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Using a Dual-Sourcing Option in the Presence of Asymmetric Information About Supplier Reliability: Competition vs. Diversification

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We study a buyer's strategic use of a dual-sourcing option when facing suppliers possessing private information about their disruption likelihood. We solve for the buyer's optimal procurement contract. We show that the optimal contract can be interpreted as the buyer choosing between diversification and competition benefits. Better information increases diversification benefits and decreases competition benefits. Therefore, with better information the buyer is more inclined to diversify. Moreover, better information may increase or decrease the value of the dual-sourcing option, depending on the buyer's unit revenue: for large revenue, the buyer uses the dual sourcing option for diversification, the benefits of which increase with information; for small revenue, the buyer uses the dual sourcing option for competition, the benefits of which decrease with information. Surprisingly, as the reliability of the entire supply base decreases, the buyer may stop diversifying under asymmetric information (to leverage competition), whereas it would never do so under symmetric information. Finally, we analyze the effect of codependence between supply disruptions. We find that lower codependence leads the buyer to rely less on competition. Because competition keeps the information costs in check, a reduction in supplier codependence increases the buyer's value of information. Therefore, strategic actions to reduce codependence between supplier disruptions should not be seen as a substitute for learning about suppliers' reliabilities.

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1. Introduction

The average U.S. manufacturer spends roughly half its revenue procuring goods and services (U.S. Census Bureau 2006). Although outsourcing production of a critical component can offer cost advantages for the manufacturer, it can also introduce the risk that a supplier's failure to deliver will halt the manufacturer's production. A labor strike or financial bankruptcy might shut down supplier operations (for examples, see Babich 2010). Changes in a supplier's ownership status can also trigger disruptions. For example, after purchasing Dovatron in April 2000, Flextronics announced that it would completely shut down Dovatron's low-volume specialty circuit board facility in Anaheim as part of restructuring to focus on low-mix, high-volume products. As a result of Flextronics's decision, Beckman Coulter Inc., a medical device manufacturer who single-sourced a critical component from Dovatron's Anaheim facility, lost its supplier. The supply disruption was very expensive for Beckman Coulter (Knapp 2004).[1]

In an effort to deal with supply risks, many manufacturers resort to multisourcing, that is, maintaining a supply base with many suppliers. To mitigate supply risks, multisourcing manufacturers can and do employ diversification, i.e., ordering from multiple suppliers to take advantage of imperfect correlation between random supply events. The ability to diversify risk is only one benefit of multisourcing, however. The other possible benefit of multisourcing is competition: a manufacturer with a large supply base may

[1] For additional details, see http://www.callahan-law.com/Verdicts-and-Settlements/Callahan-Blaine-Wins-934-Million-for-Beckman-Coulter.shtml.

have suppliers bid against one another to obtain more favorable terms. Indeed, Wu and Choi (2005), who use the case study method to analyze why and how manufacturers get involved in relationships among their suppliers, present cases in which manufacturers had at least two suppliers with two explicit goals in mind: managing supply risk *and* reducing costs by putting competitive pressure on the suppliers. Nissan is a recent example of a firm who used multisourcing for both competition and diversification, the latter being particularly useful when the recent earthquake hit Japan (*The Economist* 2011).

In this paper we say that a manufacturer ("buyer") has a *dual-sourcing option* if it has two suppliers in the supply base. In contrast, if there is only one supplier in the supply base, we say that the buyer is *single sourcing*. A buyer with a dual-sourcing option may choose to order from only one supplier (*winner-take-all* strategy) or both suppliers (*diversification* strategy).

The more the buyer favors a winner-take-all strategy, the greater the competition benefits. But with only one supplier awarded business, the supply-risk diversification benefits are lost. Conversely, the more the buyer favors a diversification strategy, the less the suppliers compete. This is the key trade-off examined in this paper. Furthermore, it is quite common for suppliers to have better information than the buyers about the likelihood of supply disruptions. For example, Dovatron enjoyed better information than Beckman Coulter about its acquisition by Flextronics. Similarly, buyers may have no knowledge of suppliers outsourcing components to second-tier suppliers and, thus, suppliers have better knowledge of supply risks that accompany such outsourcing decisions. Our model incorporates asymmetric information about supplier reliability by assuming that each supplier privately knows whether it is a high- or a low-reliability-type supplier.

The buyer contracts with one (or both) supplier(s) for production by setting quantity, fixed payment, and variable payment terms. The latter ensures that the suppliers have an incentive to deliver. The buyer maximizes its expected profit, and in so doing must strategically account for each supplier's incentive to misrepresent their reliability.

To find the trade-off between competition and diversification, we first rigorously define their benefits (§4). We do so by comparing the profit of a single-sourcing buyer to profits of a buyer with a dual-sourcing option, who is constrained to use pure winner-take-all or pure diversification strategies. Articulating the diversification and competition benefits creates a useful device and forms the central theme of this paper: the buyer's optimal procurement contract can be understood as the buyer's choice between competition and diversification benefits. Continuing to use the same device, we explain the value of the dual-sourcing option, the role of information, and the effects of the business environment on the procurement (§§5 and 6). Section 7 summarizes our results.

2. Literature

Our paper contributes to the important and fast growing literature on supply disruptions management (for recent reviews, see Tomlin and Wang 2010, Aydın et al. 2012). A number of these papers study multisourcing, for example, Tomlin and Wang (2005), Tomlin (2006), Babich et al. (2007), Dada et al. (2007), Federgruen and Yang (2009), and Babich et al. (2010). However, the majority do not account for competition among suppliers. A paper that does explicitly consider the trade-off between competition and diversification is Babich et al. (2007), where powerful, but risky, suppliers engage in Bertrand competition by setting wholesale prices in an effort to win the buyer's business. In contrast to Babich et al. (2007), we endow the buyer with the power to offer procurement contracts, we consider a more general model of competition, and we allow the buyer to commit to ordering from one or two suppliers. Furthermore, unlike Babich et al. (2007) and the majority of the supply disruptions literature, we account for the fact that suppliers in practice are often privileged with better information than the buyers about the likelihood of supply disruptions.

A handful of papers study asymmetric information about supply risks, for example, Lim (2001), Baiman et al. (2000), Gurnani and Shi (2006), Yang et al. (2009), Tomlin (2009), Chaturvedi and Martínez-de-Albéniz (2011), and Gümüş et al. (2012). The first four papers, unlike the present paper, do not use multisourcing. Tomlin (2009) studies multisourcing, but relies on Bayesian updating over time as a mechanism for the buyer to learn the supplier's reliability, whereas we invoke optimal incentive-compatible contracts instead. Chaturvedi and Martínez-de-Albéniz (2011) study multisourcing with asymmetric information about supply risk and supply costs, but focus on characterizing formats of the objective function and belief distributions for which a solution to the optimal mechanism design problem can be derived. Gümüş et al. (2012) is a recent paper that features supplier competition in the presence of supplier risk. They study a problem where only one of two suppliers is risky and a supplier signals its private information through supply guarantees.

A model similar to the one in the present paper, but with only a single supplier, was used by Yang et al. (2009), who study a backup production option as a contingent claim used to remedy a supply disruption. We study a vastly different approach to managing supply risk—diversification across multiple suppliers (which reduces the chance of not having supply, but provides no protection after a disruption occurs). Moreover, by having multiple suppliers the buyer can induce competition among them. We focus on the trade-off between competition and diversification, neither of which would be possible in the setting of Yang et al. (2009), which had only one supplier.

This paper is related to work in procurement and economics that study asymmetric information about suppliers' costs (e.g., Dasgupta and Spulber 1989, Corbett 2001, Beil and Wein 2003, Elmaghraby 2004, Wan and Beil 2009, Kostamis et al. 2009, Li 2010). We employ mechanism design theory to find how the buyer optimally deploys its dual-sourcing option in the presence of asymmetric information about supply risk. Consistent with general observations of mechanism design theory (e.g., Fudenberg and Tirole 1991, Chap. 7), in our paper asymmetric information about supplier reliabilities affects the contract between the buyer and the low-type supplier. Our contribution is not in exposing this fact, but rather exploring the operational implications of the trade-off between competition and diversification. We show how this trade-off profoundly affects the buyer's valuation and optimal deployment of its dual-sourcing option, and analyze how these effects change with the underlying business environment.

3. Model

We model a stylized supply chain with a buyer and two suppliers. The suppliers' production processes are subject to random disruptions. When a disruption occurs, the production process yields zero output and the supplier delivers nothing. There are two types of suppliers in the market: high reliability (H) and low reliability (L), with low-reliability suppliers being more prone to production disruptions. The two supplier types differ from each other in their likelihoods of disruptions and their costs of production. Let $t_n \in \{H, L\}$ denote the type of supplier $n = 1, 2$. The commonly known probability of a supplier being of high type is α^H, and the probability of a supplier being of low type is α^L, where $\alpha^H + \alpha^L = 1$. We assume that the two suppliers' types are independent of one another.

In keeping with our assumption that a disruption results in nondelivery, we represent supplier n's proportional random yield as a Bernoulli random variable and denote it by $\rho_n^{t_n}$:

$$\rho_n^{t_n} \stackrel{\text{def}}{=} \begin{cases} 1 & \text{with probability } \theta^{t_n}, \\ 0 & \text{with probability } 1 - \theta^{t_n}, \end{cases} \qquad (1)$$

where $\theta^H = h$ and $\theta^L = l$, $h > l$. For the time being, we assume that the two suppliers' production disruption processes are independent of each other, that is, $\rho_1^{t_1}$ and $\rho_2^{t_2}$ are independent (§6 relaxes this assumption). The probability θ^{t_n} is a measure of supplier n's reliability. Notice that a supplier's reliability depends only on its type.

A production attempt costs a type t supplier ($t \in \{H, L\}$) c^t per unit regardless of whether it is successful or not. We allow c^H and c^L to be different (e.g., $c^H > c^L$). The high type is assumed to be more cost efficient than the low type, that is, the expected cost of successfully producing one unit is smaller for high-type suppliers: $c^L/l > c^H/h$. (Note that, for one unit of input going into production, the expected output of a type t supplier is θ^t. Hence, were repeated production attempts allowed, the expected cost of successfully producing one unit would be c^t/θ^t.)

To capture the buyer's lack of visibility into the suppliers' reliabilities and costs, we assume that a supplier's reliability type is its private information, unknown to the buyer and the other supplier. (Our results can be extended to the case where the suppliers perfectly know each other's type.)

The buyer incurs a setup cost, denoted by K, for ordering from a supplier in addition to the cost of purchasing parts. The setup cost can be the cost of transferring technology to the supplier, or administrative costs incurred to manage the procurement process. We assume the parts from the two suppliers are perfect substitutes.

The buyer uses the parts to produce a product, which it sells to meet demand, D. To focus on the effects of supply risk, we assume a demand is known at the time the buyer places its orders. When supplier deliveries do not cover the entire demand D, the buyer loses r per unit shortfall. The value r represents the buyer's revenue per item, or alternatively its per item recourse cost to secure a backup supply. (For instance, after its supplier Dovatron's production was shut down, Beckman Coulter created their own in-house specialty circuit board production line, which cost them 2.1 million dollars to construct.) Thus, the buyer's expected profit of meeting demand D using a high-type supplier (known to be high type) is $(hr - c^H)D - K$. Because the high type is more efficient than the low type, if this profit is negative the buyer will not order at all. To keep the problem interesting, for the rest of the discussion we will assume the following:

Assumption 1. $(hr - c^H)D - K > 0$.

To govern its relationship with the two suppliers, the buyer uses contracts. Each contract comprises a fixed payment, X, an order quantity q, and a variable payment of p per unit of delivered part. As is common in practice, the variable payment serves to hold the supplier liable for shortage (one can show that there exists an equivalent contract form featuring a nondelivery penalty in lieu of the variable payment).

Intuitively, the buyer would like the fixed payments, order quantities, and variable payments to depend on the suppliers' true reliabilities. However, the buyer does not know the suppliers' true reliabilities, and instead—as is standard in the economics literature—we assume that the buyer offers several contract options (a contract menu) from which the suppliers choose. To find the buyer's optimal contract menu, we apply the Revelation Principle (Myerson 1979) and focus on the class of incentive-compatible direct-revelation menus. Under such a contract menu, both suppliers will truthfully report their reliability types to the buyer. For simplicity in the analysis, we assume that the suppliers cannot collude. (For instance, the suppliers might not even know who they are competing against. Jap (2003) surveys implementations of reverse auctions for procurement and notices that most bidding events are anonymous.)

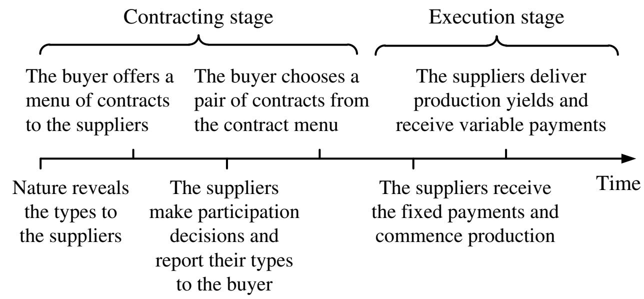
The contract menu is a modeling construct that captures the general practice of tailoring contracts to specific suppliers in a procurement process. In particular, the contract menu captures two salient features of a typical contracting process. First, the contract for a supplier is tailored according to the reliability risk perceived by the buyer. Thus, a high- and a low-type supplier can end up with different contracts. Second, the contract for one supplier depends on the reliability of the other supplier, both of whom compete for business from the buyer: intuitively, a supplier's likelihood of receiving an order decreases as the other supplier becomes more reliable.

Thus, the contract menu in this model consists of four pairs of contracts, each pair corresponding to one of four combinations of supplier types: $\{[X_n(t_1,t_2), q_n(t_1,t_2), p_n(t_1,t_2)], n=1,2\}$ for $t_1, t_2 \in \{H, L\}$. To simplify notation, we use $(X_n, q_n, p_n)(t_1, t_2)$ as shorthand to denote the contract for supplier n. We consider a problem in which the buyer has only one contracting opportunity. Figure 1 shows the timing of events.

3.1. The Buyer's Contract Design Problem

We now explore the buyer's decisions in the contracting stage. Recall that t_n is supplier n's reliability type. At the beginning of the contracting stage, the buyer, who does not know the suppliers' types, designs and offers a contract menu to maximize its expected profit. Let $s_n \in \{H, L\}$ denote supplier n's report of its type upon observing the contract menu offered by the buyer. (If $s_n \neq t_n$, then the supplier is misrepresenting itself.) Based on the reported types, supplier n receives a contract $(X_n, q_n, p_n)(s_1, s_2)$.

Figure 1 **Timing of Events**



Let $z^t(q,p)$ be the optimal production decision for the supplier of type t, given a contract (X, q, p) (as we will show in Lemma 1, the optimal production quantity expression does not depend on X). Then for contract $(X_n, q_n, p_n)(s_1, s_2)$ supplier n's optimal size of production attempt is $z_n^{t_n}[(q_n, p_n)(s_1, s_2)]$, and the supplier delivers $\rho_n^{t_n} z_n^{t_n}[(q_n, p_n)(s_1, s_2)]$ to the buyer. Let $\pi^t(X, q, p)$ be the optimal expected profit of a supplier of type t given a contract (X, q, p) (see Lemma 1). Then, for contract $(X_n, q_n, p_n)(s_1, s_2)$, supplier n earns a profit of $\pi_n^{t_n}[(X_n, q_n, p_n)(s_1, s_2)]$. At the time when the suppliers are reporting their types to the buyer, they do not know each other's type. Hence, the two suppliers' expected profits are $\Pi_1^{t_1}(s_1) \stackrel{\text{def}}{=} E_{t_2}\{\pi_1^{t_1}[(X_1, q_1, p_1)(s_1, t_2)]\}$ and $\Pi_2^{t_2}(s_2) \stackrel{\text{def}}{=} E_{t_1}\{\pi_2^{t_2}[(X_2, q_2, p_2)(t_1, s_2)]\}$.

The buyer designs its contract menu to maximize its expected profit while inducing the suppliers to report their true reliability types, as given in the following optimization problem:

$$
\begin{aligned}
\max_{\substack{(X_n, q_n, p_n)(t_1, t_2)\\ n=1,2;\, t_1, t_2 \in \{H, L\}}} \Bigg\{ \sum_{t_1, t_2 \in \{H, L\}} \alpha^{t_1} \alpha^{t_2} \Big[& rE \min\big\{D, \\
& \rho_1^{t_1} z_1^{t_1}[(q_1, p_1)(t_1, t_2)] + \rho_2^{t_2} z_2^{t_2}[(q_2, p_2)(t_1, t_2)]\big\} \\
& - X_1(t_1, t_2) - p_1(t_1, t_2)\, E\min\big\{q_1(t_1, t_2), \\
& \rho_1^{t_1} z_1^{t_1}[(q_1, p_1)(t_1, t_2)]\big\} - K\,\mathbf{1}_{\{q_1(t_1, t_2) > 0\}} \\
& - X_2(t_1, t_2) - p_2(t_1, t_2)\, E\min\big\{q_2(t_1, t_2), \\
& \rho_2^{t_2} z_2^{t_2}[(q_2, p_2)(t_1, t_2)]\big\} - K\,\mathbf{1}_{\{q_2(t_1, t_2) > 0\}} \Big] \Bigg\};
\end{aligned} \tag{2a}
$$

$$
\begin{aligned}
\text{subject to} \quad & \text{for } n = 1, 2 \\
\text{(I.C.)} \quad & \Pi_n^H(H) \ge \Pi_n^H(L), \\
& \Pi_n^L(L) \ge \Pi_n^L(H); \qquad \text{(2b)} \\
\text{(I.R.)} \quad & \Pi_n^H(H) \ge 0, \quad \Pi_n^L(L) \ge 0; \qquad \text{(2c)} \\
& q_n(t_1, t_2) \ge 0, \quad p_n(t_1, t_2) \ge 0, \\
& \qquad \text{for } t_1, t_2 \in \{H, L\}.
\end{aligned}
$$

The buyer's objective function (2a) is the buyer's expected revenue minus the fixed payments and the expected variable payments to the two suppliers minus the setup costs of ordering from the suppliers, weighted by the probabilities of drawing different supplier types.

Constraints (I.C.) are *incentive compatibility* constraints for high-type and low-type supplier n, respectively. The left-hand side of each of these constraints is supplier n's expected profit when it truthfully reports its type, given that the other supplier's type is unknown. The right-hand side is supplier n's expected profit when it misrepresents itself. The constraints ensure that supplier n finds it optimal to report its true type. Constraints (I.R.) are the *individual rationality* constraints for high- and low-type supplier n.

For problem (2), we have assumed that neither supplier perfectly knows the other supplier's reliability type, leading to a Bayesian mechanism. For general mechanism design problems in which the payoff functions of the principal and the agents are quasilinear in the fixed payments (as in our model), the optimal dominant-strategy mechanism is also an optimal Bayesian mechanism (Mookherjee and Reichelstein 1992). That is, the set of optimal Bayesian mechanisms subsumes the set of optimal dominant-strategy mechanisms. We later show that in our model we can choose a Bayesian-mechanism optimal contract menu such that it is also an optimal dominant-strategy mechanism. Consequently, the optimal Bayesian mechanism outcome could be implemented regardless of the suppliers' beliefs about each other, and the mechanism remains optimal even if the suppliers perfectly know each other's reliability type.

3.2. Supplier's Production Decisions

To simplify the notation in this subsection, we suppress subscript n for the suppliers. In the execution stage, given a contract (X, q, p) from the buyer, a supplier of type $t \in \{H, L\}$ chooses the size of its production attempt, z, to maximize its expected profit. Subsequently, the supplier delivers the production output $\rho^t z$, or the order quantity q, whichever is smaller, and receives a variable payment of $p \min(q, \rho z)$. The supplier's expected profit is

$$\pi^t(X, q, p) = \max_{z \geq 0}\{X - c^t z + pE\min(q, \rho^t z)\}. \tag{3}$$

When choosing the size of production attempt, z, the supplier trades off the cost of production, $c^t z$, against the expected variable payment, $pE\min(q, \rho^t z)$. Notice that the choice of z is independent of the fixed payment X, and, hence, the optimal z depends on q and p only (although X affects the supplier's participation decision). Let $z^t(q, p)$ denote the optimal size of the production attempt, given contract (X, q, p). Lemma 1 presents the optimal production size attempted by the supplier and optimal expected profit (proofs of this and all remaining results can be found in the online appendix, available at http://msom.journal.informs.org/). As the lemma shows, the supplier will produce the entire order quantity as long as its expected cost of successfully producing one unit, c^t/θ^t, is lower than the rate of the variable payment, p.

Lemma 1. *For a given contract (X, q, p), the supplier's optimal production size, $z^t(q, p)$, and expected profit, $\pi^t(X, q, p)$, are*

$$z^t(q, p) = \begin{cases} 0 & \text{if } p < c^t/\theta^t, \\ q & \text{otherwise;} \end{cases}$$
$$\pi^t(X, q, p) = \begin{cases} X & \text{if } p < c^t/\theta^t, \\ X - c^t q + \theta^t pq & \text{otherwise.} \end{cases} \tag{4}$$

In case $p < c^t/\theta^t$ of Lemma 1, the variable payment is lower than the expected cost of successfully producing one unit and the supplier makes no production attempt. As we will see later, this situation never arises under the buyer's optimal contract menu.

Lemma 1 shows that the supplier's expected profit is increasing in its reliability, θ^t. (In this paper, we use increasing and decreasing in the weak sense.) Thus, a high-type supplier earns a larger expected profit than a low-type supplier if both suppliers are offered the same contract. We define a high-type supplier's reliability advantage over a low-type supplier to be the difference between their optimal expected profits under the same contract.

Definition 1. Under contract (X, q, p), the supplier's reliability advantage for being of high type as opposed to low type is $\Gamma(q, p) \stackrel{\text{def}}{=} \pi^H(X, q, p) - \pi^L(X, q, p)$.

Notice that Γ is not a function of the fixed payment, X, because it cancels out in the calculation. Applying the expression for the supplier's optimal profit in Lemma 1 to the definition yields

$$\Gamma(q,p) = \begin{cases} 0 & p < c^H/h, \\ (hp - c^H)q & c^L/l > p \geq c^H/h, \\ [(h-l)p - (c^H - c^L)]q & p \geq c^L/l. \end{cases} \tag{5}$$

4. Competition, Diversification, and Optimal Sourcing

In this section, we study three sourcing strategies of the buyer under asymmetric information. We first analyze a model where the buyer is committed to the winner-take-all policy. We compare this model to the single-sourcing benchmark model, in which there is only one supplier in the supply base, and quantify the benefits of promoting competition between the two suppliers. We then analyze a model where the buyer is committed to ordering from both suppliers at the same time and quantify the diversification benefits. Finally, we analyze the optimal sourcing strategy and the value of the dual-sourcing option and prove that they can be understood as the buyer choosing between competition benefits and diversification benefits.

4.1. Single-Sourcing Benchmark Model

We first introduce the single-sourcing model in which the buyer has a single supplier in its supply base. We will use this model to benchmark the three sourcing strategies that we will discuss.

When there is a single supplier in the supply base, we replace the contract menu in the dual-sourcing model (2) with $(X, q, p)(t)$, $t \in \{H, L\}$, while retaining all other assumptions in (2). The buyer's contract design problem is represented by model (6):

$$\max_{\substack{(X,q,p)(H)\\(X,q,p)(L)}} \Bigg\{ \sum_{t\in\{H,L\}} \alpha^t \Big[rE\min\{D, \rho^t z^t[(q,p)(t)]\} - X(t) - p(t)E\min\{q(t), \rho^t z^t[(q,p)(t)]\} - K\mathbf{1}_{\{q(t)>0\}} \Big] \Bigg\}; \tag{6a}$$

subject to

$$\text{(I.C.)}\quad \pi^H(H) \ge \pi^H(L), \quad \pi^L(L) \ge \pi^L(H); \tag{6b}$$

$$\text{(I.R.)}\quad \pi^H(H) \ge 0, \quad \pi^L(L) \ge 0; \tag{6c}$$

$$q(t) \ge 0,\ p(t) \ge 0, \quad \text{for } t \in \{H, L\}.$$

The intuition for finding the optimal contracts under asymmetric information comes from the economics literature on contract design (see Laffont and Martimort 2002). Specifically, if the buyer's contract calls for an order with a low-type supplier, then the high-type supplier has an incentive to misrepresent its type. By doing so, the high-type supplier would receive the contract offered to the low-type supplier and collect the high type's reliability advantage (see Definition 1), which can be shown to be $h(c^L/l - c^H/h)D$ (we formally show this in the online appendix). To induce truthful reporting from a high-type supplier, the buyer would have to pay the high-type supplier an *incentive payment*, which matches the reliability advantage. This incentive payment is called the information cost, which can be shown to be

$$\Phi \stackrel{\text{def}}{=} \frac{\alpha^H}{\alpha^L} h\left(\frac{c^L}{l} - \frac{c^H}{h}\right)D. \tag{7}$$

As is standard in the information economics literature, although the high-type supplier receives the incentive payment, the information cost is attributed to a contract that orders from a low-type supplier, because by changing the contract with the low type, the buyer can alter the high-type's behavior.

To facilitate presentation of the optimal sourcing actions and the expected profit, we also define

$$\psi^t \stackrel{\text{def}}{=} (\theta^t r - c^t)D - K, \tag{8}$$

where $t \in \{H, L\}$, $\theta^H = h$ and $\theta^L = l$. Quantity ψ^t has an intuitive interpretation—it is the buyer's expected profit of ordering quantity D exclusively from a supplier known to be of type t.

Lemma 2 summarizes the buyer's optimal ordering decisions and profit under asymmetric information. The abbreviation "n.a." means "not applicable."

Lemma 2. *In the single-sourcing, asymmetric information model, the buyer's optimal contract menu is*

Case	*Order quantity*	*Variable payment*	*Fixed payment*
$\psi^L - \Phi \le 0$	$q(L) = 0$	$p(L)$ *is n.a.*	$X(L) = 0$
	$q(H) = D$	$p(H) = c^H/h$	$X(H) = 0$
$\psi^L - \Phi > 0$	$q(L) = D$	$p(L) = c^L/l$	$X(L) = 0$
	$q(H) = D$	$p(H) = c^L/l$	$X(H) = 0$

The buyer's expected profit is

$$\alpha^H \psi^H + \alpha^L(\psi^L - \Phi)^+. \tag{9}$$

4.2. Winner-Take-All Strategy and Competition Benefits

We now study the winner-take-all strategy, under which the buyer commits to ordering from only one of the two suppliers, and discuss competition benefits inherent in this strategy. In defining competition, we are guided by Moorthy (1985, p. 262): "The essence of competition is interdependence. Interdependence means that the consequences to a firm of taking an action depend not just on that firm's action, but also on what actions its competitors take." Although in classical Bertrand, Cournot, and Hotelling models firms compete by selecting prices, quantities, and product characteristics, other forms of actions can be used to compete. For instance, in our model (and in the majority of work on auctions), the suppliers compete by sending messages about their types. What message a supplier chooses to send depends on the other supplier's message.

To characterize competition benefits, we use the variant of the dual-sourcing model (2) in which the buyer is constrained to ordering from at most one supplier, i.e., $q_1(t_1, t_2)$ or $q_2(t_1, t_2) = 0$, for all t_1 and

$t_2 \in \{H, L\}$. We will call this variant of the dual-sourcing model the *competition* model. When the two suppliers are of the same reliability type, we assume without loss of generality that the buyer breaks ties in favor of awarding business to supplier 1. The following proposition presents the buyer's optimal sourcing actions and profit in the competition model.

Proposition 1. *The buyer's optimal contract terms in the competition model are as follows. For all (t_1, t_2), the fixed payments are $(X_1, X_2)(t_1, t_2) = (0, 0)$, and the order sizes and variable payments are*

Condition	$(q_1^*, q_2^*)(H, H)$	$(p_1^*, p_2^*)(H, H)$
$\psi^L - \Phi \le 0$ $\psi^L - \Phi > 0$	$(D, 0)$	$(c^H/h, n.a.)$

Condition	$(q_1^*, q_2^*)(H, L)$	$(p_1^*, p_2^*)(H, L)$
$\psi^L - \Phi \le 0$ $\psi^L - \Phi > 0$	$(D, 0)$	$(c^H/h, n.a.)$ $(c^L/l, n.a.)$

Condition	$(q_1^*, q_2^*)(L, H)$	$(p_1^*, p_2^*)(L, H)$
$\psi^L - \Phi \le 0$ $\psi^L - \Phi > 0$	$(0, D)$	$(n.a., c^H/h)$

Condition	$(q_1^*, q_2^*)(L, L)$	$(p_1^*, p_2^*)(L, L)$
$\psi^L - \Phi \le 0$	$(0, 0)$	$n.a.$
$\psi^L - \Phi > 0$	$(D, 0)$	$(c^L/l, n.a.)$

The buyer's optimal expected profit is

$$\alpha^H \psi^H + (\alpha^L \alpha^H)\psi^H + (\alpha^L \alpha^L)(\psi^L - \Phi)^+. \tag{10}$$

In Proposition 1, when the high type is drawn for supplier 1 (with probability α^H), the buyer orders from high-type supplier 1 regardless of the type of supplier 2, and makes profit ψ^H. When the low type is drawn for supplier 1 (with probability α^L) and the high type is drawn for supplier 2 (with probability α^H), the buyer orders only from high-type supplier 2, and makes profit ψ^H. When the low type is drawn for both suppliers, the buyer orders only from low-type supplier 1 if and only if its profit of doing so ψ^L exceeds the information cost Φ. In expectation, the buyer makes profit $(\alpha^L \alpha^L)(\psi^L - \Phi)$ whenever it is positive.

4.2.1. Competition Benefits. We are now ready to compare the competition model to the single-sourcing benchmark model to define and quantify the *competition* benefits. In the sequel, expanding the single-sourcing model to the dual-sourcing one, we treat the incumbent supplier as supplier 1 and the new supplier as supplier 2.

Definition 2. The expected competition benefit is the difference between the buyer's optimal expected profits in the competition model (10) and the single-sourcing model (9).

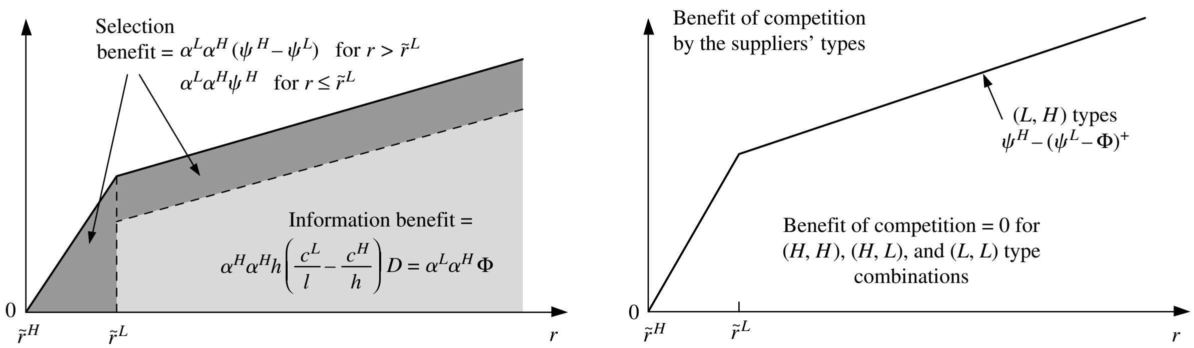
We compute this difference, obtaining

$$\begin{aligned}&[\alpha^H \psi^H + (\alpha^L \alpha^H)\psi^H + (\alpha^L \alpha^L)(\psi^L - \Phi)^+]\\ &\quad - [\alpha^H \psi^H + \alpha^L(\psi^L - \Phi)^+]\\ &= (\alpha^L \alpha^H)\psi^H - (\alpha^L \alpha^H)(\psi^L - \Phi)^+. \end{aligned} \tag{11}$$

The benefits of competition can be understood by using the left panel of Figure 2. The expressions of $\tilde{r}^H$, $\tilde{r}^L$ and other threshold values of r are presented in Table A.1 in the appendix. As the figure shows, these benefits comprise two components: selection benefit and information benefit.

First, consider the selection component. When r is sufficiently small ($r \le \tilde{r}^L$), the unit revenue does not justify the cost of ordering from a low-type supplier. Hence, in the single-sourcing model, the buyer makes no profit if the supplier turns out to be low type (which happens with probability α^L). In contrast, under the competition model, if the new supplier turns out to be high type (which happens with probability α^H), the buyer will select the high-type supplier

Figure 2 **Left Panel: The Buyer's Expected Benefit of Competition as a Function of the Revenue r; Right Panel: The Benefit of Competition by the Suppliers' Types**



and obtain a profit of ψ^H. Thus, the buyer enjoys an expected selection benefit of $\alpha^L\alpha^H\psi^H$. The same type of benefit occurs even when r is larger ($r > \tilde{r}^L$); the only difference is that now r is large enough for the buyer to order from the low-type supplier (earning an expected profit ψ^L), and so in this case the expected selection benefit is $\alpha^L\alpha^H(\psi^H - \psi^L)$.

Second, consider the information component. It arises when r is large ($r > \tilde{r}^L$) where the buyer finds it profitable to order from the low-type supplier. Knowing this, a high-type supplier in the single-sourcing model has an incentive to misrepresent itself, causing information cost Φ as discussed in §4.1. In the competition model, however, the presence of a new supplier removes the incumbent's incentive to misrepresent itself for fear of losing the order if the new supplier turns out to be high type. Because this competition component arises because of the contracts for the (L, H) type, the information benefit of competition is attributed to (L, H) types. Thus, both the selection and information components of competition benefits are attributed to the (L, H) contract.

4.3. Diversification Strategy and Diversification Benefits

In this section, we study another sourcing strategy: committing to ordering from both suppliers. Sourcing from several suppliers brings diversification benefits: reducing the probability of no supply by investing in multiple sources. The *diversification* model is the variant of the dual-sourcing model (2) that restricts the buyer to ordering from both suppliers, i.e., with additional constraint $q_1(t_1, t_2) = q_2(t_1, t_2) \geq D$, for all t_1 and $t_2 \in \{H, L\}$. The results in this paper hold with a more general model where the additional constraint is $q_1(t_1, t_2) = q_2(t_1, t_2) > 0$ instead, but the exposition becomes less transparent.

The buyer benefits by ordering from supplier 2 only if supplier 1 failed to deliver (with probability $1-\theta^{t_1}$) and supplier 2 succeeded (with probability θ^{t_2}). This benefit is given by

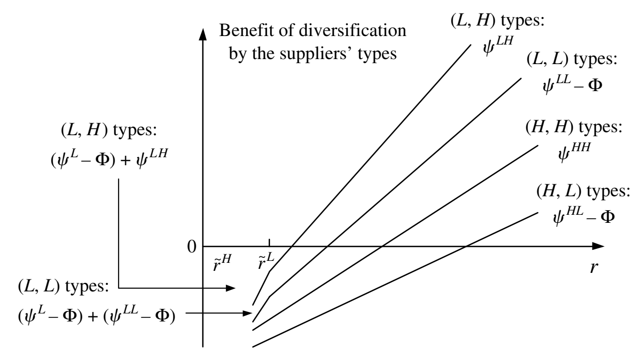
$$\psi^{t_1, t_2} \stackrel{\text{def}}{=} [\theta^{t_2}(1-\theta^{t_1})r - c^{t_2}]D - K. \tag{12}$$

Proposition 2. *The buyer's optimal contract terms in the diversification model are* $(X_1, X_2)(t_1, t_2) = (0, 0)$, $(q_1, q_2)(t_1, t_2) = (D, D)$, *and* $(p_1, p_2)(t_1, t_2) = (c^L/l, c^L/l)$, *for all* t_1 *and* $t_2 \in \{H, L\}$. *The buyer's expected profit is*

$$\alpha^H\alpha^H(\psi^H + \psi^{HH}) + \alpha^H\alpha^L[\psi^H + (\psi^{HL} - \Phi)] + \alpha^L\alpha^H[(\psi^L - \Phi) + \psi^{LH}] + \alpha^L\alpha^L[(\psi^L - \Phi) + (\psi^{LL} - \Phi)]. \tag{13}$$

The buyer's expected profit is the weighted sum of four cases, each corresponding to one of four combinations of the suppliers' types (t_1, t_2): (H, H), (H, L), (L, H), and (L, L). In each case, the buyer earns a profit from supplier 1, ψ^{t_1}, and an incremental profit from supplier 2, $\psi^{t_1 t_2}$, and pays information cost, Φ, when ordering units from low-type suppliers.

Figure 3 **The Buyer's Diversification Benefits by the Suppliers' Types**



4.3.1. Diversification Benefits.

We now characterize *diversification* benefits, by comparing the single-sourcing benchmark model in §4.1 with the diversification model.

Definition 3. The expected diversification benefit is the difference between the buyer's optimal expected profits in the diversification model (13) and the single-sourcing model (9).

This benefit is

$$(\alpha^H\alpha^H)\psi^{HH} + (\alpha^H\alpha^L)(\psi^{HL} - \Phi) + (\alpha^L\alpha^H)[\psi^{LH} - (\Phi - \psi^L)^+] + (\alpha^L\alpha^L)[(\psi^{LL} - \Phi) - (\Phi - \psi^L)^+]. \tag{14}$$

Figure 3 illustrates diversification benefits by supplier-type combination. When the unit revenue is sufficiently small, the additional supply security obtained through diversification is not worth the fixed cost of ordering from the second supplier. Hence, at small r values, the diversification benefits are negative. (Recall that in the diversification model the buyer diversifies with all type combinations regardless of the model parameters.) Once the revenue becomes sufficiently large, the diversification benefits turn positive. The diversification strategy is most attractive for a buyer who originally sourced from a low type who can then diversify by ordering from a high-type supplier. Symmetrically, the diversification strategy is the least attractive when the buyer originally sourced from a high-type supplier and the supplier it can diversify with is a low type.

4.4. The Buyer's Optimal Sourcing Strategy and Trade-offs

In §§4.2 and 4.3 the buyer made a blanket choice to follow either the winner-take-all strategy or diversification strategy. Now, we consider the most general contract, where the buyer does not commit to any given strategy a priori. What makes this problem challenging is that the buyer must determine its optimal contracting strategy while accounting for the fact that the suppliers' types are private and actions of each supplier depend on what it anticipates the other supplier will do. We solve the buyer's contract design problem (2), obtaining the following proposition:

Proposition 3. *The buyer's optimal order quantities, (q_1^*, q_2^*), under the four supplier-type combinations are as follows. When $(t_1, t_2) = (H, H)$, (H, L), or (L, L),*

$$(q_1^*, q_2^*)(t_1, t_2) = \begin{cases} (0, 0) & \text{if } \psi^{t_1} \le 0, \\ (D, 0) & \text{if } \psi^{t_1, t_2} \le 0 < \psi^{t_1}, \\ (D, D) & \text{if } \psi^{t_1, t_2} > 0; \end{cases} \tag{15}$$

when $(t_1, t_2) = (L, H)$,

$$(q_1^*, q_2^*)(t_1, t_2) = \begin{cases} (0, D) & \text{if } \psi^{HL} \le 0, \\ (D, D) & \text{otherwise}. \end{cases} \tag{16}$$

The optimal fixed payments are $X_n^*(t_1, t_2) = 0$ for $n \in \{1, 2\}$ and $t_1, t_2 \in \{H, L\}$. The optimal variable payments, $p_n^*(t_1, t_2)$, for $n \in \{1, 2\}$ and $t_1, t_2 \in \{H, L\}$, are

Condition	$(p_1^*, p_2^*)(H, H)$
$\psi^{HH} \le 0$	$(c^H/h, n.a.)$
$\psi^{HL} - \Phi \le 0 < \psi^{HH}$	$(c^H/h, c^H/h)$
$\psi^{HL} - \Phi > 0$	$(c^L/l, c^L/l)$
Condition	$(p_1^*, p_2^*)(H, L)$
$\psi^{L} - \Phi \le 0$	$(c^H/h, n.a.)$
$\psi^{HL} - \Phi \le 0 < \psi^{L} - \Phi$	$(c^L/l, n.a.)$
$\psi^{HL} - \Phi > 0$	$(c^L/l, c^L/l)$
Condition	$(p_1^*, p_2^*)(L, H)$
$\psi^{LL} - \Phi \le 0$	$(n.a., c^H/h)$
$\psi^{HL} - \Phi \le 0 < \psi^{LL} - \Phi$	$(n.a., c^L/l)$
$\psi^{HL} - \Phi > 0$	$(c^L/l, c^L/l)$.
Condition	$(p_1^*, p_2^*)(L, L)$
$\psi^{L} - \Phi \le 0$	$n.a.$
$\psi^{LL} - \Phi \le 0 < \psi^{L} - \Phi$	$(c^L/l, n.a.)$
$\psi^{LL} - \Phi > 0$	$(c^L/l, c^L/l)$

Without loss of optimality, we choose the optimal contract menu to be a dominant-strategy mechanism. The buyer's expected profit (before knowing supplier types) is

$$(\alpha^H)^2[\psi^H + (\psi^{HH})^+] + (\alpha^H\alpha^L + \alpha^L\alpha^H)[\psi^H + (\psi^{HL} - \Phi)^+] + (\alpha^L)^2[\psi^L + (\psi^{LL} - \Phi)^+]. \tag{17}$$

This is a complex problem with a complex solution where the buyer has to weigh interactions between four contract pairs because of interdependency across two suppliers and across two types. Fortunately, we come up with a convenient device that explains this contract menu as an economic trade-off between competition and diversification benefits (these benefits were derived in §§4.2 and 4.3). This is summarized in Proposition 4.

Proposition 4. *If for every type combination the buyer selects the greater between competition benefits and diversification benefits (see the left panel of Figure 4), then the buyer will be following the optimal policy given in Proposition 3.*

We can elucidate the buyer's decision even further by pointing out that the choice between competition and diversification abides by a threshold structure, as illustrated in the right panel of Figure 4, for the complex case of type combination (L, H). From the left panel, there exists a threshold, $\tilde{r}^{HL}$ (all threshold expressions are presented in Table A.1 in the appendix), such that for revenue, r, below the threshold, the benefit of competition is always greater than the benefit of diversification and the buyer chooses the winner-take-all strategy. The choices for the other three supplier-type combinations have similar threshold structures, such that for all r above the thresholds the buyer diversifies and for all r below the thresholds it follows the winner-take-all strategy.

Now that we understand how a buyer will strategically use its dual-sourcing option, we value the dual-sourcing option and show that it too can be understood through the prism of competition and diversification trade-offs. The following proposition computes the value of the dual-sourcing option using the values of the competition and diversification benefits.

Proposition 5. *The value of the dual-sourcing option is the difference between the buyer's optimal expected profits in the dual-sourcing model* (17) *and the single-sourcing model* (9), *and it equals*

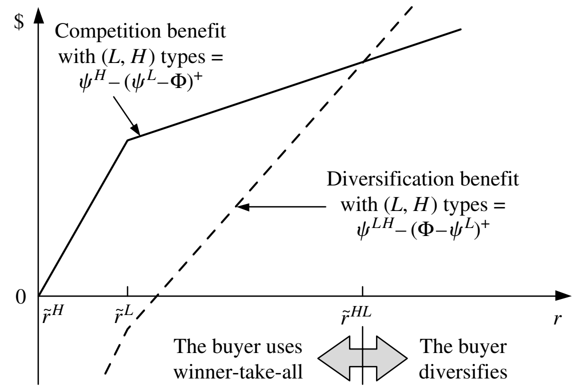
$$\tilde{O} = \alpha^H\alpha^H \cdot \tilde{O}^{HH} + \alpha^H\alpha^L \cdot \tilde{O}^{HL} + \alpha^L\alpha^H \cdot \tilde{O}^{LH} + \alpha^L\alpha^L \cdot \tilde{O}^{LL}, \tag{18}$$

where $\tilde{O}^{t_1t_2}$, $t_1, t_2 \in \{H, L\}$, is the greater of the corresponding competition benefits and diversification benefits (given in the left panel of Figure 4).

In Proposition 5, the value of the dual-sourcing option is divided into four parts, by supplier-type combination. For each combination, the value of the dual-sourcing option is derived either from competition benefits or from diversification benefits, whichever is larger, but not both. However, the total

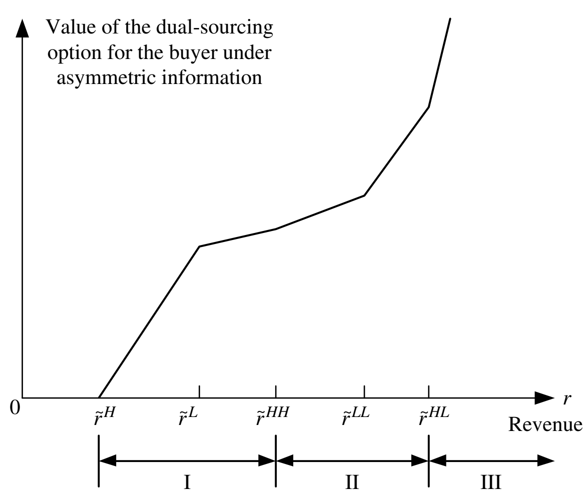
Figure 4 Left Panel: Summary of Competition and Diversification Benefits; Right Panel: Threshold Structure of Buyer's Choice, Illustrated for the (L, H) Type Combination

Suppliers' types	Competition benefits	Diversification benefits
(L, L)	0	$(\psi^{LL} - \Phi) - (\Phi - \psi^L)^+$
(L, H)	$\psi^H - (\psi^L - \Phi)^+$	$\psi^{LH} - (\Phi - \psi^L)^+$
(H, L)	0	$\psi^{HL} - \Phi$
(H, H)	0	ψ^{HH}



value of the dual-sourcing option, being the sum of these four parts, may contain both benefits simultaneously. This helps to explain how the value of the dual-sourcing option depends on the unit revenue, r, as illustrated in Figure 5. When the unit revenue is small, the benefit of diversification is negative under all type combinations, and the competition benefits are nonnegative (for any r). Therefore, the buyer sources from the more reliable of the two suppliers, and collects competition benefits (region I). As r increases, the benefits of diversification gradually increase and become positive for some type combinations, but do not exceed the competition benefits for type combinations (H, L) and (L, H). Thus, the buyer may diversify for type combinations (H, H) and (L, L), but still chooses competition for types (H, L) and (L, H) and the total value of the dual-sourcing option is a combination of these benefits (region II). Finally, as r becomes so large that diversification benefits with types (H, L) and (L, H) exceed competition benefits, the buyer diversifies under all supplier types (region III). Both benefits are increasing (nonstrictly) in r, and, therefore, overall the curve in Figure 5 is increasing.

Figure 5 Value of the Dual-Sourcing Option for the Buyer as a Function of Revenue r



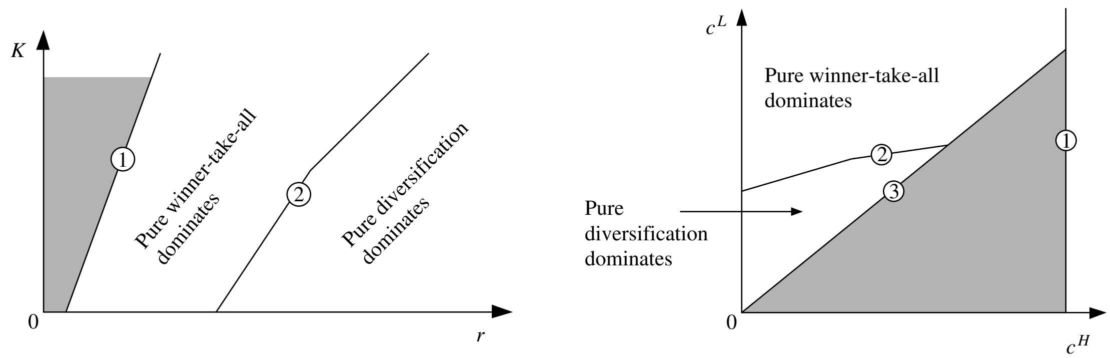
4.5. Comparison of the Three Models

In the previous section we saw that the optimal contract can be understood through the prism of competition and diversification benefits. This preference toward one or the other benefit depends on the type combination, for example, the buyer may use winner-take-all with (L, H) type combination and use diversification with (L, L) and (H, H) type combinations. This leads to a complex contract. The buyer might find it easier to design and implement a simpler contract where the buyer commits to pure winner-take-all or pure diversification. In this section we identify business environments (parameter values) for which committing to the pure winner-take-all or diversification strategies does not result in loss of optimality for the buyer.

We first compare the strategy of committing to pure winner-take-all with the strategy of committing to pure diversification. We find that if the buyer prefers pure diversification to pure winner-take-all, it continues to prefer diversification when (1) revenue, r, increases; (2) setup cost, K, decreases; (3) the high type's production cost, c^H, increases; and (4) the low type's production cost, c^L, decreases. These observations are illustrated on Figure 6 (the shaded areas correspond to the regions ruled out by the assumptions on the model parameters).

One might expect that as the suppliers' production becomes more costly, the buyer would prefer pure winner-take-all over pure diversification. This is indeed true when the suppliers' types are common knowledge. Furthermore, this observation holds when the suppliers' types are their private information and the low-type supplier's cost, c^L, increases. Interestingly, however, when the suppliers' types are

Figure 6 Comparison of the Pure Winner-Take-All and Pure Diversification Strategies, Illustrated on the (r, K) Plane (Left Panel) and on the (c^H, c^L) Plane (Right Panel)



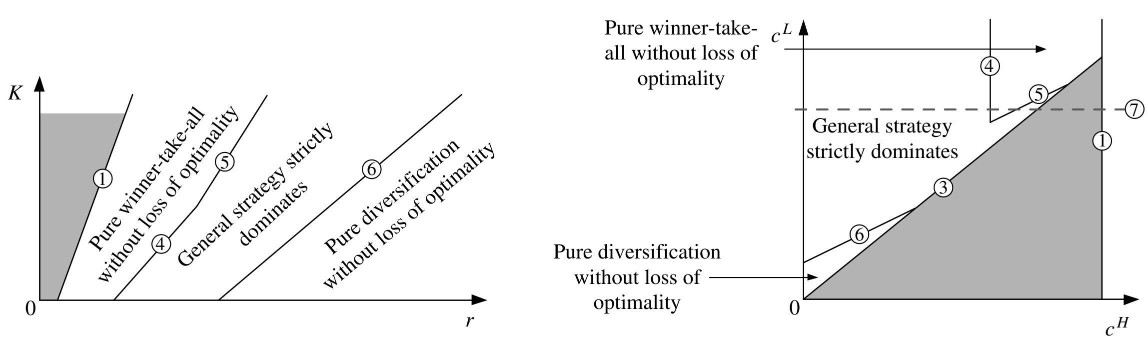
Note. Line (1): $\psi^H = 0$; line (2): $-\alpha^L\alpha^L(\Phi - \psi^L)^+ + \alpha^H\alpha^H\psi^{HH} + (\alpha^H\alpha^L + \alpha^L\alpha^H)(\psi^{HL} - \Phi) + \alpha^L\alpha^L(\psi^{LL} - \Phi) = 0$; line (3): $c^L/l - c^H/h = 0$.

their private information and the high type's cost, c^H, increases, the buyer may switch from the winner-take-all strategy to the diversification strategy. The key to this result is what happens to the information cost, Φ. When the high type's production cost increases the high type's reliability advantage decreases, reducing the buyer's information cost. The reduction in information cost shrinks the competition benefit, making the winner-take-all strategy less attractive. At the same time, the diversification benefits either remain the same or increase when the information cost decreases, thus making the diversification strategy more attractive.

Next, we add the optimal strategy to the comparison. The general optimal sourcing strategy in Proposition 3 (the general strategy) strictly dominates the strategies of committing purely to winner-take-all and committing purely to diversification when the revenue, r, is moderate relative to the setup cost, K. This observation is illustrated on the left panel of Figure 7.

We now analyze how the buyer's preference of sourcing strategy changes when the supplier's production costs, c^H and c^L, vary (see the right panel of Figure 7). In the lower-left corner, where both types' production costs are small, the pure diversification strategy coincides with the general strategy; in this region both suppliers are cheap enough and it is best to order from both of them no matter what their types are. Conversely, in the upper-right corner, the pure winner-take-all strategy is used without loss of optimality; in this region the suppliers are so expensive that it is never advantageous to order from both. In between the two corners, the general strategy is strictly better than the two pure strategies. Interestingly, there exists a range of c^L values such that as c^H increases the buyer may first completely forego diversification and then start diversifying again. One such c^L is indicated by line (7) on the right panel of Figure 7. At this c^L value, as the high type's cost c^H increases to surpass line (4), the buyer foregoes diversifying with the (H, H) supplier types, shifting to the pure winner-take-all strategy. As c^H continues to increase to surpass line (5), however, the buyer starts diversifying with the (L, L) type combination, reverting the buyer's preference strictly to the general strategy. The latter change occurs because as c^H increases, the high type's cost advantage decreases. This reduces the buyer's information cost of diversifying with type combination (L, L), pushing the diversification benefit with (L, L) to exceed the competition benefit. This switch back to the general strategy would never arise under symmetric information.

Figure 7 Comparison of the Three Sourcing Strategies, Illustrated on the (r, K) Plane (Left Panel) and on the (c^H, c^L) Plane (Right Panel)



Note. Lines (1)–(3) are defined in Figure 6; line (4): $\psi^{HH} = 0$; line (5): $\psi^{LL} - \Phi = 0$; line (6): $\psi^{HL} - \Phi = 0$.

5. Effect of Information

In practice, buyers can become better informed about suppliers (e.g., by undertaking audits). In this section we study the buyer's benefit from acquiring information about suppliers and the effect this information has on the buyer's optimal sourcing actions. We again explain changes in the sourcing actions through the prism of the competition and diversification benefits. We then analyze the effect of information on the value of the dual-sourcing option and the buyer's expected profit.

5.1. Optimal Contracts under Symmetric Information

To understand the effect of information, we solve a version of problem (2) in which suppliers' reliabilities are common knowledge. We refer to this version as the symmetric information model.

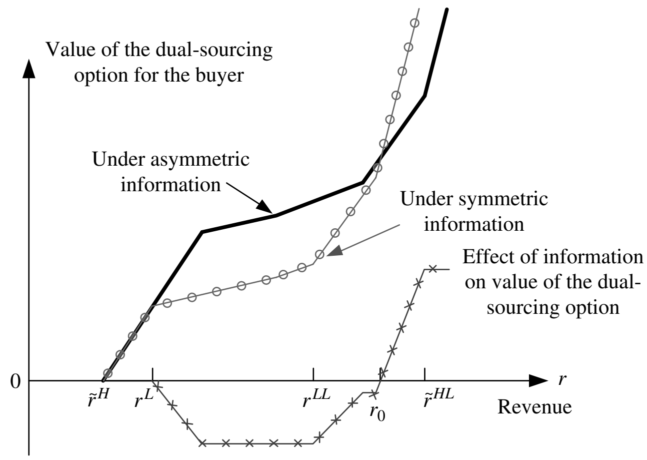
Similar to the asymmetric information model (§4), we derive competition and diversification benefits. When supplier reliabilities are common knowledge, the information cost, Φ, disappears from the problem and, therefore, the expressions for the competition and diversification benefits are obtained from the left panel of Figure 4 by setting $\Phi = 0$. With information, the competition benefits decrease and diversification benefits increase. Parallel to the analysis under asymmetric information (Proposition 4), the buyer's optimal sourcing action under symmetric information can be explained as the choice between competition and diversification benefits. Because the diversification benefits increase and the competition benefits decrease with information, under symmetric information the buyer is more likely to choose to diversify.

With diversification used more, we conclude that the total quantity received by the buyer from the two suppliers under symmetric information first-order stochastically dominates the quantity received under asymmetric information, and the buyer is more likely to meet its customers' demand.

5.2. Effect of Information on the Dual-Sourcing Option

In Proposition 5, we explained the value of the dual sourcing option as the trade-off between competition and diversification benefits. In §5.1 we demonstrated information effects on each benefit. Combining the two, we examine the effect of information on the value of the dual sourcing option. Intuitively, one may expect that information should increase the dual-sourcing option value because the buyer can identify the suppliers' types and exercise the option better. However, we show that information reduces the value of the dual-sourcing option when revenue, r, is small, but increases the value of the dual-sourcing option when revenue, r, is large (as shown in Figure 8; the existence of the threshold r_0 is proved in Proposition 8 in the online appendix). Thus, information and the dual-sourcing option are substitutes when the revenue is small and are complements when the revenue is large.

Figure 8 **Values of the Dual-Sourcing Option for the Buyer Under Symmetric and Asymmetric Information**



In Figure 8 at low r values, where competition benefits significantly outweigh diversification benefits, the dual-sourcing option is exercised to promote competition. In that region, the value of the dual-sourcing option decreases in information because information reduces competition benefits. Conversely, at high r values, the dual-sourcing option is exercised to diversify. In that region, the value of the dual-sourcing option increases in information because information increases diversification benefits.

5.2.1. Sensitivity to Supply-Base Reliability and Information. A worsening of reliability in the supply base may have different effects on the use of diversification under symmetric and asymmetric information. One may intuitively expect that whenever the supply base becomes less reliable, the buyer will find it more attractive to diversify. Indeed, with symmetric information the buyer may start diversifying when the supply base becomes less reliable, and will never stop diversifying. However, under asymmetric information, the opposite may be true: under certain parameter values (see Corollary 10 in Yang 2009), a worsening of reliability causes the buyer to stop diversifying under asymmetric information for (H, L) and (L, H) supplier-type combinations. The explanation of this result lies in high-type suppliers' incentives to misrepresent themselves. When both supplier types are sufficiently unreliable, a further reduction in their reliabilities leads to an increase in a high-type supplier's reliability advantage, which in turn translates into a larger incentive payment from the buyer. Thus, even though a worsening of the supply base reliability makes diversifying attractive as it would increase the chance of meeting the demand, the buyer prefers using the winner-take-all strategy, so that competition can curtail large incentive payments.

5.3. Value of Information

From the definition of the dual-sourcing option, the value of information for the buyer equals the value of information in the single-sourcing model plus the effect of information on the dual-sourcing option value. These values of information under symmetric and asymmetric information are presented in Lemma 3 in the appendix.

5.3.1. Sensitivity of the Buyer's Value of Information to Reliability Gap, $h-l$. One may expect that the buyer's value of information increases if the reliability gap between the two supplier-types expands, because the buyer would be more eager to distinguish between the types. However, we find that the opposite may happen.

Proposition 6. *Suppose that the low-type's reliability, l, is fixed. If $\max\{r^{HL}, \tilde{r}^{LL}, c^L/l^2\} < r \le \tilde{r}^{HL}$, then the buyer's value of information is decreasing in h.*

As the reliability, h, of the high-type supplier increases, the buyer does not care as much about diversification and is content to source only from the high-type supplier when facing an (H, L) pair. This imparts competition benefits and makes information less valuable. Thus, even as an increase in h widens the reliability gap between the high and low types $h-l$, meaning there is seemingly more gleaned by learning a supplier's true type, information may, surprisingly, become less valuable.

6. Codependent Supplier Production Disruptions

Thus far we assumed that the two suppliers' production disruption processes are independent. In practice, they can be correlated because of common infrastructure, geographic proximity, similar production technologies, overlapping supply bases, and other factors. In this section we extend our model and analysis to capture codependence between the two suppliers' disruption processes.

We capture codependence between the two suppliers' disruption processes by allowing the Bernoulli yield random variables of the two suppliers to be statistically dependent. If the two suppliers are of reliability types, $t_1, t_2 \in \{H, L\}$, we may represent codependence between their disruption processes via a joint probability matrix (a similar model was used in Babich et al. 2007):

$$\Omega^{t_1, t_2} \stackrel{\text{def}}{=} \begin{bmatrix} \omega^{t_1, t_2}(1,1) & \omega^{t_1, t_2}(1,0) \\ \omega^{t_1, t_2}(0,1) & \omega^{t_1, t_2}(0,0) \end{bmatrix}, \qquad (19)$$

where $\omega^{t_1, t_2}(x_1, x_2) = P\{\rho_1^{t_1} = x_1, \rho_2^{t_2} = x_2\}$, $x_1, x_2 \in \{0, 1\}$, is the joint probability that the yield rates of the two suppliers' production attempts are x_1 and x_2, respectively. We choose the two suppliers' joint success probability, $\omega^{t_1, t_2}(1,1)$, to be the indicator of the level of codependence between the two suppliers' disruption processes. The larger $\omega^{t_1, t_2}(1,1)$, the greater the codependence.

To obtain an analytical solution, we assume that $\omega^{HL}(1,1)/l > \omega^{HH}(1,1)/h$. This assumption is equivalent to the following restriction on the conditional probability of high-type supplier 1 producing successfully, given that supplier 2 produced successfully: $P\{\rho_1^H = 1 \mid \rho_2^L = 1\} > P\{\rho_1^H = 1 \mid \rho_2^H = 1\}$. In words, high-type supplier 1's probability of successful production conditional on supplier 2 producing successfully is decreasing in supplier 2's reliability. For example, consider a situation where the two suppliers are located in the same region and share an unreliable infrastructure and where a supplier's reliability increases in its experience of working with this infrastructure. Production success of an inexperienced supplier 2 provides a stronger signal than success of an experienced supplier 2 regarding the chance that the other supplier (supplier 1) will succeed as well.

Proposition 7. *For codependent disruption processes, the buyer's optimal contract menu and expected profit under asymmetric information are given in Proposition 3, with ψ^{t_1, t_2} redefined as $\psi^{t_1, t_2} \stackrel{\text{def}}{=} \{[\theta^{t_2} - \omega^{t_1, t_2}(1,1)]r - c^{t_2}\} \cdot D - K$ for $t_1, t_2 \in \{H, L\}$.*

To model an increase in codependence, we increase at least one of the three joint success probabilities, $\omega^{HH}(1,1)$, $\omega^{HL}(1,1)$ and $\omega^{LL}(1,1)$, by a small amount, keeping the others fixed.

6.1. Effects of Codependence on Sourcing

Because in the competition model (see §4.2) the buyer works with a single supplier, codependence does not affect the corresponding benefits. For the diversification benefits, to incorporate codependence, we need to replace $(1-h)h$, $(1-h)l$, $(1-l)h$ and $(1-l)l$ in expressions (14) with $h-\omega^{HH}(1,1)$, $l-\omega^{HL}(1,1)$, $h-\omega^{HL}(1,1)$ and $l-\omega^{LL}(1,1)$, respectively. Consistent with intuition, the diversification benefits decrease with codependence. This applies to both asymmetric and symmetric information models. Therefore, the dual-sourcing option value, derived from these two benefits, decreases with codependence. Consequently, the buyer's expected profit (17) decreases. Because diversification benefits decrease, the buyer is more inclined to choose competition benefits when deciding its actions (Proposition 4). Thus, as codependence increases, the buyer will rely more on the winner-take-all strategy.

6.2. Information and Codependence

Interestingly, the buyer's profit under asymmetric information is less sensitive to an increase in codependence than under symmetric information. As greater codependence pushes the buyer away from diversification toward competition, it receives competition benefits that compensate for lost diversification benefits. This compensation is larger under asymmetric information because (as we have shown in §5) the competition benefits are larger under asymmetric information. Considering the value of information, as codependence decreases, the value of information increases. Consequently, reducing codependence is not a substitute for better information. Conversely, better information about suppliers' reliabilities is not a substitute to taking strategic actions to reduce codependence between supplier disruptions (e.g., sourcing from different geographic regions).

7. Concluding Remarks

Supply disruptions cause significant losses in shareholders' value (Hendricks and Singhal 2003). A common operational tool for controlling supply disruption risks is placing orders with several suppliers (diversification), so that if one of the suppliers experiences a problem, others might still deliver parts to the buyer. Working with several suppliers is administratively expensive, and managers must carefully weigh the benefits of diversification against its costs. However, in this paper we show that the decision to diversify involves considerations beyond simply weighing fixed costs of working with extra suppliers against potential benefits of avoiding losses due to disruptions.

To appreciate these additional considerations we first observe that the suppliers are frequently better informed than the buyer about the likelihood of disruptions. In the presence of this private information, we point out that a dual-sourcing option (the option of the buyer to order from more than one supplier) has several benefits, with the risk reduction due to diversification being just one of them. The other important benefits (which we collectively call competition benefits) are the buyer's ability to select the better of the two suppliers, and the reduction in informational rent payments to the suppliers. If the buyer commits to ordering from only one of the two suppliers, diversification benefits are lost, but the buyer enjoys the selection and rent reduction benefits of competition. Thus, under asymmetric information the buyer is more willing to forgo diversification in order to enjoy the competition benefits. If the buyer orders from both suppliers (i.e., diversifies) then it loses competition benefits, and one can view the loss of competition benefits as additional diversification costs under asymmetric information. We find that, surprisingly, these additional costs may cause the buyer to cease diversifying even as the supply base reliability erodes, which would never happen under symmetric information.

Diversification is still used by the buyer even under asymmetric information, but only if the buyer's recourse cost for not meeting demand is very high. Because diversification comes at a high price (loss of competition), buyers that choose to diversify have a strong incentive to learn about suppliers' reliabilities, for example, by forming long-term relationships with suppliers, auditing supplier factories, etc. In contrast, when costs of disruptions are low and consequently the buyer orders from only one supplier, competition between suppliers is very effective in curtailing informational rents and the buyer would not gain much by knowing everything the suppliers know. Thus, in such cases, arm's-length relationships between the buyer and the suppliers are more tenable.

Introducing codependence between supplier disruptions does not alter any of the above insights, but adds new findings. Greater supplier codependence reduces the buyer's diversification benefits, and pushes the buyer to use more competition. In fact, greater codependence reduces the suppliers' incentives to misrepresent their reliabilities and reduces the value of information for the buyer. Hence, strategic actions to reduce supplier codependence (such as choosing suppliers from different regions) should not be seen as a substitute for learning suppliers' reliabilities.

To spotlight the main features of our model we omitted both salvage value and disposal costs for the buyer. It is straightforward to see that incorporating a salvage value would make diversification more attractive. Because, as we already discussed, the value of information about suppliers' reliabilities increases in the buyer's propensity to diversify, a larger salvage value translates into a larger value of information. Analogously, because disposal costs discourage diversification, information about reliabilities becomes less valuable in the presence of disposal costs.

We believe that if we extend our analysis to include multisourcing, the informational and selection benefits of competition and the benefits of diversification will continue to shape the solution of the buyer's problem. In fact, our insights suggest that with more suppliers competition effects will intensify and the buyer will rely more on competition and less on diversification. However, there will be many more combinations of suppliers that are candidates for receiving an order, complicating the analysis.

In our model each supplier can be one of two possible types, and the buyer's demand is known at the time it places its order. Although we suspect that having more than two supplier types or modeling random demand would leave the spirit of our insights unchanged, the analysis would become substantially more complex. In particular, the monotonicity condition, which enables the incentive compatibility conditions to be verified, might be violated, making the derivation of the optimal contract very cumbersome.

We consider suppliers having all-or-nothing yield. The analytical tractability afforded by all-or-nothing yield allows us to derive closed-form expressions for the optimal contract, which then enables further analysis. We expect that more general risk models would lead to similar insights, but one might have to arrive at those insights without the benefit of explicit knowledge of the optimal contract terms.

In our model, the high-type supplier was assumed to have a lower expected cost of successfully producing one unit, $c^H/h < c^L/l$. There could be settings where the cost relationship is reversed, namely, the low-type supplier has a lower cost of successfully producing one good unit. If $c^L/l \le c^H/h < (1-l)/(1-h)c^L/l$, the monotonicity condition again might be violated, making the derivation of the optimal contract difficult. However, if $c^H/h \ge (1-l)/(1-h)c^L/l$, our analysis carries through by reversing the labels "high" and "low." This makes $l > h$, but interprets the high type supplier as again being the supplier with the lower expected cost of successfully producing one unit.

We allowed cost to be a function of reliability, to capture situations where, for example, greater reliability is associated with higher cost. However, suppose instead that cost is independent of reliability and supplier 1's cost is known to be c_1 and supplier 2's cost is known to be c_2, regardless of their reliabilities. If one sets $c_1 = c_2$, this is equivalent to setting $c^H = c^L$ in our model and all of our results are unchanged. If $c_1 < c_2$, but not by much, our analysis can be extended and the results remain intact. On the other hand, if c_1 is well below c_2, the buyer prefers to procure from supplier 1 regardless of supplier 2's reliability and hence does not enjoy competition benefits. Therefore, adding a very expensive supplier to the supply base provides diversification benefits only.

In our model the buyer collects revenue r per unit sold to the end consumer, but the parameter r admits other interpretations (as mentioned in §3). We could envision a buyer who can count on a spot market (with stochastic price) to meet end-customer demand when the suppliers fail, where r becomes the buyer's expected cost of procuring one unit from the spot market. The buyer's objective would be to minimize its expected total cost (instead of maximizing expected profit) and all our results go through without any changes. For a recent paper that emphasizes the use of spot markets in the presence of supply disruptions, see Gümüş et al. (2012).

In future work, it could be interesting to consider the effects of supplier collusion on the contract design and the value of the dual-sourcing option. Colluding suppliers could agree to misreport their types to the buyer, receive higher payments, and then split the resulting benefits. Therefore, we expect that supplier competition will be weakened in the presence of supplier collusion, pushing the buyer toward diversification. At the same time, informational rents could be significantly higher if the buyer diversifies, pushing the buyer away from diversification. Therefore, it is difficult to say, a priori, if collusion will encourage or discourage diversification. Future research could also study a risk-averse buyer, making objective function (2a) an argument of a nonlinear utility function. Intuitively, risk aversion may enhance the benefit of diversification relative to competition, which, as the results of this paper suggest, would make information about suppliers' reliability more valuable.

Electronic Companion

An electronic companion to this paper is available as part of the online version that can be found at http://msom.journal.informs.org/.

Appendix. Table for Propositions and Technical Lemma

Table A.1 Expressions for Thresholds $\tilde{r}^t$ and $\tilde{r}^{t_1,t_2}$ Under Asymmetric Information, and r^t and r^{t_1,t_2} Under Symmetric Information

$\tilde{r}^t$ and $\tilde{r}^{t_1,t_2}$ (asymmetric information)	r^t and r^{t_1,t_2} (symmetric information)
$\tilde{r}^H = \dfrac{c^H}{h} + \dfrac{K}{hD}$	$r^H = \tilde{r}^H$
$\tilde{r}^L = \dfrac{c^L}{l} + \dfrac{K}{lD} + \dfrac{\Phi}{l}$	$r^L = \tilde{r}^L - \frac{\Phi}{l}$
$\tilde{r}^{HH} = \dfrac{c^H}{h(1-h)} + \dfrac{K}{h(1-h)D}$	$r^{HH} = \tilde{r}^{HH}$
$\tilde{r}^{HL} = \dfrac{c^L}{l(1-h)} + \dfrac{K}{l(1-h)D} + \dfrac{\Phi}{l(1-h)}$	$r^{HL} = \tilde{r}^{HL} - \dfrac{\Phi}{l(1-h)}$
$\tilde{r}^{LH} = \dfrac{c^H}{h(1-l)} + \dfrac{K}{h(1-l)D}$	$r^{LH} = \tilde{r}^{LH}$
$\tilde{r}^{LL} = \dfrac{c^L}{l(1-l)} + \dfrac{K}{l(1-l)D} + \dfrac{\Phi}{l(1-l)}$	$\tilde{r}^{LL} = r^{LL} - \dfrac{\Phi}{l(1-l)}$

Note. $\tilde{r}^t$ is the r value that makes $\tilde{\psi}^t = 0$, and $\tilde{r}^{t_1,t_2}$ is the r value that makes $\tilde{\psi}^{t_1,t_2} = 0$; r^t and r^{t_1,t_2} are defined similarly.

Technical Lemma

Lemma 3. *In the single-sourcing model, value of information for the buyer is*

$$\begin{cases} \alpha^L \psi^L & \text{if } \psi^L - \Phi \le 0 < \psi^L, \\ \alpha^L \Phi & \text{otherwise.} \end{cases} \tag{20}$$

In the dual-sourcing model, value of information for the buyer is

$$\alpha^H(\gamma_1+\gamma_2)+[2(\alpha^H\alpha^L)\delta^{HL}+(\alpha^L)^2(\delta^L+\delta^{LL})], \qquad (21)$$

where the expressions for γ_1, γ_2, δ^{HL}, and δ^{LL} are as follows:

Condition	γ_1	γ_2
$\psi^L-\Phi\le 0$	0	0
$\psi^{LL}-\Phi\le 0<\psi^L-\Phi$	$((\alpha^L)^2/\alpha^H)\Phi$	0
$\psi^{HL}-\Phi\le 0<\psi^{LL}-\Phi$	$((\alpha^L)^2/\alpha^H)\Phi$	$((\alpha^L)^2/\alpha^H)\Phi$
$\psi^{HL}-\Phi>0$	$(\alpha^L/\alpha^H)\Phi$	$(\alpha^L/\alpha^H)\Phi$

$$\delta^{HL}=\begin{cases}\psi^{HL} & \text{if } \psi^{HL}-\Phi\le 0<\psi^{HL},\\ 0 & \text{otherwise};\end{cases}$$

$$\delta^{L}=\begin{cases}\psi^{L} & \text{if } \psi^{L}-\Phi\le 0<\psi^{L},\\ 0 & \text{otherwise};\end{cases}$$

$$\delta^{LL}=\begin{cases}\psi^{LL} & \text{if } \psi^{LL}-\Phi\le 0<\psi^{LL},\\ 0 & \text{otherwise}.\end{cases}$$

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