\gamma}_i)\hat{u}_i(\hat{\gamma}_i \mid \gamma_i) = (\hat{\gamma}_i - \gamma_i) q_i'(\hat{\gamma}_i) \geq 0$ for any $\hat{\gamma}_i \in [\underline{c}_i - e_i, \bar{c}_i - e_i]$ and $\hat{u}_i(\bar{c}_i - e_i \mid \gamma_i) = (\bar{c}_i - e_i - \gamma_i) q_i(\hat{\gamma}_i) \leq 0$, we have $\hat{u}_i(\hat{\gamma}_i \mid \gamma_i) \leq 0$ for any $\hat{\gamma}_i \in [\underline{c}_i - e_i, \bar{c}_i - e_i]$, and thus supplier i should quit. □

Because the comparison of $J(\gamma_1, e_1, \hat{c})$ and $J(\gamma_2, e_2, \underline{c})$ depends on $e_1 - e_2$ but not e_1 and e_2 individually, we redefine $\bar{q}_i$ on $e_1 - e_2$: Hereafter, let $\bar{q}_i(e_1 - e_2, \hat{c}, \mathbf{K})$ be the expected quantity of supplier i for given $\mathbf{e}$, $\hat{c}$ and $\mathbf{K}$.

Proof of Lemma 2. For a supplier with cost realization γ_i, his expected profit $u_i(\gamma_i)$ from renegotiation, excluding the cost of effort, is $\pi_i(\gamma_i)$ if $\gamma_i \in [\underline{c} - e_i, \bar{c} - e_i]$, $\pi_i(\underline{c} - e_i) + (\underline{c} - e_i - \gamma_i) q_i(\gamma_i)$ if $\gamma_i < \underline{c} - e_i$, otherwise 0 for $\gamma_i > \bar{c} - e_i$. Define $\bar{u}_i(\hat{e}_i) \equiv \mathbb{E}_{c_i}[u_i(c_i - \hat{e}_i)]$. Then $\bar{u}_i'(e_i) = \bar{q}_i(e_1 - e_2, \hat{c}, \mathbf{K})$. By investing effort $\hat{e}_i$, supplier i's expected profit is $\hat{\Pi}_i(\hat{e}_i) = \bar{u}_i(\hat{e}_i) - \varphi(\hat{e}_i)$, with $\hat{\Pi}_i'(\hat{e}_i) = \bar{u}_i'(\hat{e}_i) - a\hat{e}_i$. It can be shown that $\bar{u}_i'(\hat{e}_i)$ is increasing convex in $\hat{e}_i$ for $\hat{e}_i < e_i$ and increasing concave for $\hat{e}_i \geq e_i$, with $\bar{u}_i''(e_i) = \bar{q}_i(\underline{c} - e_i)/\Delta \leq \mu_d/\Delta$. Then under the assumption $a\Delta \geq \mu_d$, $\bar{u}_i'(\hat{e}_i)$ single crosses $a\hat{e}_i$ from above at some $\hat{e}_i \geq 0$. Thus, e_i as an equilibrium effort is the unique solution to $ae_i = \bar{u}_i'(e_i)$. Since $\sum_{i=1,2} \bar{q}_i(e_1 - e_2, \hat{c}, \mathbf{K})$ is equal to the total sourcing quantity $S(\bar{K})$, $e_1 + e_2 = S(\bar{K})/a$ follows.

Since $\bar{q}_i(e_1 - e_2, \hat{c}, \mathbf{K})$ increases in K_i and decreases in K_{-i}, e_i is increasing in K_i and decreasing in K_{-i}. Since $\bar{q}_1(e_1 - e_2, \hat{c}, \mathbf{K})$ increases while $\bar{q}_2(e_1 - e_2, \hat{c}, \mathbf{K})$ decreases in $\hat{c}$, e_1 is increasing while e_2 is decreasing with $\hat{c}$. □

Lemma 7. *Based on the equilibrium of supplier efforts defined in Lemma 2, $\hat{c}$ is strictly increasing in p_1^0.*

Proof. For given $\mathbf{e}$ and c_1, supplier 1's expected quantity $q_1(c_1 - e_1)$ strictly increases in $\hat{c}$, $\partial q_1/\partial\hat{c} > 0$, because a greater $\hat{c}$ reduces the virtual cost $J(c - e_1, e_1, \hat{c})$ for any $c \in [\hat{c}, \bar{c}]$. Then from $ae_1 = \bar{q}_1(e_1 - e_2, \hat{c}, \mathbf{K})$, e_1 is increasing in $\hat{c}$. Thus, if $\hat{c}$ decreases in p_1^0, e_1 would also decrease in p_1^0. We show that the latter is not possible.

The sign of de_1/dp_1^0 complies with the sign of $(d\bar{q}_1/dp_1^0)|_{\mathbf{e}} = (\partial\bar{q}_1/\partial\hat{c})(\partial\hat{c}/\partial p_1^0)$. Now we prove that $\partial\hat{c}/\partial p_1^0 > 0$, which leads to $de_1/dp_1^0 > 0$. From $(p_1^0 - \hat{c} + e_1)S(K_1) = \pi_1(\hat{c} - e_1)$, $\partial\hat{c}/\partial p_1^0 = S(K_1)/(S(K_1) + \partial\pi_1/\partial\hat{c})$. But $\partial\pi_1/\partial\hat{c} = \int_{\hat{c}}^{\bar{c}} (\partial q_1(c)/\partial\hat{c})\,dc - q_1(\hat{c})$ is strictly greater than $-S(K_1)$ because $\partial q_1/\partial\hat{c} > 0$ and $q_1(\hat{c}) \le S(K_1)$. Thus, $\partial\hat{c}/\partial p_1^0 > 0$. □

Proof of Lemma 3. Define $\eta \equiv (e_1 - e_2)/(2\Delta)$ and $\delta \equiv (\hat{c} - \underline{c})/(2\Delta)$. For brevity, denote $J(\hat{c} - e_1, e_1, \hat{c})$, $J(\bar{c} - e_1, e_1, \hat{c})$, $J(\underline{c} - e_2, e_2, \underline{c})$, and $J(\bar{c} - e_2, e_2, \underline{c})$ by $\hat{J}_1$, $\bar{J}_1$, $\underline{J}_2$, and $\bar{J}_2$, respectively. The comparison between $\hat{J}_1$, $\bar{J}_1$, $\underline{J}_2$, and $\bar{J}_2$ leads to the following five cases that have different boundary types for each region of quantity allocation: (1) $\underline{J}_2 \le \bar{J}_2 \le \hat{J}_1 \le \bar{J}_1$, i.e., $\eta \le -1 + \delta$. (2) $\underline{J}_2 \le \hat{J}_1 \le \bar{J}_2 \le \bar{J}_1$, i.e., $-1 + \delta < \eta \le -\delta$. (3) $\underline{J}_2 \le \hat{J}_1 \le \bar{J}_1 \le \bar{J}_2$, i.e., $-\delta < \eta \le \delta$. (4) $\hat{J}_1 \le \underline{J}_2 \le \bar{J}_1 \le \bar{J}_2$, i.e., $\delta < \eta \le 1 - \delta$. (5) $\hat{J}_1 \le \bar{J}_1 \le \underline{J}_2 \le \bar{J}_2$, i.e., $1 - \delta < \eta$. For each case, we can write the interim expected quantity $q_i(c_i - e_i)$, which gives the ex ante quantity $\bar{q}_i(e_1 - e_2, \hat{c}, \mathbf{K})$, for each supplier $i = 1, 2$. Then based on Lemma 2, η is the solution to $2a\Delta\eta = \bar{q}_1(2\Delta\eta, \hat{c}, \mathbf{K}) - \bar{q}_2(2\Delta\eta, \hat{c}, \mathbf{K})$, and $e_1 = S(\bar{K})/(2a) + \Delta\eta$ and $e_2 = S(\bar{K})/(2a) - \Delta\eta$. In addition, the price committed to supplier 1 p_1^0 can be derived from $\int_{\hat{c}}^{\bar{c}} q_1(c_1 - e_1)dc_1 = (p_1^0 - \hat{c} + e_1)S(K_1)$. Then, using the expressions of e_1, e_2, and p_1^0, the buyer's expected profit Π can be written as a function of η and δ. It can be shown that Π is decreasing in δ in cases (1), (2), and (3), and increasing in δ in case (4). For case (5), it can be shown that the maximal η is $S(\bar{K})/(2a\Delta) \le 1/2$, which is reached with $K_2 = 0$. But the condition $\eta > 1 - \delta$ requires $\eta > 1/2$ given $\delta \le 1/2$. Thus, this case is not feasible.

From the above analysis, for both cases (1) and (2), the optimal Π is reached with $\delta = 0$, in which case $\eta \le 0$. Then by switching K_1 and K_2, we can construct an equivalent solution with $\delta = 0$ and $\eta \ge 0$, which falls in the region of case (4). The above analysis also suggests that the optimal solution under cases (3) and (4) has $\delta = \eta$; i.e., $\hat{c} - e_1 = \underline{c} - e_2$.

Next we prove that $K_1 \ge K_2$. Given $\delta = \eta \in [0, 1/2]$, we have

$$\Pi = -k\bar{K} + \left(r - \bar{c} + \frac{S(\bar{K})}{2a}\right)S(\bar{K}) + \Delta\eta(\mathbf{K})A(\mathbf{K}) + \frac{\Delta}{3}B(\mathbf{K})(1 - 2\eta(\mathbf{K}))^2(1 + \eta(\mathbf{K})),$$

with $\eta(\mathbf{K})$ defined by $2a\Delta\eta = A(\mathbf{K}) - B(\mathbf{K})(1 - 2\eta)^2$. This leads to

$$\frac{\partial\Pi}{\partial K_1} - \frac{\partial\Pi}{\partial K_2} = \frac{\Delta}{3}(\bar{G}(K_1)((1 - 2\eta)^3 + 12\eta) - \bar{G}(K_2)(1 - 2\eta)^3).$$

If $\bar{G}(K_1) > \bar{G}(K_2)$, then $\partial\Pi/\partial K_1 > \partial\Pi/\partial K_2$, which cannot be optimal. Thus, we have $K_1 \ge K_2$ in the optimal solution. □

Proof of Lemma 4. It follows the analysis of case (4) in the proof of Lemma 3, with $\delta = \eta$. □

To prove Proposition 1, we first show Lemma 8:

Lemma 8. *When $\sigma_d = 0$, there exists k_D such that the optimal sourcing strategy is*

(i) *for $k \le k_D$ and $a\Delta \ge 2\mu_d$, $K_1 = K_2 = \mu_d$ and $\hat{c} = 0$;*

(ii) *for $k \le k_D$ and $a\Delta < 2\mu_d$, $K_1 = K_2 = \mu_d$ and $\hat{c} = \underline{c} + \Delta(2 - a\Delta/\mu_d)$;*

(iii) *for $k > k_D$, $K_1 = \mu_d$, $K_2 = 0$, and $\hat{c} = \mu_d/(2a\Delta)$.*

Proof. With certain demand, the optimal supply base has $0 \le K_2 \le K_1 \le \mu_d$ and $\bar{K} \ge \mu_d$. Thus, $B(\mathbf{K}) = K_1 + K_2 - \mu_d$, $A(\mathbf{K}) = 2K_1 - \mu_d$. It can be shown that $\partial\Pi/\partial K_1 - \partial\Pi/\partial K_2 = 4\Delta\eta \ge 0$, leading to $K_1 = \mu_d$. Then $A(\mathbf{K}) = \mu_d$, $B(\mathbf{K}) = K_2 = (\mu_d - 2a\Delta\eta)/(1 - 2\eta)^2$, and thus Π can be written as a function of η, with

$$\Pi'(\eta) = \frac{4a\Delta^2}{3(1 - 2\eta)^3}\left(\eta - \frac{\mu_d}{a\Delta} + \frac{1}{2}\right)\left(\frac{3k}{\Delta} - (1 - 2\eta)^3\right).$$

It can be shown that $\Pi'(\eta) = 0$ when η is equal to $\eta_1 \equiv \mu_d/(a\Delta) - (1/2)$ or $\eta_2 \equiv (1/2)(1 - (3k/\Delta)^{1/3})$. Denote the optimal η by η^*.

Note that η is the larger of the two solutions to Equation (2). The maximal η is $\bar{\eta} \equiv \mu_d/(2a\Delta)$, and it is reached with $K_1 = \mu_d$, $K_2 = 0$, and $\hat{c} = \underline{c} + \mu_d/a$. Let the minimal η be $\underline{\eta}$; it is reached with $K_1 = K_2 = \mu_d$. If $\mu_d/(a\Delta) < 1/2$, then $\underline{\eta} = 0$ with $\hat{c} = \underline{c}$. If $\mu_d/(a\Delta) \ge 1/2$, then $\underline{\eta} = 1 - a\Delta/(2\mu_d)$ with $\hat{c} = \underline{c} + \Delta(2 - a\Delta/\mu_d)$. It can be shown that in both cases $\eta_1 \le \underline{\eta}$. Therefore, $\Pi(\eta)$ is convex for $\eta \in [\underline{\eta}, \bar{\eta}]$, and η^* is chosen by comparing $\Pi(\underline{\eta})$ and $\Pi(\bar{\eta})$.

If $\mu_d/(a\Delta) < 1/2$, then $\underline{\eta} = 0$, and $\Pi(\underline{\eta}) \ge \Pi(\bar{\eta})$ if and only if $k \le \Delta/3 - \mu_d/(2a)$. If $\mu_d/(a\Delta) \ge 1/2$, then $\underline{\eta} = 1 - a\Delta/(2\mu_d)$, and $\Pi(\underline{\eta}) \ge \Pi(\bar{\eta})$ if and only if $k \le \Delta\varphi(\mu_d/(a\Delta))$, where $\varphi(x) \equiv 1 - 1/(2x) + (1/3)(1/x - 1)^2(2 - 1/(2x)) - x/2$ is decreasing in $x \in [1/2, 1]$. Let $k_D = \Delta/3 - \mu_d/(2a)$ if $a\Delta \ge 2\mu_d$; otherwise, $k_D = \Delta\varphi(\mu_d/(a\Delta))$. Then the conclusions follow.

It can be shown that $\varphi(x)$ is decreasing in $x \in [1/2, 1]$. Thus, k_D is increasing in a and Δ. □

Proof of Proposition 1. The proof is summarized as follows. When $\sigma_d = 0$, from Lemma 8 the optimal $\mathbf{K}$ is either (μ_d, μ_d) or $(\mu_d, 0)$. Thus, when $\sigma_d \to 0$, we can focus on the local solutions with $\mathbf{K} \to (\mu_d, \mu_d)$ or $(\mu_d, 0)$. With $\mathbf{K} \to (\mu_d, \mu_d)$, we analyze when $K_1 = K_2$ is (not) optimal, resulting in sD (aD). With $\mathbf{K} \to (\mu_d, 0)$, we analyze when $K_2 = 0$ is optimal, resulting in S (aD). These results about the local optimal structures, combined with the results (from the analysis with certain demand) establishing which location is better, lead to the structure of the global optimal solution. Below is a more detailed analysis of the two cases with (1) $\mathbf{K} \to (\mu_d, \mu_d)$ and (2) $\mathbf{K} \to (\mu_d, 0)$.

Case 1: $K_1 \to \mu_d$ and $K_2 \to \mu_d$. In this case, $A(\mathbf{K}) \to \mu_d$, $B(\mathbf{K}) \to \mu_d$,

$$\frac{\partial\Pi}{\partial K_i} \to -k + \frac{\Delta}{3}(1 - 2\eta)^2(1 + \eta)\frac{\partial B}{\partial K_i} + \Delta\eta\frac{\partial A}{\partial K_i} + 4\Delta\mu_d\eta^2\frac{\partial\eta}{\partial K_i},$$

where $\partial B/\partial K_i = \bar{G}(K_i)$, $\partial A/\partial K_1 = 2\bar{G}(K_1)$, $\partial A/\partial K_2 = 0$, $\partial\eta/\partial K_1 = \bar{G}(K_1)(2 - (1 - 2\eta)^2)/(2a\Delta - 4B(\mathbf{K})(1 - 2\eta))$, and $\partial\eta/\partial K_2 = -\bar{G}(K_2)(1 - 2\eta)^2/(2a\Delta - 4B(\mathbf{K})(1 - 2\eta))$.

When $a\Delta \ge 2\mu_d$, the symmetric solution has $K_1 = K_2 = K^s \equiv \bar{G}^{-1}(3k/\Delta)$ and $\eta = 0$. Then $(\partial\Pi/\partial K_i)|_{K_i = K^s} = 0$. In addition, $(\partial^2\Pi/\partial K_i^2)|_{K_i = K^s} \to (\Delta/3)\bar{G}^2(K^s)(3/(a\Delta - 2\mu_d) - g(K^s)/\bar{G}^2(K^s)) \le 0$. (If $g(K^s)/\bar{G}^2(K^s) < 3/(a\Delta - 2\mu_d)$, then with $g(K)/\bar{G}^2(K)$ increasing in K, $g(K) < \bar{G}^2(K)(3/(a\Delta - 2\mu_d))$ for all $K \le K^s$, and thus $G(K^s) = \int_{\underline{d}}^{K^s} g(K)\,dK \to 0$, where $\underline{d}$ is the lower bound of demand. This contradicts $G(K^s) = 1 - 3k/\Delta \ge 3\mu_d/(2a\Delta) > 0$.) This suggests that the sD solution with $K_1 = K_2 = K^s$ is optimal for $a\Delta \ge 2\mu_d$ and $k \le k_D$.

When $a\Delta < 2\mu_d$, the solution has $K_1 = K_2 = \tilde{K}^s \equiv \bar{G}^{-1}(3k/(\Delta(1+4\eta^3)))$ and $\eta \to 1 - a\Delta/(2\mu_d)$. Then $(\partial\Pi/\partial K_1)|_{K_i=\tilde{K}^s} \geq 0$ and $(\partial\Pi/\partial K_2)|_{K_i=\tilde{K}^s} \leq 0$, suggesting this symmetric investment solution cannot be optimal. Thus, when $a\Delta < 2\mu_d$ and $k \leq k_D$, aD is optimal with $K_1 \to \mu_d$, $K_2 \to \mu_d$.

Case 2: $K_1 \to \mu_d$ and $K_2 \to 0$. In this case, $\eta \to \bar{\eta} = \mu_d/(2a\Delta)$, $\bar{G}(K_1) \to k/(r - \bar{c} + 2\mu_d/a)$, and $(\partial\Pi/\partial K_2)|_{K_2=0} \to (\Delta/3)((-8\bar{\eta}^3 + 12\bar{\eta}^2 + 6\bar{\eta} + 1)/(r - \bar{c} + 2\mu_d/a))(k_S - k)$, where $-8\bar{\eta}^3 + 12\bar{\eta}^2 + 6\bar{\eta} + 1 \geq 1$ for $\bar{\eta} \in [0, 1/2]$, and $k_S \equiv (r - \bar{c} + 2\mu_d/a)(1 - 2\bar{\eta})^3/(-8\bar{\eta}^3 + 12\bar{\eta}^2 + 6\bar{\eta} + 1) \geq 0$. $(\partial\Pi/\partial K_2)|_{K_2=0} > 0$ if and only if $k < k_S$. Therefore, when $k_D \leq k < k_S$, aD is optimal with $K_1 \to \mu_d$ and $K_2 \to 0$, and when $k \geq \max(k_D, k_S)$, S is optimal with $K_1 \to \mu_d$ and $K_2 = 0$.

Given k_D defined in the proof of Lemma 8, $k_D \leq k_S$ if r is sufficiently large. Also from the proof of Lemma 8, k_D is increasing in a and Δ. Next we show that k_S is increasing in a and Δ.

Define $\omega(\eta) \equiv (1 - 2\eta)^3/(-8\eta^3 + 12\eta^2 + 6\eta + 1)$, with $\omega(\eta) \geq 0$ and $\omega'(\eta) \leq 0$ for $\eta \in [0, 1/2]$. Then $k_S = (r - \bar{c} + 4\bar{\eta}\Delta)\omega(\bar{\eta})$, with $dk_S/d\bar{\bar{\eta}} = 4\Delta\omega(\bar{\eta}) + (r - \bar{c} + 4\bar{\eta}\Delta)\omega'(\bar{\eta})$. Note that $(r - \bar{c})/\Delta \geq 1$. Then $dk_S/d\bar{\bar{\eta}} \leq \Delta\omega'(\bar{\eta})(4(\omega(\bar{\eta})/\omega'(\bar{\eta})) + 1 + 4\bar{\eta}) \leq 0$. Thus, $dk_S/da = -(\bar{\eta}/a)(\partial k_S/\partial\bar{\eta}) \geq 0$ and $dk_S/d\Delta = 4\bar{\eta}\omega(\bar{\eta}) - (\bar{\eta}/\Delta)(\partial k_S/\partial\bar{\eta}) \geq 0$. □

To prove Proposition 2, we first prove the following lemma:

Lemma 9. *With $X = \mu_d + \sigma_d X_0$, define $S_{\sigma_d}(K)$ as the derivative of $S(K)$ with respect to σ_d. Then $S_{\sigma_d}(K)/(1 - G(K))$ is negative and decreases in K.*

Proof. For given K, define $K_0 \equiv (K - \mu_d)/\sigma_d$ and $S_0(K_0) \equiv \mathbb{E}[\min(X_0, K_0)]$. Then $S(K) = \mu_d + \sigma_d S_0((K - \mu_d)/\sigma_d)$, $S_{\sigma_d}(K) = S_0(K_0) - K_0(1 - G_0(K_0))$, and $S_{\sigma_d}(K)/(1 - G(K)) = S_0(K_0)/(1 - G_0(K_0)) - K_0$. Based on

$$\frac{d}{dK}\frac{S_{\sigma_d}(K)}{1 - G(K)} = \frac{S_0(K_0)g_0(K_0)}{\sigma_d(1 - G_0(K_0))^2} < 0 \quad \text{and} \quad \frac{S_{\sigma_d}(\underline{d})}{1 - G(\underline{d})} = 0,$$

the expression $S_{\sigma_d}(K)/(1 - G(K))$ is negative and decreasing in K. □

Proof of Proposition 2. From Proposition 1, the supply base structure is chosen between S and sD, and the switching point is at $k = \Delta/3 - \mu_d/(2a)$. Thus, we compare the derivatives of the buyer's S and sD profits with respect to σ_d, for $k = \Delta/3 - \mu_d/(2a)$.

In sD, given the capacity of each supplier K with $K \to \mu_d$, the buyer's profit can be written as $\Pi^{sD}(K) = (r - \bar{c} + \mu_d/(2a))\mu_d - 2kK + (\Delta/3)(2S(K) - \mu_d)$. Thus, the optimal capacity of each supplier K^{sD} is defined by $G(K^{sD}) = 1 - 3k/\Delta$. Based on the envelope theorem,

$$\frac{d\Pi^{sD}}{d\sigma_d} = \frac{2\Delta}{3}S_{\sigma_d}(K^{sD}) = 2k\frac{S_{\sigma_d}(K^{sD})}{1 - G(K^{sD})}.$$

In S, given the supplier capacity K, the buyer's profit is $\Pi^S(K) = (r - \bar{c} + S(K)/a)S(K) - kK$. Thus, the optimal capacity investment K^S is defined by $G(K^S) = 1 - k/(r - \bar{c} + 2\mu_d/a)$. Based on the envelope theorem,

$$\frac{d\Pi^S}{d\sigma_d} = \left(r - \bar{c} + \frac{2S(K^S)}{a}\right)S_{\sigma_d}(K^S) = k\frac{S_{\sigma_d}(K^S)}{1 - G(K^S)}.$$

The inequality $d\Pi^{sD}/d\sigma_d \leq d\Pi^S/d\sigma_d$ is equivalent to $2(S_{\sigma_d}(K^{sD})/(1 - G(K^{sD}))) \leq S_{\sigma_d}(K^S)/(1 - G(K^S))$. Since $K^{sD} \leq K^S$, and $S_{\sigma_d}(K)/(1 - G(K))$ is negative and decreasing in K (from Lemma 9), this inequality is satisfied if K^{sD} and K^S are sufficiently close. Because K^S increases in r and K^{sD} is independent of r, lower r brings K^S closer to K^S. Let r take the lower bound value $\bar{c} + \Delta + k = \bar{c} + 4\Delta/3 - \mu_d/(2a)$ and define $\alpha \equiv \mu_d/(a\Delta) \in (0, 1/2)$. Then $G(K^{sD}) = (3/2)\alpha$ and $G(K^S) = (6 + 12\alpha)/(8 + 9\alpha)$. Given $S_{\sigma_d}(K) = S_0(K_0) - K_0(1 - G_0(K_0))$ (see the proof of Lemma 9), it can be shown that for both normal and uniform distributions, there exists $\hat{\alpha} \in (0, 1/2)$ such that $2S_{\sigma_d}(K^{sD})/(1 - G(K^{sD})) \leq S_{\sigma_d}(K^S)/(1 - G(K^S))$ for $\alpha \geq \hat{\alpha}$. □

Analysis of Section 6.1. Let $\bar{Q} \equiv Q_1 + Q_2$. With quantity commitments $\mathbf{Q}$, if supplier i has the allocation priority, his total expected quantity is $\tilde{S}(K_i, \mathbf{Q}) \equiv Q_i + S(K_i + Q_{-i}) - S(\bar{Q})$, and that of supplier $-i$ is $Y(\bar{K}, \bar{Q}) - \tilde{S}(K_i, \mathbf{Q})$, where $Y(\bar{K}, \bar{Q}) \equiv \bar{Q} + S(\bar{K}) - S(\bar{Q})$ is the total expected quantity provided by the suppliers. Similar to (1), define $\tilde{A}(\mathbf{K}, \mathbf{Q}) \equiv 2\tilde{S}(K_1, \mathbf{Q}) - Y(\bar{K}, \bar{Q})$ and $\tilde{B}(\mathbf{K}, \mathbf{Q}) \equiv \tilde{S}(K_1, \mathbf{Q}) + \tilde{S}(K_2, \mathbf{Q}) - Y(\bar{K}, \bar{Q})$. Then the analysis follows the one without a quantity commitment, except to replace $S(\bar{K})$ by $Y(\bar{K}, \bar{Q})$, $A(\mathbf{K})$ by $\tilde{A}(\mathbf{K}, \mathbf{Q})$, and $B(\mathbf{K})$ by $\tilde{B}(\mathbf{K}, \mathbf{Q})$. In the result, the supplier efforts are specified by

$$e_1(\mathbf{K}, \mathbf{Q}) = \frac{Y(\bar{K}, \bar{Q})}{2a} + \Delta\tilde{\eta}(\mathbf{K}, \mathbf{Q}) \quad \text{and}$$

$$e_2(\mathbf{K}, \mathbf{Q}) = \frac{Y(\bar{K}, \bar{Q})}{2a} - \Delta\tilde{\eta}(\mathbf{K}, \mathbf{Q}),$$

where $\tilde{\eta}(\mathbf{K}, \mathbf{Q})$ is uniquely defined by

$$\tilde{A}(\mathbf{K}, \mathbf{Q}) - (1 - 2\tilde{\eta})^2\tilde{B}(\mathbf{K}, \mathbf{Q}) = 2a\Delta\tilde{\eta}. \tag{5}$$

And the buyer's expected profit is

$$\begin{aligned}\tilde{\Pi}(\mathbf{K}, \mathbf{Q}) &= rS(\bar{K}) - \left(\bar{c} - \frac{Y(\bar{K}, \bar{Q})}{2a}\right)Y(\bar{K}, \bar{Q}) - k\bar{K} \\ &\quad + \frac{\Delta}{3}(1 - 2\tilde{\eta}(\mathbf{K}, \mathbf{Q}))^2(1 + \tilde{\eta}(\mathbf{K}, \mathbf{Q}))\tilde{B}(\mathbf{K}, \mathbf{Q}) \\ &\quad + \Delta\tilde{\eta}(\mathbf{K}, \mathbf{Q})\tilde{A}(\mathbf{K}, \mathbf{Q}).\end{aligned} \tag{6}$$

Proof of Lemma 5. (i) Based on Equation (5), it can be shown that

$$\begin{aligned}&\frac{1}{\Delta}\left(\frac{\partial\tilde{\Pi}}{\partial K_1} - \frac{\partial\tilde{\Pi}}{\partial K_2} + \frac{\partial\tilde{\Pi}}{\partial Q_1} - \frac{\partial\tilde{\Pi}}{\partial Q_2}\right) \\ &\quad = \tilde{\eta}(1 + 2G(\bar{Q}) + 2G(\bar{K}) - G(Q_2)) \geq 0.\end{aligned}$$

This suggests that the buyer's profit can be improved by increasing K_1 and Q_1 while reducing K_2 and Q_2 by the same amount. Thus, $K_2 \geq Q_2 > 0$ cannot be optimal.

(ii) In sole sourcing, for given capacity investment K the expected quantity provided by the supplier is $q(Q) \equiv Q + S(K) - S(Q)$, where Q is the committed quantity. $q(Q)$ is increasing. The supplier effort is $\underline{c}$ for any Q such that $q(Q) > a\underline{c}$. Thus, without loss of generality, we focus on $Q \leq Q^h$, where Q^h is defined by $q(Q^h) = a\underline{c}$. Note that Q is constrained by K.

For given K, the buyer's expected profit is $\tilde{\Pi}(Q) = rS(K) - (\bar{c} - q(Q)/a)q(Q) - kK$. It can be shown that $\tilde{\Pi}(Q)$ is quasi-convex in Q.

When $K < a\underline{c}$, the optimal Q is between 0 and K (as $Q^h > K$ in this case). Since $(\bar{c} - x/a)x$ is increasing in x for $x \le a\bar{c}/2$, $\tilde{\Pi}(0) - \tilde{\Pi}(K) = (\bar{c} - K/a)K - (\bar{c} - S(K)/a)S(K)$ is positive for $K \le a\bar{c}/2$. If $\Delta > \underline{c}$, then $a\underline{c} < a\bar{c}/2$, and thus $K < a\bar{c}/2$. If $\Delta \le \underline{c}$, then $a\Delta < a\bar{c}/2$, suggesting that $K \le a\bar{c}/2$ because $K \le \mu_d \le a\Delta$.

When $K \ge a\underline{c}$, the optimal Q is between 0 and Q^h. Note that $\tilde{\Pi}(0) - \tilde{\Pi}(Q^h) = \Psi(S(K))$, where $\Psi(x) \equiv \Delta a\underline{c} - (\bar{c} - x/a)x$ is decreasing in x for $x \le a\bar{c}/2$, with $\Psi(a\Delta) = \Psi(a\underline{c}) = 0$. If $\Delta > \underline{c}$, then $a\underline{c} < a\bar{c}/2$; in this case, $\tilde{\Pi}(0) - \tilde{\Pi}(Q^h) \ge \Psi(a\underline{c})$ because $S(K) \le q(Q) \le a\underline{c}$. If $\Delta < \underline{c}$, then $a\Delta < a\bar{c}/2$; in this case, $\tilde{\Pi}(0) - \tilde{\Pi}(Q^h) \ge \Psi(a\Delta)$ because $S(K) \le a\Delta$. $\square$

Proof of Proposition 3. From Lemma 5, we restrict to $Q_2 = 0$. It is easy to show that $\tilde{\Pi}$ is quasi-convex in Q_1 if $Q_1 \le \underline{d}$.

We first prove for certain demand. For $K_1 \le \mu_d$, we only need to compare $Q_1 = 0$ or K_1 because $\tilde{\Pi}$ is quasi-convex. If $Q_1 = K_1$, the optimal $\tilde{\Pi}$ is achieved with $K_1 = \mu_d$ and $K_2 = 0$, equal to the profit under sole sourcing with $Q_1 = 0$.

When $\sigma_d > 0$ and $\sigma_d \to 0$, from the result of certain demand, the optimal solution falls in one of the following structures: (1) $K_1 \to \mu_d$, $K_2 \to \mu_d$, and $Q_1 \to 0$; (2) $K_1 \to \mu_d$, $K_2 \to 0$, and $Q_1 \to 0$; and (3) $K_1 \to \mu_d$, $K_2 \to 0$, and $Q_1 \to \mu_d$. Following Lemma 5(ii), structure (3) cannot be optimal, and structure (2) has $Q_1 = 0$. Next we focus on structure (1), analyzing $\partial\tilde{\Pi}/\partial Q_1$ at $Q_1 = 0$. Note that $\bar{S}(K_1, \mathbf{Q})$, $\bar{S}(K_2, \mathbf{Q})$, $Y(\bar{K}, \bar{Q})$, $\tilde{B}(\mathbf{K}, \mathbf{Q})$, and $\tilde{A}(\mathbf{K}, \mathbf{Q})$ all approach μ_d as $\sigma_d \to 0$. From the proof of Proposition 1, if $a\Delta \ge 2\mu_d$, then the optimal solution with $Q_1 = 0$ has $\tilde{\eta} = 0$; in this case, it can be shown that $(\partial\tilde{\Pi}/\partial Q_1)|_{K_i = K^s, Q_1 = 0} \to (\Delta/3)(\bar{G}(K_2) - 1) \le 0$. If $a\Delta < 2\mu_d$, then the optimal solution with $Q_1 = 0$ has $\tilde{\eta} \to \underline{\eta} \equiv 1 - a\Delta/(2\mu_d)$; in this case, it can be shown that $(\partial\tilde{\Pi}/\partial Q_1)|_{K_i = \tilde{K}^s, Q_1 = 0} \to (\Delta/3)(\bar{G}(K_2) - 1)(1 - 2\underline{\eta})^3 \le 0$. Therefore, $Q_1 = 0$ is optimal under structure (1). $\square$

Proof of Proposition 4. From the buyer's perspective, given the price commitments and her belief of supplier efforts, the design of the best-response renegotiation mechanism in each period t follows the one in Lemma 1. Thus, in period t, if supplier i exerts effort $\hat{e}$ while the buyer and the other supplier play their equilibrium strategies, his expected profit in that period will be $\mathbb{E}[u_{i,t}(c_i - \hat{e} - \bar{e}_{i,t-1})]$, where $\bar{e}_{i,0} \equiv 0$, and $u_{i,t}(\gamma_i)$ is defined as in the main text based on the belief of supplier (cumulative) efforts $\bar{e}_{i,t}$, $i = 1, 2$, and price commitment $\hat{c}_t$. We now analyze supplier i's best-response effort.

First it can be proven that for period T, there exists $\tilde{e}_{i,T}$ defined as the unique solution of θ to $(d/d\theta)\mathbb{E}_{c_i}[u_{i,T}(c_i - \theta)] = a\theta$, such that supplier i's new effort in period T is zero if $\bar{e}_{i,T-1}$ is greater than $\tilde{e}_{i,T}$; otherwise, it is $\tilde{e}_{i,T} - \bar{e}_{i,T-1}$. Then using backward induction, it can be shown that for any $1 \le t < T$, the supplier's ongoing profit is concave in his incremental effort. Define $\tilde{e}_{i,t}$ as the unique solution of θ to $\sum_{l=t}^{T} \alpha^{l-t}(d/d\theta)\mathbb{E}_{c_i}[u_{i,l}(c_i - \theta)] = a\theta$. Then for α sufficiently large, $\tilde{e}_{i,t}$ is decreasing in t, and the optimal incremental effort in period t is zero if $\bar{e}_{i,t-1} \ge \tilde{e}_{i,t}$, and $\tilde{e}_{i,t} - \bar{e}_{i,t-1}$ otherwise. This implies $e_{i,t} = 0$ for $t \ge 2$ and $\bar{e}_{i,1} = \cdots = \bar{e}_{i,T}$ follows.

Let $e_i \equiv \bar{e}_{i,1}$, $i = 1, 2$ and $\eta \equiv (e_1 - e_2)/(2\Delta)$. Then in the equilibrium, $e_1 + e_2 = S(\bar{K})/a$, and $2a\Delta\eta = \sum_{t=1}^{T} \alpha^{t-1}(\bar{q}_1(2\Delta\eta, \hat{c}_t, \mathbf{K}) - \bar{q}_2(2\Delta\eta, \hat{c}_t, \mathbf{K}))$. Let $U_t(\hat{c}_t, \eta)$ be the buyer's expected profit in period t without considering the capacity investment cost. Then the buyer's total profit is $\Pi = \sum_{t=1}^{T} \alpha^{t-1} U_t(\hat{c}_t, \eta) - k\bar{K}$. At $\hat{c}_1 = \cdots = \hat{c}_T = \hat{c}$, we have $d\Pi/d\hat{c}_t = \alpha^{t-1}(\partial U/\partial \hat{c}) + (\partial U/\partial \eta)\sum_{t=1}^{T} \alpha^{t-1}(d\eta/d\hat{c}_t)$, where $U \equiv U_t(\hat{c}, \eta)$ and

$$\frac{d\eta}{d\hat{c}_t} = \left[\alpha^{t-1}\left(\frac{\partial}{\partial \hat{c}}\bar{q}_1(2\Delta\eta, \hat{c}, \mathbf{K}) - \frac{\partial}{\partial \hat{c}}\bar{q}_2(2\Delta\eta, \hat{c}, \mathbf{K})\right)\right] \cdot \left[2a\Delta - \frac{1-\alpha^T}{1-\alpha} \cdot \left(\frac{\partial}{\partial \eta}\bar{q}_1(2\Delta\eta, \hat{c}, \mathbf{K}) - \frac{\partial}{\partial \eta}\bar{q}_2(2\Delta\eta, \hat{c}, \mathbf{K})\right)\right]^{-1}.$$

This leads to $d\Pi/d\hat{c}_t = \alpha^{t-1}\xi(\hat{c}, \eta)$, where

$$\xi(\hat{c}, \eta) = \frac{\partial U}{\partial \hat{c}} + \frac{\partial U}{\partial \eta} \cdot \left(\frac{1-\alpha^T}{1-\alpha}\frac{\partial}{\partial \hat{c}}\bar{q}_1(2\Delta\eta, \hat{c}, \mathbf{K}) - \frac{\partial}{\partial \hat{c}}\bar{q}_2(2\Delta\eta, \hat{c}, \mathbf{K})\right) \cdot \left(2a\Delta - \frac{1-\alpha^T}{1-\alpha}\left(\frac{\partial}{\partial \eta}\bar{q}_1(2\Delta\eta, \hat{c}, \mathbf{K}) - \frac{\partial}{\partial \eta}\bar{q}_2(2\Delta\eta, \hat{c}, \mathbf{K})\right)\right)^{-1}$$

is independent of t. Thus, $\hat{c}_1 = \cdots = \hat{c}_T = \hat{c}$ for $\hat{c}$ such that $\xi(\hat{c}, \eta) = 0$ is an optimal solution. Then following the same analysis for the single-period model, it can still be proved that $\hat{c} - \underline{c} = e_1 - e_2$. $\square$

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