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Does a Procurement Service Provider Generate Value for the Buyer Through Information About Supply Risks?

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We consider a supply chain with one buyer and two suppliers who are subject to disruptions and whose likelihoods of disruption are their private information. In such a setting, does the buyer benefit from engaging the services of a better-informed procurement service provider (PSP) compared to procuring directly from the suppliers? Intuition might suggest that hiring a PSP is always the right choice because the PSP's knowledge of the supply base improves supplier selection and management. On the other hand, earlier studies prove that using a PSP purely for its superior knowledge about supply costs is always worse for a buyer than contracting with the suppliers directly. Our answer to this research question is more nuanced. Contrary to the findings of earlier studies, we find that the buyer may benefit from using a PSP. We identify, quantify, and explain all of the benefits and the costs of using a PSP, and describe conditions under which the benefits exceed the costs. The benefits of using a PSP are derived when one supplier is of high reliability and the other is of low reliability, from a reduction of informational costs due to implicit supplier collusion facilitated by the PSP and an improvement of supply availability. The costs of using a PSP are derived when both suppliers are of low reliability, from the loss of direct control over the supplier's production actions, which leads to reduced supply availability and increased informational costs, and from the PSP facilitating implicit supplier collusion. Comparative statics analysis indicates that using the PSP is valuable only if the buyer diversifies with some supplier-type combinations but not others, and that hiring a PSP is not a solution to the problem of an unreliable supply base.

Keywords: supply disruption; sourcing intermediation; mechanism design; supply diversification; information asymmetry
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1. Introduction

1.1. Research Problem

We investigate whether or not a buyer, worried about supply risk, benefits from engaging the services of an intermediary firm—a procurement service provider (PSP)—due to its better information about supply risk, compared to procuring directly from the suppliers. A procurement service provider is defined as "a third party organization or consultant which is used to supplement internal procurement departments."[1] A PSP assists in tasks such as "strategic planning, implementing best practices, supplier rationalization, supplier collaboration, strategic sourcing and negotiation." PSP services are popular, and examples of procurement service providers include Li&Fung, Procurian, GEP, IBM, Accenture, and Xerox. PSPs bring many benefits. (Wu 2004 offers a classification of procurement intermediation benefits.) However, we focus on informational benefits and costs and their interplay with supply risk management.

In the UK clothing industry, for example, information asymmetry between buyers and international suppliers causes high informational costs in direct trades. To improve efficiency, buyers engage sourcing intermediaries (PSPs) with better knowledge about the supply market. Popp (2000) reports that, for UK clothing firms that purchase from the Turkish supply market, "a lack of transparency made it non-viable when attempting to trade direct" (p. 158). To address the problem, UK clothing firms engage PSPs because the "linguistic and cultural affinity between contractors and intermediary, and co-location, lower the intermediary's informational costs" (p. 158).

PSPs can also manage supply risk for the buyer. Vedel and Ellegaard (2013) observe from the clothing industry that "risk taking has always been a defining element of the services of global sourcing intermediaries, who profit by reducing the risks for buyers and suppliers ..." (p. 511). More importantly, in doing

[1] See http://www.procurementserviceprovider.com/procurement_service_provider.html (accessed September 17, 2014).

so, PSPs leverage their superior knowledge about the supply risk. As Vedel and Ellegaard (2013, p. 511) elaborate, "sourcing intermediaries specialize in entering and cultivating these immature markets, where uncertainty is extremely high.... Having established a presence at a new supply market, the intermediary can utilize the acquired knowledge to serve new customers in finding and selecting suppliers."

From these examples, an immediate intuitive answer to our research question might appear to be "yes, the buyer benefits from using a PSP with better information." Armed with better knowledge about the supply base (e.g., suppliers' costs, capabilities, quality, and reliabilities), a PSP should be able to execute procurement better, selecting the right suppliers and reducing the informational costs of procurement. Access to better information is a part of the overall "value proposition" that PSPs advertise to potential clients (buyers).

However, on reflection, another intuitive answer to our research question is "no, the buyer does not benefit from using a PSP with better information." It is not obvious that PSPs will share the benefits of better information with the buyer. In fact, when using a PSP, the buyer adds another layer to its supply chain, loosening control of the suppliers and exacerbating double marginalization. The buyer relinquishes direct control over procurement and supply risk management, and cannot guarantee that the PSP will act in the buyer's best interest.

Prior work in economics on intermediation supports the "no" answer. For instance, Mookherjee and Tsumagari (2004, p. 1194) prove in their Proposition 5(i) that, when the PSP has an informational advantage over the buyer with respect to the supplier's production costs for substitutable products, the buyer will always be better off contracting with the suppliers directly. This is a surprising result in light of the popularity of PSP services in practice. It means that the popularity of the procurement outsourcing cannot be explained by informational benefits alone, so the value of the procurement outsourcing must come from transactional or other benefits (e.g., economies of scale, reduced logistics costs, and access to a larger supplier pool).

Our analysis shows that the answer to the question on whether a buyer enjoys a benefit from using a PSP because of the informational benefits is "maybe." Furthermore, we can explain how the benefits of using a PSP are derived and what costs may counterbalance the benefits. Unlike Mookherjee and Tsumagari (2004) and most other papers on intermediation that emphasize supply costs, we focus on supply risk and asymmetric information about supply risk. Similar to Mookherjee and Tsumagari (2004), we disregard the transactional benefits of using a PSP because the effects of these benefits are predictable. In our model (§2), the suppliers are unreliable. To derive insights, we assume the suppliers' production outcomes are Bernoulli random variables. The Bernoulli yield model is appropriate for modeling supply disruption, but not for other forms of supply uncertainty. (See §7 for additional discussion of model limitations and their consequences.) The suppliers possess private information about their own reliabilities. The PSP has access to the suppliers' private information, but the buyer does not. Methodologically, we solve a mechanism design problem in which an agent (the PSP) has two dimensions of private information about supply risk (§3). We focus on a simple form of mechanism that extends the one used in Mookherjee and Tsumagari (2004) (i.e., payment and order quantity) to the setting with supply-side risk by adding a penalty on nondelivery. In general, mechanism design problems with multidimensional private information are difficult to solve. However, we are able to derive the optimal procurement contracts for the buyer and the corresponding decisions of the PSP and the suppliers. We contrast these results with the optimal procurement policies in the benchmark model of direct procurement (§4).

In doing so, we derive a number of interesting and practical results. First, contrary to the results in Proposition 5(i) of Mookherjee and Tsumagari (2004), there are situations in which the value of using a PSP is positive for the buyer (§5). Second, to explain this observation we decompose the buyer's value of using a PSP by the combination of the suppliers' reliability types and offer economic insights into the forces acting on the value. We explain that the positive value of using a PSP is derived from a reduction of the informational costs for using the risk management tool of order diversification, due to implicit supplier collusion enabled by the PSP, and from an improvement of the supply availability, due to better execution of order diversification by the PSP. Supply risk, which is absent in Mookherjee and Tsumagari (2004), along with its interplay with information and intermediation, is the key driver for our finding of the positive value of using a PSP. We quantify the negative value of using a PSP and show that it comes from the loss of direct control of the supplier's production actions, from the PSP facilitating implicit supplier collusion, and from reduced supply availability in some cases. Interestingly, implicit supplier collusion under PSP procurement may affect the buyer not only negatively, but also positively. The explanations of various costs and benefits constituting the net value of using a PSP are novel and practically important. Third, by finding opposite results to Mookherjee and Tsumagari (2004), we highlight the importance of supply risk management and the interplay between contracting, asymmetric information, and risk management.

Comparative statics analysis (§6) offers several managerially important observations on the value of using a PSP. We prove that the value of using a PSP is always negative if the disruption cost is too small or too large, when the buyer will either never diversify or always diversify regardless of the procurement model. Interestingly, we show that the positive PSP value can arise only if the buyer diversifies in one and sole sources in the other procurement model. Numerical analysis indicate that, to derive positive PSP benefits, the fraction of reliable suppliers in the economy should be high, and as that fraction increases, the value of using a PSP can either increase or decrease. Therefore, an unreliable supply base is not a sufficient reason to hire a PSP. Similarly, as the gap between reliabilities increases, the value of using a PSP may decrease, contrary to the a priori intuition. We summarize these managerial insights and conclude in §7.

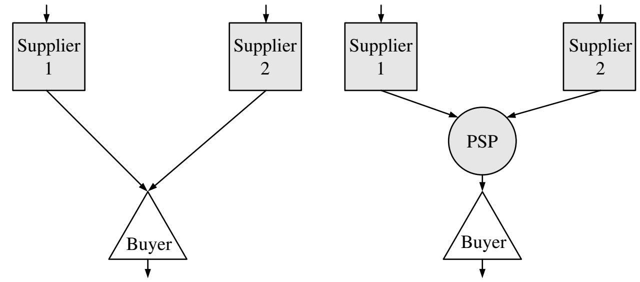
1.2. Literature Review

Our work builds on the research in operations management on the use of procurement intermediation. In this literature, Wu (2004) presents bargaining frameworks with complete and incomplete information for modeling supply chain intermediation and reviews various benefits that intermediation generates. In particular, Wu (2004) classifies benefits into transactional and informational. Belavina and Girotra (2012) show that, beyond transactional and informational benefits, there is also a relational benefit of intermediation. Belavina and Girotra (2012) use the framework of relational contracts to show how a PSP can influence the behaviors of both suppliers and buyers with an implicit promise of future business. Adida et al. (2012) study a model of competing PSPs and retailers and observe that using PSPs can be valuable when supply risk is present. However, their paper focuses on competition between PSPs, and in their model, the suppliers have private information about supply costs, but not supply risk.

Our work is relevant to the literature in economics that studies intermediation in the presence of information asymmetry between the buyer and the supplier (e.g., Biglaiser 1993, Gilbert and Riordan 1995, McAfee and McMillan 1995, Baron and Besanko 1999, Faure-Grimaud and Martimort 2001, Mookherjee and Tsumagari 2004). The paper that is closest to our work is Mookherjee and Tsumagari (2004). Similar to most of these papers (except Biglaiser 1993), our approach is also that of mechanism design. But, unlike these papers, we study the PSP's informational advantage over the buyer with respect to the likelihood of the suppliers' disruption.

For a benchmark model where the buyer directly contracts with the suppliers, we rely on the results derived by Yang et al. (2012). Other papers that consider asymmetric information about supply risk are Yang et al. (2009), Chaturvedi and Martínez-de Albéniz (2011), and Gümüş et al. (2012). However, these papers do not study the use of procurement service providers.

Figure 1 **Procurement Models: Direct Procurement (Left) and PSP Procurement (Right)**



These papers, together with our work, belong to the research area of decentralized supply risk management. A review of this research area is available in Aydin et al. (2012).

2. The General Model Setting

In this paper, we shall compare two procurement models: direct procurement and PSP procurement (see Figure 1). As the name implies, under direct procurement, the buyer contracts directly with the suppliers; under PSP procurement, the buyer contracts with a PSP, who then contracts with the suppliers.[2] To highlight the effect of supply risk on the buyer's value of using the PSP and the interaction between supply risk and intermediation under asymmetric information, we make our models align with the models in Mookherjee and Tsumagari (2004) (those without direct supplier collusion), except that in our models asymmetric information is about supply risk, but not supply cost. Our direct-procurement model corresponds to the C (i.e., centralization without supplier collusion) model of Mookherjee and Tsumagari (2004), and our PSP-procurement model corresponds to the DM (i.e., delegation to a perfectly informed middleman) model of Mookherjee and Tsumagari (2004).

The direct- and PSP-procurement models share many modeling assumptions, as follows. We shall introduce the model-specific setting for the two models in §§3 and 4. Both models are of one period, with one buyer and two suppliers. It is possible for only one or both of the suppliers to receive an order. We assume that suppliers do not collude directly, and their products are perfectly substitutable.

A supplier may experience a production disruption, which destroys the entire production batch. The supplier's production cost is incurred as soon as production begins and cannot be recovered if a disruption happens. Supplier i's (where $i = 1, 2$) random production yield is ρ_i, where $\rho_i = 1$ with probability θ_i and $\rho_i = 0$ with probability $1 - \theta_i$. The suppliers' production yields are independent.

Two types of supplier exist (denoted by H and L), with the reliability being either "high" or "low," as

[2] Appendix D contains a list of definitions and notation.

measured by the probability of successful production $\theta_i = h$ or l for supplier i, where $1 > h > l > 0$. Because there are two suppliers, the system may have (H, H), (H, L), (L, H), and (L, L) combinations of the suppliers' types. The supplier is of the high type with probability α^H, and of the low type with probability α^L, where $\alpha^H + \alpha^L = 1$.

In both models, the suppliers know their reliability types, but the buyer does not know their types. However, the buyer has probabilistic estimates of them: it believes that a supplier's reliability is high with probability α^H and low with probability α^L. The buyer's beliefs regarding the two suppliers are identical and independent. In the PSP-procurement model, the PSP also knows the suppliers' reliabilities. The PSP's superior knowledge relative to the buyer may be due to the PSP's history with the suppliers, geographic proximity, or better knowledge of the suppliers' technologies.

Let c_i be supplier i's production cost per unit. If the production cost does not depend on the reliability type, then the high-type supplier i's expected cost of yielding one unit of output, c_i/h, is less than that of the low-type, c_i/l. We generalize the model by allowing the supplier's production cost to depend on the reliability type. Specifically, the high-type supplier i's production cost is $c_i = c^H$ per unit, and the low-type supplier i's production cost is $c_i = c^L$ per unit. We assume $c^L/l > c^H/h$ to ensure that the less reliable supplier is less cost efficient in expectation (which is true in the special case of $c^H = c^L$).

To focus on the role of supply risk, we shall assume that the buyer operates in a make-to-order system. At the time when the buyer places orders, it knows both the demand D and revenue per unit r in the consumer market, and thus they are deterministic. We normalize the buyer's market demand to be $D = 1$. We can relax the assumption of deterministic r and think of r as the expected revenue per unit or, alternatively, the expected cost of a replacement product on a spot market. Thus, r represents the expected cost of product shortage for the buyer. We restrict the per-unit revenue to be greater than the high-reliability supplier type's expected cost of production.

Assumption 1. $r > c^H/h$.

If this assumption is not satisfied, the buyer will not order in either procurement model.

Finally, all firms have zero reservation values, and will participate as long as this value is met.

3. The PSP-Procurement Model and Solution

In this model, the buyer contracts with the PSP, who then brokers production with the suppliers. The suppliers possess private information about their reliability types, and the PSP has the same information. Thus, there is information asymmetry between the buyer and the PSP. This is the key feature of this model.

The timing of events is as follows. (1) Nature reveals the suppliers' types to the suppliers and the PSP. (2) The buyer offers a menu of contracts to the PSP, and the PSP sends the buyer a message, which determines the contract to be executed. (3) Fixed payment is made. Governed by the chosen contract, the PSP assigns production to the suppliers. (4) The suppliers begin production, incurring production costs. (5) After production uncertainty is realized, the PSP delivers goods to the buyer, and payments contingent on delivery happen. Finally, (6) the buyer sells available goods in the consumer market up to quantity $D = 1$ or the quantity delivered, receiving revenue r per unit.

3.1. Contracts

In general, there is an infinite number of mechanisms (contracts) that might be employed by the principal (the buyer) to govern its interactions with the agent (the PSP) with private information. However, as is usually done in information economics and the contracting literature, to simplify the analysis, we invoke the revelation principle[3] and focus only on the class of direct and incentive-compatible mechanisms. Under such mechanisms, the PSP will send the buyer messages that report the suppliers' reliability types, and the buyer structures the contracts such that these reports will be truthful.

The PSP's private information is two-dimensional: one dimension per supplier. Because each supplier is either the H or the L type, the PSP can send one of the following four messages: (H, H), (H, L), (L, H), and (L, L). The buyer believes that the PSP is (H, H) with probability $(\alpha^H)^2$, (H, L) with probability $(\alpha^H\alpha^L)$, (L, H) with probability $(\alpha^L\alpha^H)$, and (L, L) with probability $(\alpha^L)^2$. This contracting problem is difficult to solve in that the agent (the PSP) has a discrete type space of more than two types. We shall discuss the technical challenges and our solution procedure in §3.4.

The contract menu between the buyer and the PSP specifies payments and quantities, for each possible message the buyer may receive. Each contract in the menu has three parts: (X, q, p). Here X is the lump-sum upfront payment from the buyer to the PSP, regardless of the delivery status; q is the quantity that the buyer desires to receive from the PSP; and p is the penalty for each unit that the PSP falls short of the desired quantity q. Thus, the buyer offers the following menu

[3] The revelation principle applies to our model. In the PSP-procurement model, the buyer and the PSP play a Bayesian game, in which the PSP has private information and the buyer moves first with an offer of contracts to maximize its expected payoff of contracting with the PSP. The revelation principal applies to such Bayesian games of one principal. For example, for a proof of the revelation principal in the setting of one principal, refer to Section 3.3 of (Gibbons 1992, pp. 165–168).

of contracts to the PSP: $(X, q, p)(H, H)$, $(X, q, p)(H, L)$, $(X, q, p)(L, H)$, and $(X, q, p)(L, L)$.

The contract form of (X, q, p) mirrors the one used in Mookherjee and Tsumagari (2004), (X, q), and extends it to the setting with supply-side risk by adding the penalty term p. Our contract form is parsimonious and general, because it captures the fundamentals of the relationship between the principal and an agent with the risk of nondelivery. The purpose of the fixed-payment term, X, is to transfer value between the principal and the agent, independent of the delivery status. This is a familiar feature in mechanism design models. The penalty term, p, specifies the variable component of the contract that depends on the delivered quantity. It provides an economic incentive for the agent to deliver product to the buyer. This variable term is particularly needed in situations where the suppliers' production outcome is unobservable or noncontractible, for example, if the buyer and the supplier (or PSP) are located in different countries, or even different continents.

In theory, the penalty contract (X, q, p) is equivalent to the variable-payment contact that comprises of an upfront payment, a quantity, and a per-unit price for delivery (e.g., the contract used in Yang et al. 2012), if the upfront payment in the latter contract is allowed to be negative. However, the negative upfront payment may be impractical. If the upfront payment is restricted to be positive, the variable-payment contract may cause channel inefficiencies even under symmetric information, when the per-unit revenue r is so high that the buyer prefers using diversification. Specifically, to induce the PSP to use diversification, the buyer has to set a high per-unit price, which causes the buyer to cede a large surplus to the PSP. To extract the PSP's surplus, the buyer must reduce the upfront payment. Nonetheless, even at zero upfront payment, the PSP may still earn a positive surplus. In comparison, using a penalty contract of all positive terms the buyer can always expropriate all surplus of the PSP except for its informational rent, by setting the upfront payment to be equal to the sum of the PSP's total costs and informational rent. Therefore, the penalty contract (X, q, p) enables us to focus on the inefficiencies caused by the interplay between information asymmetry, supply risk, and intermediation, but not the inefficiencies inherent in the contract form.

Having seen the buyer's contract menu, the PSP signs contracts with the suppliers, specifying production quantities and payments. In this model, the PSP is the principal with respect to the suppliers, and the PSP knows the suppliers' types. In general, the PSP can coordinate the PSP–supplier subsystem using any coordinating contract. For simplicity, we assume that the PSP uses a coordinating contract, under which the PSP expropriates all profits and the suppliers make their reservation profits, which are normalized to be zero. (For example, the PSP can use a payment-penalty contract, similar to the one employed by the buyer.) Therefore, we shall not explicitly model contracting between the PSP and the suppliers, but study their coordinated actions and profits.

We shall solve the problem in reverse chronological order, analyzing first the PSP's production assignment in the next subsection. We shall then use the solution of the PSP's problem in designing the buyer's contract in §3.4.

3.2. The PSP's Optimal Production Assignment

In this subsection, we solve the PSP's production assignment problem, given any contract (X, q, p) from the buyer. Recall that the PSP is able to coordinate the PSP–supplier subsystem. The PSP chooses the production assignments to the suppliers, (z_1, z_2), to maximize the expected subsystem profit. Program (1) models the PSP's decision, given the suppliers' reliability types $(t_1, t_2) \in \{(H, H), (H, L), (L, H), (L, L)\}$:

$$\pi^{t_1, t_2}(X, q, p) = X - \min_{z_1 \geq 0,\, z_2 \geq 0} \{c^{t_1} z_1 + c^{t_2} z_2 + pE(q - \rho_1^{t_1} z_1 - \rho_2^{t_2} z_2)^+\}. \quad (1)$$

In (1), term $c^{t_i} z_i$ is the production cost of supplier i, and $\rho_i^{t_i} z_i$ is the quantity supplier i delivers, where $\rho_i^{t_i}$ is the production yield of supplier $i = 1, 2$. The expectation is taken over the suppliers' random production yields $(\rho_1^{t_1}, \rho_2^{t_2})$. Note that the payment X is irrelevant in search for the optimal production assignments. Lemma 1 presents the PSP's optimal production assignments $(z_1^*, z_2^*)(q, p)$.

Lemma 1. *Under the manufacturer's contract (X, q, p) and $q > 0$, the supplier coalition's optimal production sizes, $(z_1^*, z_2^*)(q, p)$, are as follows:*

(t_1, t_2)	Penalty	$(z_1^*, z_2^*)(q, p)$
(H, H)	$p < \frac{c^H}{h}$	$(0, 0)$
	$\frac{c^H}{h} \leq p < \frac{c^H}{h(1-h)}$	$(q, 0)$
	$p \geq \frac{c^H}{h(1-h)}$	(q, q)
(H, L) and (L, H)	$p < \frac{c^H}{h}$	$(0, 0)$
	$\frac{c^H}{h} \leq p < \frac{c^L}{l(1-h)}$	$(q, 0)$ for (H, L); $(0, q)$ for (L, H)
	$p \geq \frac{c^L}{l(1-h)}$	(q, q)
(L, L)	$p < \frac{c^L}{l}$	$(0, 0)$
	$\frac{c^L}{l} \leq p < \frac{c^L}{l(1-l)}$	$(q, 0)$
	$p \geq \frac{c^L}{l(1-l)}$	(q, q)

We relegate all proofs in this paper to Online Appendix E, available at http://ssrn.com/abstract=2287561.

In Lemma 1, the PSP's production assignment to a supplier is 0 or q. This is due to the suppliers' linear production costs and shortfall penalties and their Bernoulli production yields, which represent the outputs from random production disruption. Under these assumptions, it is sufficient to search for the PSP's optimal production assignment among the four corner-point solutions: $(z_1, z_2) = (0, 0)$, $(0, q)$, $(q, 0)$, and (q, q). In particular, when the shortfall penalty is high, the PSP diversifies the supply with the production assignment $(z_1, z_2) = (q, q)$. If other random yield models are used (e.g., stochastically proportional yield), overordering and diversification will still occur. But, we may not have explicit expressions for the PSP's production assignment, which are necessary for the analysis of the buyer's contracts with the PSP.

We now introduce the PSP's profit from production. For this, we first define two intermediate expressions that will be used repeatedly in the rest of this paper. First, let us define the PSP's incremental *benefit of sole-sourcing* (i.e., sourcing from one supplier relative to none):

$$\psi^{t_1}(q,p) \stackrel{\text{def}}{=} (\theta^{t_1} p - c^{t_1})q, \quad \text{for } t_1 \in \{H, L\}, \qquad (2)$$

where $\theta^H \stackrel{\text{def}}{=} h$ and $\theta^L \stackrel{\text{def}}{=} l$. When the PSP sole sources from a supplier of type t_1, the PSP–supplier subsystem avoids penalty p if the supplier's production is successful (with probability θ^{t_1}), but incurs a production cost of c^{t_1} per unit.

Next, let us define the PSP's incremental *benefit of diversifying* (i.e., sourcing from two suppliers relative to one):

$$\psi^{t_1,t_2}(q,p) \stackrel{\text{def}}{=} [\theta^{t_2}(1-\theta^{t_1})p - c^{t_2}]q,$$
$$\text{for } (t_1, t_2) \in \{(H,H), (H,L), (L,L)\}. \qquad (3)$$

Given that the PSP has assigned production to the supplier of type t_1, the production assignment to the second supplier of type t_2 helps the PSP–supplier subsystem avoid the penalty with probability $\theta^{t_2}(1-\theta^{t_1})$. This probability represents the likelihood of the joint events that the first supplier's production fails and the second supplier produces successfully.

Using these definitions, we can concisely write the PSP's expected profit as the sum of incremental benefits relative to the profit of taking no production action, $X - pq$.

Lemma 2. *Under contract (X, q, p), the optimal expected profit of the PSP is*

$$\pi^{t_1,t_2}(X,q,p) = (X - pq) + [\psi^{t_1}(q,p)]^+ + [\psi^{t_1,t_2}(q,p)]^+, \qquad (4)$$

for $(t_1, t_2) \in \{(H,H), (H,L), (L,L)\}$, and $\pi^{LH}(X,q,p) = \pi^{HL}(X,q,p)$.

3.3. Reliability Advantages of the More Reliable Types of PSP

We will compare the profits of the (L,L), (H,L), (L,H), and (H,H) PSP types. Because the (H,L) and (L,H) types make the same profit, it suffices to compare (L,L), (H,L), and (H,H). All results regarding the (H,L) type in this subsection will hold for the (L,H) type.

For a fixed contract (X,q,p), as the PSP's reliability type increases from (L,L) to (H,L) and to (H,H), the PSP's profit increases. The (H,H) type of the PSP earns a premium over the (H,L) type, because the (H,H) type incurs a smaller total expected cost and penalty than the (H,L) type. We refer to the premium earned by (H,H) over (H,L) as the (H,H) type's *reliability advantage* over the (H,L) type. Similarly, the (H,L) type earns a reliability advantage over the (L,L) type. We shall use the following notation for these reliability advantages:

$$\Gamma^{HH}_{HL}(q,p) \stackrel{\text{def}}{=} \pi^{HH}(X,q,p) - \pi^{HL}(X,q,p), \qquad (5a)$$
$$\Gamma^{HL}_{LL}(q,p) \stackrel{\text{def}}{=} \pi^{HL}(X,q,p) - \pi^{LL}(X,q,p). \qquad (5b)$$

From Lemma 2,

$$\Gamma^{HH}_{HL}(q,p) = [\psi^{HH}(q,p)]^+ - [\psi^{HL}(q,p)]^+, \qquad (6a)$$
$$\Gamma^{HL}_{LL}(q,p) = [\psi^{H}(q,p)]^+ + [\psi^{HL}(q,p)]^+ - [\psi^{L}(q,p)]^+ - [\psi^{LL}(q,p)]^+. \qquad (6b)$$

One can apply the expressions for $\psi^t(q,p)$ and $\psi^{t_1,t_2}(q,p)$ in (2) and (3) to obtain the expressions of $\Gamma^{HH}_{HL}(q,p)$ and $\Gamma^{HL}_{LL}(q,p)$. The results are presented in Lemma 6 in Appendix B.

The concept of reliability advantage will play a critical role in the design of the buyer's contracts. Ideally, the buyer would want to design a menu of contracts where each PSP type earns zero profit if the PSP selects the menu option intended for its type. However, a more reliable PSP type has an incentive to pretend to be a less reliable type (as long as the latter type is invited to do business with the buyer) and earn a positive profit in the form of reliability advantage. Specifically, the (H,H) type wants to pretend to be the (H,L), (L,H), or (L,L) type, and the (H,L) and (L,H) types want to pretend to be the (L,L) type. We shall discuss these incentive issues in §3.4.

3.4. The Buyer's Optimal Contract Menu for the PSP

In this subsection, we analyze the buyer's mechanism design problem, knowing the PSP's optimal production assignments to the suppliers (§3.2) and the more reliable PSP types' incentive of misrepresentation due to their reliability advantages (§3.3). We present the model in (7a)–(7o), outline the solution procedure, and present the optimal contract menu in Proposition 1.

The buyer's optimal contract design problem is presented formally in optimization program (7a)–(7o). There, $(z_1^*, z_2^*)(t_1, t_2) \stackrel{\text{def}}{=} (z_1^*, z_2^*)((q, p)(t_1, t_2))$ is the PSP's optimal production assignment under the contract designed for the (t_1, t_2) type of the PSP, and $\pi^{t_1, t_2}(s_1, s_2) \stackrel{\text{def}}{=} \pi^{t_1, t_2}((X, q, p)(s_1, s_2))$ is the expected profit of the PSP of type (t_1, t_2) when it reports type (s_1, s_2) and receives contract $(X, q, p)(s_1, s_2)$:

$$\max_{\substack{\{(X,q,p)(t_1,t_2),\\ t_1,t_2\in\{H,L\}\}}} \sum_{t_1,t_2\in\{H,L\}} \alpha^{t_1}\alpha^{t_2}\Big\{rE\min\big\{D, \min\{q(t_1,t_2), \rho_1^{t_1} z_1^*(t_1,t_2) + \rho_2^{t_2} z_2^*(t_1,t_2)\}\big\} - X(t_1,t_2) + p(t_1,t_2)E[q(t_1,t_2) - \rho_1^{t_1} z_1^*(t_1,t_2) - \rho_2^{t_2} z_2^*(t_1,t_2)]^+\Big\} \quad (7a)$$

subject to

(IC.HH)

$$\pi^{HH}(H,H) \geq \pi^{HH}(H,L) \text{ (local, downward)}, \quad (7b)$$
$$\pi^{HH}(H,H) \geq \pi^{HH}(L,H) \text{ (local, downward)}, \quad (7c)$$
$$\pi^{HH}(H,H) \geq \pi^{HH}(L,L) \text{ (global, downward)}; \quad (7d)$$

(IC.HL)

$$\pi^{HL}(H,L) \geq \pi^{HL}(H,H) \text{ (local, upward)}, \quad (7e)$$
$$\pi^{HL}(H,L) \geq \pi^{HL}(L,H) \text{ (local)}, \quad (7f)$$
$$\pi^{HL}(H,L) \geq \pi^{HL}(L,L) \text{ (local, downward)}; \quad (7g)$$

(IC.LH)

$$\pi^{LH}(L,H) \geq \pi^{LH}(H,H) \text{ (local, upward)}, \quad (7h)$$
$$\pi^{LH}(L,H) \geq \pi^{LH}(H,L) \text{ (local)}, \quad (7i)$$
$$\pi^{LH}(L,H) \geq \pi^{LH}(L,L) \text{ (local, downward)}; \quad (7j)$$

(IC.LL)

$$\pi^{LL}(L,L) \geq \pi^{LL}(H,H) \text{ (global, upward)}, \quad (7k)$$
$$\pi^{LL}(L,L) \geq \pi^{LL}(H,L) \text{ (local, upward)}, \quad (7l)$$
$$\pi^{LL}(L,L) \geq \pi^{LL}(L,H) \text{ (local, upward)}; \quad (7m)$$

(IR)

$$\pi^{HH}(H,H) \geq 0, \quad \pi^{HL}(H,L) \geq 0, \quad \pi^{LH}(L,H) \geq 0, \quad \text{and} \quad \pi^{LL}(L,L) \geq 0; \quad (7n)$$

$$X(t_1,t_2) \geq 0, \quad q(t_1,t_2) \geq 0, \quad r \geq p(t_1,t_2) \geq 0. \quad (7o)$$

The buyer maximizes its expected profit of sourcing via the PSP (before knowing the PSP's type), subject to the incentive compatibility (IC) and individual rationality (IR) constraints. Because this problem features an agent (the PSP) of more than two discrete types, the PSP's incentive compatibility is enforced by two categories of constraints: those that prevent a type from falsely reporting it as adjacent types (i.e., where misinformation is along only one dimension) and as nonadjacent types (i.e., where misinformation is along both dimensions), respectively. In the principal–agent theory, the former are known as *local* IC, and the latter as *global* IC, constraints (see Laffont and Martimort 2002). In our problem, besides the local IC constraints, we also impose a global IC constraint on the (H, H) and (L, L) types to prevent them from mimicking each other. Furthermore, the IC constraints are directional. An IC constraint that prevents a less reliable type from reporting to be of a more reliable type is an *upward* IC constraint, and is a *downward* IC constraint vice versa. The IR constraints ensure that the PSP's payoff from the game is greater than its reservation profit, which we normalize to be zero. Finally, to be consistent with the procurement practice, we impose the "limited liability" constraints $r \geq p(t_1, t_2)$ on the shortage penalties (in constraints (7o)), which specify that the PSP does not pay a penalty that exceeds the buyer's loss of revenue due to shortage.

We are able to fully characterize the optimal solution when the model parameters satisfy Condition 1.

Condition 1. *The model parameters satisfy the following conditions*:

(a) *If* $2(\alpha^H\alpha^L)\psi^{HL} - (\alpha^H)^2\phi \geq 0$, *then no additional restrictions are imposed on the model parameters*.

(b) *If* $2(\alpha^H\alpha^L)\psi^{HL} - (\alpha^H)^2\phi < 0$, *then* $c^H/(h(1-h))$ *must satisfy an additional restriction that is specified in the following table*:

Model parameters satisfy	*Restriction on* $c^H/(h(1-h))$
$(\alpha^L)^2\psi^L - [1-(\alpha^L)^2]\phi < 0$ *and* $(\alpha^L)^2(\psi^L + \psi^{LL}) - [1-(\alpha^L)^2]\omega < 0$	*No additional restriction*
$(\alpha^L)^2\psi^L - [1-(\alpha^L)^2]\phi > \{(\alpha^L)^2(\psi^L + \psi^{LL}) - [1-(\alpha^L)^2]\omega\}^+$	$\dfrac{c^H}{h(1-h)} \geq \dfrac{c^L}{l}$
$(\alpha^L)^2(\psi^L + \psi^{LL}) - [1-(\alpha^L)^2]\omega \geq \{(\alpha^L)^2\psi^L - [1-(\alpha^L)^2]\phi\}^+$ *and* $(1-l)^2 - (1-h) \geq 0$	$\dfrac{c^H}{h(1-h)} \geq \dfrac{c^L}{l(1-l)}$

where ϕ *and* ω *are defined in* (9b) *and* (9c):

Condition 1 ensures that the incentive compatibility constraints are nonbinding at the optimal solution, so we can solve the mechanism design problem following the canonical solution procedure, such as the one in Myerson (1981). Condition 1 is a mild restriction on the model parameters. For example, a sufficient condition for Condition 1 is such that $h > l \geq 0.5$ and $c^H \geq c^L$, which are satisfied in a wide range of situations. In Proposition 1, we present the results under Condition 1 using the following definitions:

$$\psi^t \stackrel{\text{def}}{=} \psi^t(q,p) \quad \text{at } (q,p) = (1,r), \quad \text{for } t \in \{H, L\}, \quad (8a)$$

$$\psi^{t_1,t_2} \stackrel{\text{def}}{=} \psi^{t_1,t_2}(q,p) \quad \text{at } (q,p) = (1,r), \quad \text{for } (t_1,t_2) \in \{(H,H),(H,L),(L,L)\}. \quad (8b)$$

Proposition 1. *Under the parameter values that satisfy Condition* 1, *the buyer's optimal order quantity,* $q^*(t_1, t_2)$, *and penalty,* $p^*(t_1, t_2)$, *for the PSP and the PSP's production assignments to the suppliers,* $(z_1^*, z_2^*)(t_1, t_2)$, *are as follows:*

Model parameters	*Quantity,* q^*	*Penalty,* p^*	*PSP assignment,* (z_1^*, z_2^*)
	(H, H) *PSP type*		
$(\alpha^H)^2\psi^{HH} < 0$	1	r	$(1, 0)$
$(\alpha^H)^2\psi^{HH} \geq 0$	1	r	$(1, 1)$
	(H, L) *and* (L, H) *PSP types*		
$2(\alpha^H\alpha^L)\psi^{HL} - (\alpha^H)^2\phi < 0$	1	$\min\left\{r, \dfrac{c^H}{h(1-h)}\right\}$	$(1, 0)$ *for* (H, L) $(0, 1)$ *for* (L, H)
$2(\alpha^H\alpha^L)\psi^{HL} - (\alpha^H)^2\phi \geq 0$	1	$\dfrac{c^L}{l(1-h)}$	$(1, 1)$
	(L, L) *PSP type*		
$(\alpha^L)^2\psi^L - [1-(\alpha^L)^2]\phi < 0$ *and* $(\alpha^L)^2(\psi^L + \psi^{LL}) - [1-(\alpha^L)^2]\omega < 0$	0	0	$(0, 0)$
$(\alpha^L)^2\psi^L - [1-(\alpha^L)^2]\phi >$ $\{(\alpha^L)^2(\psi^L + \psi^{LL}) - [1-(\alpha^L)^2]\omega\}^+$	1	$\dfrac{c^L}{l}$	$(1, 0)$
$(\alpha^L)^2(\psi^L + \psi^{LL}) - [1-(\alpha^L)^2]\omega \geq$ $\{(\alpha^L)^2\psi^L - [1-(\alpha^L)^2]\phi\}^+$	1	$\tilde{p}$	$(1, 1)$

where

$$\tilde{p} \stackrel{\text{def}}{=} \begin{cases} \dfrac{c^L}{l(1-l)} & \textit{if } (1-l)^2-(1-h) \geq 0, \\ \min\left\{r, \dfrac{c^L}{l(1-h)}\right\} & \textit{if } (1-l)^2-(1-h) < 0, \\ & \quad \textit{and } r \geq c^L/(l(1-l)), \\ n.a. & \textit{otherwise}, \end{cases} \tag{9a}$$

$$\phi \stackrel{\text{def}}{=} \Gamma^{HH}_{HL}\left(1, \frac{c^L}{l(1-h)}\right) = \Gamma^{HL}_{LL}\left(1, \frac{c^L}{l}\right) = h\left(\frac{c^L}{l} - \frac{c^H}{h}\right), \tag{9b}$$

$$\omega \stackrel{\text{def}}{=} \Gamma^{HL}_{LL}(1, \tilde{p}). \tag{9c}$$

The optimal payment $X^*(t_1, t_2)$ *can be derived from Equation* (A1) *provided in Remark* 1 *in Appendix A. The buyer's expected profit under the optimal contract menu is*

$$(\alpha^H)^2\psi^H + (\alpha^H)^2(\psi^{HH})^+ \tag{10a}$$

$$+ 2(\alpha^H\alpha^L)\psi^H + [2(\alpha^H\alpha^L)\psi^{HL} - (\alpha^H)^2\phi]^+ \tag{10b}$$

$$\left.\begin{aligned} &+ \{(\alpha^L)^2\psi^L - [1-(\alpha^L)^2]\phi\}^+ \\ &+ (\{(\alpha^L)^2(\psi^L + \psi^{LL}) - [1-(\alpha^L)^2]\omega\} \\ &- \{(\alpha^L)^2\psi^L - [1-(\alpha^L)^2]\phi\}^+)^+ \end{aligned}\right\}. \tag{10c}$$

The economic insight into the contract design problem in program (7a)–(7o) is that the buyer trades off between having to pay for information and deviating from the optimal procurement actions under symmetric information and thus losing profits. In the face of the PSP's incentives to misrepresent its type to benefit from the *reliability advantage* (see §3.3), the buyer has two choices. The buyer can simply resign itself to the fact that the more reliable types of the PSP will earn positive profits, and pay them enough to make their lying unnecessary. For instance, the buyer can offer the same contract to the (H, H) and (H, L) types, effectively paying the (H, H) type its *reliability advantage* over the (H, L) type. The *reliability advantage* earned by the (H, H) type is a cost on the buyer due to contracting with the (H, L) type. We shall refer to this cost as the *informational cost* for contracting with the (H, L) type. Similarly, the buyer incurs *informational costs* for contracting with the (L, L) type, because the (H, H), (H, L), and (L, H) types all have incentives to exploit their *reliability advantage* over the (L, L) type. Alternatively, the buyer may fight the more reliable types' incentives by altering the contracts with the less reliable types to make them less lucrative. For example, if the buyer stops doing business with the PSP of type (H, L), the (H, H) type has no incentive to pretend to be the (H, L) type. However, by altering the contracts with the less reliable PSP types, the buyer deviates from the optimal procurement actions for these types and loses profits.

We now introduce the definitions of informational costs ϕ and ω in (9b) and (9c), because they will be used repeatedly in the rest of this paper. In (9b), $\phi \stackrel{\text{def}}{=} \Gamma^{HH}_{HL}(1, c^L/(l(1-h)))$ represents the buyer's informational cost of using diversification with the (H, L) (or (L, H)) PSP type. This informational cost arises from the (H, H) PSP type's reliability advantage over the (H, L) (or (L, H)) type, $\Gamma^{HH}_{HL}(q, p)$, when the buyer orders $q = 1$ and sets the optimal penalty $p = c^L/(l(1-h))$ for the latter type to diversify. Because of this informational cost, the buyer's expected incremental profit from using diversification with the (H, L) and (L, H) PSP types, $2(\alpha^H\alpha^L)\psi^{HL}$, is reduced by $(\alpha^H)^2\phi$ (see the term in $[\,]^+$ of (10b)).

The term ϕ in (9b) also coincides with the buyer's informational cost of using sole sourcing with the (L, L) PSP type, that is, $\phi \stackrel{\text{def}}{=} \Gamma^{HL}_{LL}(1, c^L/l)$. This informational cost arises from the (H, L) and (L, H) PSP types' reliability advantage over the (L, L) type, $\Gamma^{HL}_{LL}(q, p)$, when the buyer orders $q = 1$ from the (L, L) PSP type and sets the optimal penalty $p = c^L/l$ to induce it to sole source. As a result of this informational cost, the buyer's expected profit from using sole sourcing with the (L, L) type, $(\alpha^L)^2\psi^L$, is reduced by $[1-(\alpha^L)^2]\phi$ (see the terms in the first $\{\,\}^+$ in (10c)).

Finally, in (9c), $\omega \stackrel{\text{def}}{=} \Gamma^{HL}_{LL}(1, \tilde{p})$ represents the buyer's informational cost of using diversification with the (L, L) PSP type under the optimal penalty $p = \tilde{p}$. This informational cost also arises from the (H, L) and (L, H) PSP types' reliability advantage over the (L, L) type. Because of this informational cost, the buyer's expected profit from using diversification with the (L, L) PSP type, $(\alpha^L)^2(\psi^L + \psi^{LL})$, is reduced by $[1-(\alpha^L)^2]\omega$ (see the terms in the first $\{\}$ in $()^+$ of (10c)).

In §5, we shall analyze the economic forces for the PSP value under different levels of the per-unit revenue r. To prepare for this analysis, from the conditions of the model parameters (the leftmost column) in the table of Proposition 1, we define r^{HL}, r^L, and r^{LL}:

$$r^{HL} \stackrel{\text{def}}{=} r \quad \text{such that } 2(\alpha^H\alpha^L)\psi^{HL} - (\alpha^H)^2\phi = 0, \quad (11a)$$

$$r^{L} \stackrel{\text{def}}{=} r \quad \text{such that } (\alpha^L)^2\psi^{L} - [1-(\alpha^L)^2]\phi = 0, \quad (11b)$$

$$r^{LL} \stackrel{\text{def}}{=} r \quad \text{such that } (\alpha^L)^2(\psi^L + \psi^{LL}) - [1-(\alpha^L)^2]\omega = \{(\alpha^L)^2\psi^L - [1-(\alpha^L)^2]\phi\}^+. \quad (11c)$$

The quantity r^{HL} defines the threshold of the revenue per unit for the buyer to use diversification with the (H, L) and (L, H) PSP types; r^L and r^{LL} are the thresholds of the revenue per unit for the buyer's choice of procurement action with the (L, L) PSP type. There are two cases, depending on whether or not $r^L < r^{LL}$. If $r^L \le r^{LL}$, then the buyer takes no procurement action for $r < r^L$, uses sole sourcing for $r^L \le r < r^{LL}$, and uses diversification for $r > r^{LL}$. If $r^L > r^{LL}$, then sole sourcing will not be used. Specifically, the buyer takes no procurement action for $r < r^{LL}$ and uses diversification for $r \ge r^{LL}$.

4. The Direct-Procurement Model

In the direct-procurement model, the buyer orders directly from the suppliers. This is the benchmark model needed to quantify the value of using the PSP. A similar direct-procurement model was studied in Yang et al. (2012), but with three main differences: in this paper, (1) the setup cost of working with a supplier is $K = 0$, (2) the buyer's market demand is normalized to be $D = 1$, and (3) instead of the variable payment term, we use the penalty term, p. We shall take advantage of the solution derived in Yang et al. (2012), and, without duplicating their analysis, present the results needed in this paper.

In contrast to PSP procurement (§3), in the direct-procurement model the principal (the buyer) faces two agents (the suppliers). Each supplier has one-dimensional private information about its reliability type. The buyer offers a menu of four pairs of contracts: $(X_1, q_1, p_1)(t_1, t_2)$ and $(X_2, q_2, p_2)(t_1, t_2)$ for $(t_1, t_2) = (H, H)$, (H, L), (L, H), and (L, L).

Having received a contract (X, q, p) from the buyer, supplier i independently decides its production size z_i to maximize its expected profit: $X - c^{t_i}z_i - pE\cdot(q-\rho^{t_i}z_i)^+$, where t_i is supplier i's true reliability type. The supplier's optimal production decision and expected profit are summarized in Lemma 3.

Lemma 3. *Under contract (X, q, p), the optimal production size of supplier i, denoted as $z_i^{t_i}(q, p)$, is $z_i^{t_i}(q, p) = q$ if $p \ge c^{t_i}/\theta^{t_i}$, and $z_i^{t_i}(q, p) = 0$ otherwise. The supplier's optimal expected profit is $\pi_i^{t_i}(X, q, p) = X - pq + [\psi^{t_i}(q, p)]^+$.*

In the supplier's optimal profit $\pi_i^{t_i}(X, q, p)$, term $\psi^t(q, p)$ is the supplier's incremental benefit of running production, relative to the profit of taking no action, $X - pq$, and $\psi^t(q, p)$ coincides with the PSP incremental benefit of sole sourcing from a supplier of type t, which is defined in (2). The implication is that, in the face of the same contract for sole sourcing, the coordinated subsystem of the PSP and a single supplier enjoys the same profit as the supplier does under direct procurement.

Similar to the PSP-procurement model, in this model the high-reliability type enjoys a *reliability advantage* over the low type, which is defined to be $\Gamma^{\frac{H}{L}}(q, p) \stackrel{\text{def}}{=} \pi_i^H(X, q, p) - \pi_i^L(X, q, p)$. From the expression for $\pi_i^{t_i}(X, q, p)$ in Lemma 3, we derive the expression for $\Gamma^{\frac{H}{L}}(q, p)$ to be $\Gamma^{\frac{H}{L}}(q, p) = [\psi^H(q, p)]^+ - [\psi^L(q, p)]^+$. At $(q, p) = (1, c^L/l)$, the high type's *reliability advantage* coincides with the (H, L) PSP type's *reliability advantage* when it sole sources (see (9b) in the PSP-procurement model); that is,

$$\Gamma^{\frac{H}{L}}\left(1, \frac{c^L}{l}\right) = \Gamma^{\frac{HL}{LL}}\left(1, \frac{c^L}{l}\right) = \phi. \quad (12)$$

With such a *reliability advantage*, the high type has an incentive to pretend to be the low type to earn a positive profit. In the face of the suppliers' misrepresentation incentives, the buyer designs its contract menu for direct procurement. The buyer's decision is represented by program (13a)–(13d), in which the IC constraints ensure that the suppliers will report their true reliability types:

$$\max_{\substack{\{(X_i, q_i, p_i)(t_1, t_2)\\ i=1,2;\, t_1, t_2 \in \{H, L\}\}}} \Bigg[\sum_{t_1, t_2 \in \{H, L\}} \alpha^{t_1}\alpha^{t_2} \cdot (rE\min\{D, \rho_1^{t_1}z_1^{t_1}[(q_1, p_1)(t_1, t_2)] + \rho_2^{t_2}z_2^{t_2}[(q_2, p_2)(t_1, t_2)]\} - X_1(t_1, t_2) + p_1(t_1, t_2)E[q_1(t_1, t_2) - \rho_1^{t_1}z_1^{t_1}[(q_1, p_1)(t_1, t_2)]]^+ - X_2(t_1, t_2) + p_2(t_1, t_2)E[q_2(t_1, t_2) - \rho_2^{t_2}z_2^{t_2}[(q_2, p_2)(t_1, t_2)]]^+)\Bigg], \quad (13a)$$

subject to

for $i = 1, 2$,

$$\text{(IC)} \quad \Pi_i^H(H) \ge \Pi_i^H(L), \quad \Pi_i^L(L) \ge \Pi_i^L(H), \quad (13b)$$

$$\text{(IR)} \quad \Pi_i^H(H) \ge 0, \quad \Pi_i^L(L) \ge 0, \quad (13c)$$

$$X_i(t_1, t_2) \ge 0,\ q_i(t_1, t_2) \ge 0,\ r \ge p_i(t_1, t_2) \ge 0, \quad \text{for } t_1, t_2 \in \{H, L\}, \quad (13d)$$

where

$$\Pi_i^{t_i}(s_i) \stackrel{\text{def}}{=} \alpha^H\pi_i^{t_i}((X_i, q_i, p_i)(s_i, H)) + \alpha^L\pi_i^{t_i}((X_i, q_i, p_i)(s_i, L))$$

is supplier i's expected profit from reporting to be of type $s_i \in \{H, L\}$ before knowing the other supplier's type.

We present the buyer's optimal procurement actions and its optimal expected profit in Proposition 2, where terms ψ^t and ψ^{t_1,t_2} are defined in (8a) and (8b).

Proposition 2. *In the direct-procurement model, the buyer's optimal procurement quantities, $(q_1^*, q_2^*)(t_1, t_2)$, are as follows*:

Model parameters	*Penalties,* (p_1, p_2)	*Quantities,* (q_1, q_2)
	(H, H) *supplier-type pair*	
$(\alpha^H)^2\psi^{HH} \le 0$	$(c^H/h, 0)$	$(1, 0)$
$(\alpha^H)^2\psi^{HH} > 0$	$(c^H/h, c^H/h)$	$(1, 1)$
	(H, L) *supplier-type pair*	
$(\alpha^H\alpha^L)\psi^{HL} - (\alpha^H)^2\phi \le 0$	$(c^H/h, 0)$	$(1, 0)$
$(\alpha^H\alpha^L)\psi^{HL} - (\alpha^H)^2\phi > 0$	$(c^H/h, c^L/l)$	$(1, 1)$
	(L, H) *supplier-type pair*	
$(\alpha^L\alpha^H)\psi^{HL} - (\alpha^H)^2\phi \le 0$	$(0, c^H/h)$	$(0, 1)$
$(\alpha^L\alpha^H)\psi^{HL} - (\alpha^H)^2\phi > 0$	$(c^L/l, c^H/h)$	$(1, 1)$
	(L, L) *supplier-type pair*	
$(\alpha^L)^2\psi^L - (\alpha^H\alpha^L)\phi \le 0$	*N/A*	$(0, 0)$
$(\alpha^L)^2\psi^L - (\alpha^H\alpha^L)\phi > 0 \ge (\alpha^L)^2\psi^{LL} - (\alpha^L\alpha^H)\phi$	$(c^L/l, 0)$	$(1, 0)$
$(\alpha^L)^2\psi^{LL} - (\alpha^L\alpha^H)\phi > 0$	$(c^L/l, c^L/l)$	$(1, 1)$

The buyer's optimal expected profit is

$$(\alpha^H)^2\psi^H + (\alpha^H)^2(\psi^{HH})^+ \tag{14a}$$

$$+2(\alpha^H\alpha^L)\psi^H + [2(\alpha^H\alpha^L)\psi^{HL} - 2(\alpha^H)^2\phi]^+ \tag{14b}$$

$$+[(\alpha^L)^2\psi^L - (\alpha^H\alpha^L)\phi]^+ + [(\alpha^L)^2\psi^{LL} - (\alpha^L\alpha^H)\phi]^+. \tag{14c}$$

Because ψ^{t_1} and ψ^{t_1,t_2} increase in the revenue per unit r, for each type pair (t_1, t_2), there exist thresholds of the per-unit revenue at which the buyer is indifferent between not ordering and sole sourcing, and between sole sourcing and diversification, respectively. We define these thresholds as follows:

$$\tilde{r}^{HL} \stackrel{\text{def}}{=} r \quad \text{such that } (\alpha^H\alpha^L)\psi^{HL} - (\alpha^H)^2\phi = 0, \tag{15a}$$

$$\tilde{r}^{L} \stackrel{\text{def}}{=} r \quad \text{such that } (\alpha^L)^2\psi^{L} - (\alpha^H\alpha^L)\phi = 0, \tag{15b}$$

$$\tilde{r}^{LL} \stackrel{\text{def}}{=} r \quad \text{such that } (\alpha^L)^2\psi^{LL} - (\alpha^H\alpha^L)\phi = 0. \tag{15c}$$

To prepare for the analysis of the value of using the PSP in §5, we compare the buyer's informational costs for using diversification with the (L, L) pair under the two procurement models. Under direct procurement, the buyer orders from both low-type suppliers, incurring informational cost ϕ with each supplier. Recall that under PSP procurement the buyer incurs informational cost ω for using diversification with the (L, L) PSP type (defined in (9c)). We find that $\omega > \phi$ and present the result in Lemma 4.

Lemma 4. *The buyer's informational cost for using diversification with the (L, L) PSP type, ω, is larger than the buyer's informational cost for ordering from a low-type supplier under direct procurement, ϕ.*

The key driver of the result in Lemma 4 is the buyer's loss of control over the suppliers' production actions caused by the adoption of the PSP as the intermediary. The effect of loss of control manifests itself in a greater penalty needed for diversification under PSP procurement. Specifically, $p = \tilde{p}$ from Proposition 1 for PSP procurement, and $p = c^L/l$ from Proposition 2 for direct procurement, with $\tilde{p} > c^L/l$. Why is $p = \tilde{p}$ under PSP procurement larger than c^L/l? If the PSP receives the penalty $p = c^L/l$, it has at most the same incentive to produce as a single supplier does. To induce the PSP to diversify, the buyer must increase the penalty to be higher than $c^L/[l(1-l)]$, obtaining $p = \tilde{p}$. Compared to $p = c^L/l$, the higher penalty $\tilde{p} \ge c^L/[l(1-l)]$ under PSP procurement leads to a larger reliability advantage of the (H, L) pair over the (L, L) pair, and, thus, $\omega > \phi$.

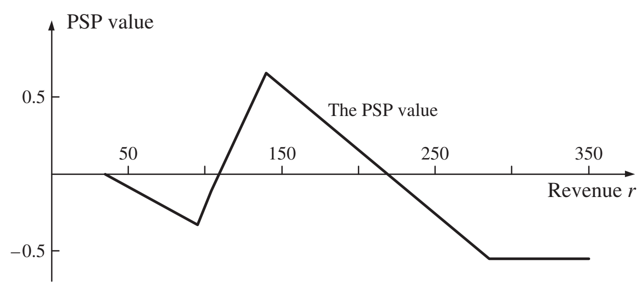
We are now ready to analyze the value of using PSP procurement.

5. The PSP Value

The main research question of this paper is whether the buyer should use a PSP due to the PSP's better information about supply risk. To answer this question, we first define the value of using the PSP for the buyer as the difference between the buyer's expected profits under PSP procurement (10a)–(10c) and direct procurement (14a)–(14c). Can this value be positive? In a setting with asymmetric cost information (but without supply risks), Proposition 5(i) of Mookherjee and Tsumagari (2004) indicates that no, we should expect the PSP value for the buyer to be negative.

Interestingly, our answer is that the PSP value may be positive, as Figure 2 illustrates, and this is the first takeaway from this section. To draw Figure 2, we

Figure 2 **The PSP Value as Function of r**



Note. The parameter values are $\alpha^H = 0.9$, $h = 0.7$, $l = 0.6$, and $c^H = c^L = 10$.

used the following parameter values: $\alpha^H = 0.9$, $h = 0.7$, $l = 0.6$, and $c^H = c^L = 10$.

In the rest of this section, we shall try to understand where the positive PSP value comes from and what explains the negative value (in Mookherjee and Tsumagari 2004 and in our model). The discussion will be quite complex. Therefore, we preview the main takeaways to come, in addition to the first the takeaway discussed above. The second takeaway in this section will be that the value of using the PSP for the buyer can be decomposed into the benefits, attributable to the contracts with the (H, L) and (L, H) types, and the costs, attributable to the contract with the (L, L) type. These results will be presented in Propositions 3 and 4. The third takeaway will be that both the benefits and costs of using the PSP can be explained by two driving forces: implicit supplier collusion enabled by the PSP and the change of control over the procurement actions from the buyer to the PSP. These drivers change the buyer's supply availability and the informational costs paid to the PSP. We shall analyze these effects in §§5.1 and 5.2. The fourth takeaway will be that implicit collusion and the change of control, individually, may have positive and negative effects on the value of using the PSP. Finally, the fifth takeaway will be that the benefits of using the PSP can only arise when the risk management tool of diversification is deployed.

To fulfill the promise of the above preview of results, we continue with the derivation of the expression for the value of using the PSP using (10a)–(10c) and (14a)–(14c) and presenting it in Proposition 3.

Proposition 3. *The buyer's value of using the PSP is*

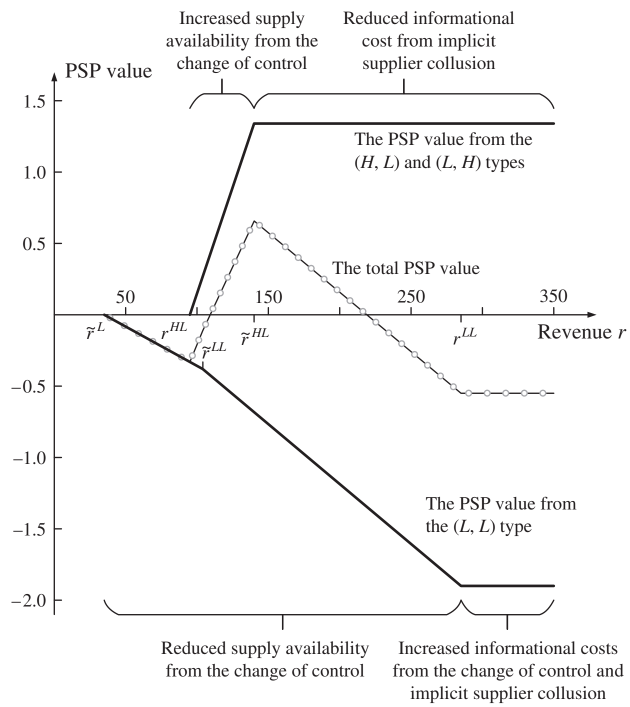
$$\left.\begin{aligned}&[2(\alpha^H\alpha^L)\psi^{HL}-(\alpha^H)^2\phi]^+\\&\quad-[2(\alpha^H\alpha^L)\psi^{HL}-2(\alpha^H)^2\phi]^+\end{aligned}\right\}\qquad(16a)$$

$$\left.\begin{aligned}&+\{(\alpha^L)^2\psi^L-[1-(\alpha^L)^2]\phi\}^+\\&+(\{(\alpha^L)^2(\psi^L+\psi^{LL})-[1-(\alpha^L)^2]\omega\}\\&\qquad-\{(\alpha^L)^2\psi^L-[1-(\alpha^L)^2]\phi\}^+)^+\\&-[(\alpha^L)^2\psi^L-(\alpha^H\alpha^L)\phi]^+\\&\quad-[(\alpha^L)^2\psi^{LL}-(\alpha^L\alpha^H)\phi]^+\end{aligned}\right\}.\qquad(16b)$$

In Proposition 3, term (16a) is the PSP value attributable to the contracts with the (H, L) and (L, H) PSP types (and the corresponding supplier types under direct procurement). Term (16b) is the PSP value attributable to the contract with the (L, L) PSP type. There is no contribution to the PSP value from the contract with the (H, H) PSP type.

We plot (16a) and (16b), creating two solid lines in Figure 3. We also provide guidance with respect to the causes behind the PSP values in (16a) and (16b) for different levels of revenue r. We will discuss these

Figure 3 **Decomposition of the PSP Value by the Contracts with (H, L) and (L, H) Types and the Contract with (L, L) Type**



Note. The parameter values are $\alpha^H = 0.9$, $h = 0.7$, $l = 0.6$, and $c^H = c^L = 10$; $r^L > r^{LL} > \tilde{r}^{HL}$.

causes in detail in §§5.1 and 5.2. The sum of the two solid lines in Figure 3 is the total PSP value in Figure 2. From Figure 3, it appears that (16a) contributes the benefits of using the PSP, whereas (16b) contributes the costs. According to Proposition 4, this observation is true in general, and it is the second takeaway from this section.

Proposition 4. *The contribution to the PSP value from the contracts with the* (H, L) *and* (L, H) *types is positive, that is, expression* (16a) *is positive. The contribution to the PSP value from the contract with the* (L, L) *type is negative, that is, expression* (16b) *is negative.*

To derive the third, fourth, and fifth main takeaways, we shall study the contribution to the PSP value from the (H, L) and (L, H) contracts in §5.1 and the contribution from the (L, L) contract in §5.2.

5.1. The PSP Value from the (H, L) and (L, H) Contracts

The PSP value from the (H, L) and (L, H) contracts (16a) is dissected by different levels of the revenue per unit r and by cause in Table 1. This table also presents the production actions and the buyer's expected profits under the optimal contracts in the two procurement models. For the definitions of r^{HL} and $\tilde{r}^{HL}$ in Table 1, refer to (11a) and (15a). It is beneficial to read this table in conjunction with Figure 3.

In Table 1, we identify two causes for the PSP value: (i) implicit supplier collusion enabled by the PSP and

Table 1 **The Optimal Procurement Actions, the Buyer's Profits, and the Buyer's Value from Using the PSP, by Cause, Attributable to the (H, L) and (L, H) Types vs. the Revenue per Unit r**

Revenue per unit, $r \in$	$(c^H/h, r^{HL})$	$[r^{HL}, \tilde{r}^{HL})$	$[\tilde{r}^{HL}, \infty)$
PSP procurement			
$(z_1^*, z_2^*)(H, L)$	$(1, 0)$	$(1, 1)$	
$(z_1^*, z_2^*)(L, H)$	$(0, 1)$	$(1, 1)$	
Buyer's profit	$2(\alpha^H\alpha^L)\psi^H$	$2(\alpha^H\alpha^L)(\psi^H + \psi^{HL}) - (\alpha^H)^2\phi$	
Direct procurement			
(z_1^H, z_2^L)	$(1, 0)$		$(1, 1)$
(z_1^L, z_2^H)	$(0, 1)$		$(1, 1)$
Buyer's profit	$2(\alpha^H\alpha^L)\psi^H$		$2(\alpha^H\alpha^L)(\psi^H + \psi^{HL}) - 2(\alpha^H)^2\phi$
PSP value = PSP profit − direct profit			
Change of control			
Supply availability	0	$2(\alpha^H\alpha^L)\psi^{HL}$	0
Informational cost	0	$-(\alpha^H)^2\phi$	0
Implicit supplier collusion	0	0	$(\alpha^H)^2\phi$
Total	0	$2(\alpha^H\alpha^L)\psi^{HL} - (\alpha^H)^2\phi$	$(\alpha^H)^2\phi$

(ii) the change of control over the procurement actions from the buyer to the PSP. Implicit supplier collusion distorts the suppliers' incentives of misrepresentation, thus, changing the buyer's informational costs. The change of control itself has two effects. First, it distorts the procurement actions for the suppliers, thus affecting the supply availability for the buyer. Second, the change of control also affects the buyer's informational costs. To appreciate the interplay between implicit supplier collusion and the change of control, we shall discuss Table 1 by going from right to left.

Consider column $r \in [\tilde{r}^{HL}, \infty)$ in Table 1. In both procurement models, both suppliers receive an order. Hence, there is no difference in the supply availability. Yet, PSP procurement dominates direct procurement for the buyer by $(\alpha^H)^2\phi$. This benefit represents the buyer's saving in the informational costs paid to stop the (H, H) pair from pretending to be (H, L) and (L, H).

Interestingly, this is a positive effect of implicit collusion between suppliers enabled by the PSP. To appreciate the origins of this benefit, note that under direct procurement the suppliers make decisions independently. In the (H, H) pair, both suppliers need to be paid to stop pretending to be the low-type one in equilibrium. This results in the expected informational costs of $2(\alpha^H)^2\phi$ for the buyer. In contrast, under PSP procurement the suppliers are coordinated by the PSP. The coordinated subsystem of the (H, H) type prefers to misreport itself as either (H, L) or (L, H). The dominated form of misreporting will not arise in equilibrium. Therefore, the buyer needs to pay only one informational cost $(\alpha^H)^2\phi$. The saved informational cost, $(\alpha^H)^2\phi$, is a benefit of using the PSP for the buyer. This observation is robust to the (H, H) PSP type's choice of the rule for breaking the tie between reporting (H, L) and (L, H).

Consider column $r \in [r^{HL}, \tilde{r}^{HL})$ in Table 1. Here we observe a combination of the change-of-control effects. First, the procurement actions under the two procurement models are different. Under direct procurement, the buyer orders from only one supplier (the high type). In contrast, under PSP procurement, the buyer induces the PSP to diversify, because the buyer's informational cost of using diversification is lower than under direct procurement. The diversification action of the PSP increases the supply availability for the buyer, so it accrues a benefit of $2(\alpha^H\alpha^L)\psi^{HL}$. Second, ordering from two suppliers instead of one comes at a cost to the buyer of having to pay an additional informational cost, $(\alpha^H)^2\phi$. The net effect, $2(\alpha^H\alpha^L)\psi^{HL} - (\alpha^H)^2\phi$, is still in favor of using PSP procurement.

The preceding observation sheds lights on the interaction between PSP procurement and information asymmetry. Under direct procurement and symmetric information, the buyer diversifies with the (H, L) and (L, H) supplier pairs in this region of r. Under direct procurement and asymmetric information, the buyer foregoes diversification with (H, L) and (L, H) (see Yang et al. 2012). Consequently, supply risk increases. Switching to PSP procurement enables the buyer to use diversification again and reduce supply risk. Therefore, using a PSP with better information can mitigate the effect of information asymmetry on supply risk. Thus, interactions between supply risk, diversification, implicit supplier collusion, and the change of control lead to new and important managerial insights, which expand the insights from previous studies (e.g., Mookherjee and Tsumagari 2004).

Finally, consider column $r \in (c^H/h, r^{HL})$ in Table 1. In both procurement models, only one of the suppliers (i.e., the high-type supplier) receives an order. Thus, there is no difference in the supply availability. It turns out that there are no informational costs in the two models either, and, therefore, the PSP value is zero. Intuitively, the buyer is indifferent between dealing with a high-type supplier directly and dealing with a coordinated subsystem of the PSP and a high-type supplier (although the PSP has access to two suppliers, the buyer knows that the PSP will optimally order from the supplier that the buyer would have used itself). This case (i.e., $r \in (c^H/h, r^{HL})$) is similar to the Mookherjee and Tsumagari (2004) result, where in the absence of supply risk there is no need for the buyer or the PSP to diversify. As we have discussed for the other two columns in Table 1, the PSP value is derived by the buyer when diversification does happen. This observation highlights the importance of supply risk and supply risk management in PSP procurement.

In summary, the key takeaway from this subsection is that we can decompose the benefits of using the PSP by the implicit-supplier-collusion effect and the change-of-control effects. When the per-unit revenue is so large that diversification happens in both PSP procurement models, the PSP benefit is derived from the reduction in informational costs due to a positive effect of implicit supplier collusion. When the PSP diversifies, whereas the buyer under direct procurement would not, the PSP benefit is derived from the reduction in supply risk due to the change of control.

5.2. The PSP Value from the (L, L) Contract

We shall break the discussion into two parts. In this subsection, we focus on the case of $r^L > r^{LL} > \tilde{r}^{LL}$, which leads to Figures 2 and 3. For this case, we reveal the main effects of implicit supplier collusion and the change of control. In Appendix C, we shall discuss the case of $r^L < r^{LL} < \tilde{r}^{LL}$, which has similar insights. For the definitions of r^L, r^{LL}, and $\tilde{r}^{LL}$, see (11b), (11c), and (15c).

In Table 2, we summarize the expressions for the PSP value from the (L, L) contract under $r^L > r^{LL} > \tilde{r}^{LL}$ and dissect them by the cause and by the level of the revenue per unit r. We also summarize the buyer's optimal profits and procurement actions under the two procurement models. Similar to Table 1, we identify two causes of the PSP value from the (L, L) PSP type: (i) implicit supplier collusion enabled by the PSP and (ii) the change of control over the procurement actions. However, compared to the effects in Table 1, in Table 2 implicit supplier collusion and the change of control have negative effects on the PSP value. We shall discuss these causes by going through Table 2 from right to left.

Consider column $r \in [r^{LL}, \infty)$ in Table 2. The buyer uses diversification in both procurement models. Therefore, there is no difference in the buyer's supply availability. This allows us to focus on changes in the informational costs due to the change of control and implicit supplier collusion.

The change of control increases the buyer's informational costs with the (L, L) type. The buyer must pay informational costs to prevent the (H, L) and (L, H) pairs from misreporting themselves as (L, L). Under direct procurement, the buyer's expected informational costs when diversifying with the (L, L) supplier pair are $2(\alpha^H\alpha^L)\phi$. Under PSP procurement, the corresponding costs are $2(\alpha^H\alpha^L)\omega$. (For the definitions of ϕ and ω, see Equations (12) and (9c).) According to Lemma 4, $\omega > \phi$. Therefore, by using PSP procurement

Table 2 **The Optimal Procurement Actions, the Buyer's Profits, and the Buyer's Value from Using the PSP, by Cause, Attributable to the (L, L) Type vs. the Revenue per Unit r**

Revenue per unit, $r \in$	$[\tilde{r}^L, \tilde{r}^{LL})$	$[\tilde{r}^{LL}, r^{LL})$	$[r^{LL}, \infty)$
PSP procurement			
$(z_1^*, z_2^*)(L, L)$ Profit	$(0, 0)$ 0		$(1, 1)$ $(\alpha^L)^2(\psi^L + \psi^{LL}) - [1 - (\alpha^L)^2]\omega$
Direct procurement			
(z_1^L, z_2^L) Profit	$(1, 0)$ $(\alpha^L)^2\psi^L - (\alpha^H\alpha^L)\phi$	$(1, 1)$ $(\alpha^L)^2(\psi^L + \psi^{LL}) - 2(\alpha^H\alpha^L)\phi$	
PSP value = PSP profit − direct profit			
Change of control			
Supply availability Informational cost	$-(\alpha^L)^2\psi^L$ $(\alpha^H\alpha^L)\phi$	$-(\alpha^L)^2(\psi^L + \psi^{LL})$ $2(\alpha^H\alpha^L)\phi$	0 $-2(\alpha^H\alpha^L)(\omega - \phi)$
Implicit supplier collusion	0		$-(\alpha^H)^2\omega$
Total	$-[(\alpha^L)^2\psi^L - (\alpha^H\alpha^L)\phi]$	$-[(\alpha^L)^2(\psi^L + \psi^{LL}) - 2(\alpha^H\alpha^L)\phi]$	$-2(\alpha^H\alpha^L)(\omega - \phi) - (\alpha^H)^2\omega$

Note. Assumption on parameter values: $r^L > r^{LL} > \tilde{r}^{LL}$.

the buyer loses $2(\alpha^H\alpha^L)(\omega-\phi)>0$ in expectation. From the intuition we developed following Lemma 4, by switching to PSP procurement, the buyer loses direct control of the suppliers production actions and ends up paying more informational cost for implementing the same production assignments as under direction procurement.

Furthermore, implicit supplier collusion results in an extra informational cost. The following is an explanation for this extra cost. Under direct procurement, the suppliers in the (H,H) pair cannot simultaneously report to be of the low type in equilibrium, because the suppliers report their types independently. If one of them pretends to be the low type, the other one is better off reporting truthfully to be the high type. In contrast, under PSP procurement, the (H,H) supplier pair can report itself as (L,L) in equilibrium, because the PSP coordinates the reports from the suppliers. To prevent this, the buyer must pay, in expectation, an amount $(\alpha^H)^2\omega$, which is the extra informational cost.

Consider columns $r\in[\tilde r^L,\tilde r^{LL})$ and $r\in[\tilde r^{LL},r^{LL})$ in Table 2. Implicit supplier collusion has no effect, because no procurement action is taken for (L,L) under PSP procurement. The PSP value is due to the change of control. Because the PSP takes no action, whereas the buyer sole sources or diversifies under direct procurement, there is a new, negative effect of the change of control—a decrease in the supply availability for the buyer. This effect causes a profit loss of $-(\alpha^L)^2\psi^L$ for $r\in[\tilde r^L,\tilde r^{LL})$, or $-(\alpha^L)^2(\psi^L+\psi^{LL})$ for $r\in[\tilde r^{LL},r^{LL})$. The profit loss comes with a saving in the informational costs for the buyer, but the net effect is still negative, favoring direct procurement.

In summary, the PSP value from the (L,L) type is due to the negative effects of implicit supplier collusion and the change of control. Implicit supplier collusion increases the buyer's informational costs for using the (L,L) supplier pair any time the PSP takes a procurement action. The contribution of implicit supplier collusion to the PSP value depends on whether the PSP diversifies or sole sources. The change of control contributes to the PSP value by altering the supply availability for the buyer and its informational costs for using the (L,L) type. Interestingly, the change of control may decrease or increase the supply availability. (See the case of $r^L<r^{LL}<\tilde r^{LL}$ in Appendix C.) But, the net contribution of the change of control is always negative.

6. Comparative Statics Analysis of the PSP Value

In this section, we shall analyze how the PSP value is affected by the revenue per unit, the supply base's reliability, and the reliability gap between the two supplier types.

6.1. The Effect of the Revenue per Unit

We have shown numerically (e.g., see Figure 2) that the total PSP value can be positive or negative. As Mookherjee and Tsumagari (2004) predict in their Proposition 5(i), and our results confirm, the PSP value is negative in the absence of diversification, corresponding to small revenues in our model. Next, we shall discuss the PSP value under large and moderate revenues.

Large revenues. The numerical result in Figure 2 suggests that the PSP value must be negative when the revenue per unit is large. The reason for this result is not straightforward. On one hand, the PSP value from the (H,L) and (L,H) contracts is positive. On the other hand, the PSP value from the (L,L) type is negative. One can prove that the net value is negative, as summarized in Proposition 5.

Proposition 5. *When the revenue per unit $r\ge\max\{\tilde r^{HL},\min\{r^L,r^{LL}\}\}$, the total PSP value is negative.*

To understand the intuition, recall from §5 that, at large per-unit revenues, using PSP procurement has a positive effect with the (H,L) and (L,H) types due to implicit supplier collusion, and two negative effects with the (L,L) type due to implicit supplier collusion and the change of control. Note that implicit supplier collusion has both a positive effect, a saving in informational costs $(\alpha^H)^2\phi$, and a negative effect, an increase in informational costs $(\alpha^H)^2\omega$. It follows from the fact that $\omega>\phi$ that the negative effect dominates the positive effect. (For the explanation for $\omega>\phi$, see the discussion following Lemma 4.) Therefore, the net effect of implicit supplier collusion is negative. Because the effect of the change of control is also negative, the total PSP value is negative.

Moderate revenues. We now characterize the condition for the total PSP value to be strictly positive at moderate revenues $r\in[r^{HL},\max\{\tilde r^{HL},\min\{r^L,r^{LL}\}\})$. Numerical studies suggest that when α^H is large and thus $\tilde r^{HL}\ll\min\{r^L,r^{LL}\}$, the total PSP value is positive. See Figure 3 for an example.

The total PSP value is positive, if under PSP procurement the buyer uses diversification with the (H,L) and (L,H) PSP types but stops ordering from the (L,L) PSP type. Using diversification with the (H,L) and (L,H) PSP types, the buyer enjoys one of the following two benefits over direct procurement: a reduction in the informational costs of using diversification or an increase in the supply availability of the (H,L) and (L,H) pairs. (See the discussion in §5.1.) On the other hand, by not ordering from the (L,L) PSP type, the buyer avoids a cost of using the PSP, i.e., the cost of implicit supplier collusion, but does not earn any revenue either. Therefore, there is a negative PSP value associated with the (L,L) type. If α^H is large, the probability of drawing the low type for both suppliers simultaneously is negligible, and so is the buyer's cost from the (L, L) type. It is much more likely that the buyer will collect a benefit from using diversification with the (H, L) and (L, H) types.

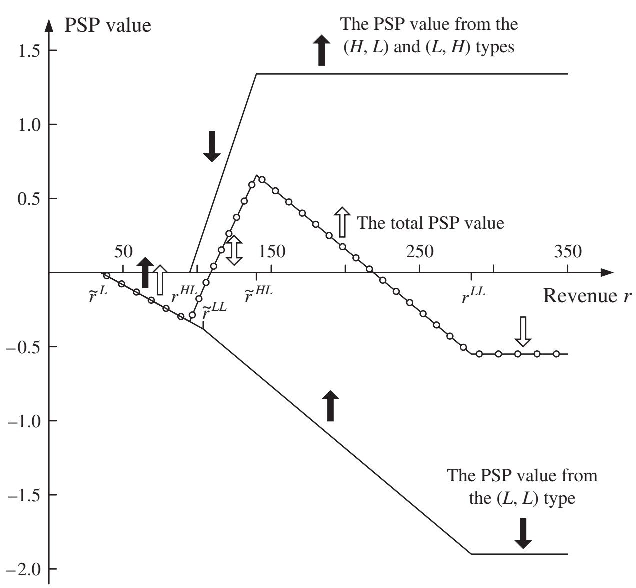
This highlights the importance of risk management strategies in procurement and their interactions with information. Only if the PSP-procurement system uses diversification but the direct-procurement system does not with some supplier types is the PSP valuable for the buyer.

6.2. The Effect of the Supply Base's Reliability

A salient feature of our model is supply disruption risk and the supply base's reliability. An interesting question is whether an improvement in the supply base's reliability is a substitute for or a complement to using PSP procurement. To explore this question, we measure the supply base's reliability using α^H, the probability of drawing a high-reliability type, and analyze the marginal change of the PSP value as α^H increases for a fixed revenue per unit r (but not how the breakpoints in r change). We assume $r^L > r^{LL} > \tilde{r}^{HL}$, under which the PSP values are illustrated in Figures 2 and 3, and their expressions are available from Tables 1 and 2. We use these expressions to analytically derive the direction of change of the PSP values and illustrate them in Figure 4.

Simple intuition suggests that as the supply base becomes more reliable, it is less important for the buyer

Figure 4 The Directions of Change in α^H and h of the PSP Value



Notes. The directions of change in h coincide with those in α^H. The parameter values are such that $r^L > r^{LL} > \tilde{r}^{HL}$. The solid black arrows indicate the directions of change of the PSP values by the PSP type. The white arrows indicate the direction of change of the total PSP value. An arrow pointing upward by a line segment indicates that the PSP value (by type) is increasing in α^H and h for the range of r that applies to the line segment. An arrow pointing downward indicates that the PSP value is decreasing in α^H and h. The bidirectional arrow indicate that the PSP value may be increasing or decreasing in α^H and h.

to take advantage of the PSP's knowledge of the suppliers' risk. Interestingly, Figure 4 shows that the total PSP value may increase in α^H at moderate and small revenues (i.e., $r < r^{LL}$).

The managerial takeaway is that an increase in the reliability of the supply base may encourage the buyer to use PSP procurement. In this paper, we focus on the informational and risk-management costs and benefits of using PSP procurement. In practice, the manager might also consider other costs and benefits (e.g., transactional). The decreasing informational and risk-management costs (or increasing benefits) of using the PSP enhance other positive benefits and may make PSP procurement a better choice than direct procurement.

The key driver of this behavior is the reduction of the supply availability of the (L, L) type due to the change of control, which occurs only at moderate and low revenues. Recall from the discussion in §5.2 that switching to PSP procurement causes the buyer to forgo ordering from the (L, L) pair and the opportunity to earn a profit. The likelihood of incurring a profit loss decreases as the supply base's reliability increases. In contrast, at large per-unit revenues, the PSP value decreases in α^H. This highlights the need to understand the driving economic forces that determine the PSP value at different revenue levels, which we explored in §5.

6.3. The Effect of the Reliability Gap Between the Two Types

We have quantified the PSP value for the buyer when the reliabilities of the two supplier types are fixed. A natural question to follow up is whether the PSP becomes more or less valuable when the reliability gap between the high and low types widens. To investigate this question, we increase h (or decrease l) while fixing l (or fixing h) and monitor the marginal change of the PSP value. (We do not analyze how the breakpoints in r change.) We assume $r^L > r^{LL} > \tilde{r}^{HL}$, under which the expressions for the PSP values are available from Tables 1 and 2. The directions of change in h are illustrated in Figure 4, and the directions of change in l are opposite to those in h. The findings are summarized in Proposition 6.

Proposition 6. *Suppose $r^L > r^{LL} > \tilde{r}^{HL}$. As h increases (or as l decreases) by a small value $\varepsilon > 0$, the total PSP value* (16) *decreases for $r \geq r^{LL}$, increases for $\tilde{r}^{HL} \leq r < r^{LL}$, and may increase or decrease for $r^{HL} \leq r < \tilde{r}^{HL}$.*

Simple intuition suggests that as the reliability gap widens, getting the right supplier matters more, so the PSP's information about the suppliers' reliabilities should become more valuable. Interestingly, Proposition 6 shows that the PSP value may decrease in h for large revenues (i.e., $r \geq r^{LL}$) and moderate revenues (i.e., $r^{HL} \leq r < \tilde{r}^{HL}$).

The managerial takeaway from Proposition 6 is that the reliability gap cannot be used as a sole indicator for choosing PSP procurement over direct procurement.

We identify two causes for why the PSP value may decrease. First, recall from §6.1 that, at large revenues, by switching to PSP procurement the buyer's profit decreases due to the extra informational costs for eliciting the more reliable types' truthful reports. The greater the reliability gap is, the more the buyer has to pay in informational costs. Second, at moderate revenues, by switching to PSP procurement, the buyer may enjoy an improvement in the supply availability of the (H, L) and (L, H) pairs, from using diversification with these pairs versus sole sourcing. As the high type becomes more reliable, the relative benefit of using the second supplier (low type) decreases. This intuition sheds light on the interaction between risk, information, and intermediation, which is a unique feature of our model.

7. Managerial Takeaways and Conclusion

What can we tell managers of a buyer firm who are contemplating whether to hire a procurement service provider in hopes of benefiting from its superior information about the suppliers? Contrary to naïve intuition about the informational benefits that PSPs bring, the PSP value can be negative. However, also contrary to the earlier results in the economics literature, the PSP value can be positive as well.

We provide intuitive explanations for how various economic forces affect the PSP value for the buyer by breaking the PSP value into positive and negative components (benefits and costs). This paper demonstrates that implicit supplier collusion enabled by the PSP may have both negative and positive effects on the PSP value. The benefits of implicit supplier collusion are surprising, a priori. They arise because the system with a PSP may have fewer credible ways of deceiving the buyer about the true reliabilities of the suppliers. This paper also shows that changing direct control to PSP control over procurement may have both positive and negative consequences for supply availability. On one hand, with some combinations of suppliers, diversification is cheaper for the PSP to implement, so the buyer enjoys an increased supply availability. On the other hand, with other combinations of suppliers, using diversification (or even ordering) is more expensive via the PSP, and the supply availability is reduced.

Our findings indicate that hiring a PSP is not the solution to the problem of an unreliable supply base. As the probability of drawing more reliable suppliers decreases, the value of PSP procurement may decrease or increase. In fact, numerical analysis indicates that for the PSP value to be positive, the probability of drawing reliable suppliers must be quite high.

Similarly, the increasing reliability gap between high- and low-reliability suppliers is not a reason to hire a PSP, because the value of the PSP may actually decrease in this gap.

This paper focuses on informational and risk management aspects of using a PSP. Besides these aspects, there are other benefits and costs that buyers can experience with PSPs (transactional, relational). Combining some of those other benefits (e.g., reduction of search costs, reduction in logistics costs) with the insights we developed in this paper should be straightforward. On the other hand, some benefits and costs (e.g., order aggregation, relational benefits) might interact with risk management and informational considerations in a nontrivial way and can be interesting subjects for future studies.

The results in this paper are derived using a static game. In a dynamic game, the interactions between information and supply risk would be complicated by the intertemporal effects of the players' decisions. These interactions are interesting, but are beyond our study. In future studies, the insights from our model can be used as a benchmark for exploring the informational benefits of using the PSP in dynamic settings.

In this paper, the buyer and the PSP use diversification for supply risk management. In practice, there are other risk management measures, such as backup production option (e.g., see Yang et al. 2009) and process improvement. These risk management measures allow for new forms of interactions between information, supply risk, and intermediation. These can be interesting subjects for future studies.

In our models, the suppliers' production outputs are 0 or 1. This Bernoulli yield model is appropriate for modeling supply disruptions (see the chapters by Tomlin and Wang 2011 and Aydin et al. 2012, which review the supply disruption literature). Even with such Bernoulli yields, our model is extremely difficult to analyze. Other forms of supply risk, such as random capacity, proportional yield, and stochastic lead time, require other models of supply uncertainty (e.g., see discussion of random capacity in Ciarallo et al. 1994, Babich 2010; see discussion of various production yield models in Sobel and Babich 2012; see discussion of stochastic lead-time models in Song and Zipkin 1996). Unfortunately, we cannot solve our problem under these alternative models of supply risk. However, we are quite confident that other models would still be subject to the economic forces and insights we have identified. For example, diversification also occurs under continuous stochastically proportional yield (e.g., see Federgruen and Yang 2009), so the interaction between diversification and implicit supplier collusion will continue to drive the PSP benefit. Of course, with different models, new insights can be found. For example, order inflation may occur in the continuous stochastically proportional yield model. We leave extensions to incorporate other models for future studies.

We have assumed that the suppliers cannot directly collude with each other. Intuitively, if direct supplier collusion reduces the buyer profit under direct procurement and supply risk, then PSP procurement will be even more attractive for the buyer. However, to justify this conjecture one would have to solve a model of direct procurement with direct supplier collusion. For example, following the setting of Mookherjee and Tsumagari (2004), such a model would be a two-stage, cascade mechanism design model: in Stage 1, the buyer designs a menu of grand contracts for the suppliers in anticipation that they will collude; in Stage 2, under the given grand contracts, supplier 1 designs a menu of side contracts for supplier 2 to agree to collude. Solving such a model is technically challenging and beyond the scope of this paper. Nevertheless, the solution would allow one to study the role of direct supplier collusion. Therefore, we leave this extension as a suggestion for future research.

Our assumption that the PSP has perfect information captures the situation where the information gap between the PSP and the suppliers is negligible relative to that between the buyer and the suppliers. There are situations where a substantial information gap persists between the PSP and the suppliers. To capture such situations, we expand the PSP-procurement model to allow the PSP to observe the suppliers' reliability types probabilistically: with probability β, the PSP is informed, perfectly observing the suppliers' types; with probability $1-\beta$, the PSP remains uninformed, having same information as the buyer. The PSP keeps private information of its state of knowledge. This problem is difficult, because it is a multidimensional mechanism design problem of two stages. We can characterize the solutions of the two extreme cases, $\beta=1$ and $\beta=0$, and develop insights for general cases from the results of these extreme cases. When $\beta=1$, the PSP is always informed as in our current PSP-procurement model. When $\beta=0$, the PSP and the buyer have the same information, so there is no value from using the PSP for the buyer. This special case is equivalent to the direct-procurement model. As β decreases from 1 to 0, the PSP's information deteriorates. We conjecture that the buyer's optimal profit under PSP procurement approaches that under direct procurement, and the value of the PSP for the buyer decreases to zero from a positive value or increases to zero from a negative value. Therefore, for any $1\geq\beta>0$, our main result that using the PSP for better information may be valuable remains true. Due to the technical difficulties, we cannot verify our conjecture for the general $1>\beta>0$. We leave this extension as a direction for future study.

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Appendix A. Supporting Materials for Proposition 1

Remark 1. Under Condition 1, the optimal transfer payment, $X^*(t_1,t_2)$, can be derived from the following equations:

$$\begin{aligned}
X^*(L,L)&=p^*(L,L)q^*(L,L)-[\psi^L((q^*,p^*)(L,L))]^+\\
&\quad-[\psi^{LL}((q^*,p^*)(L,L))]^+,\\
X^*(H,L)&=p^*(H,L)q^*(H,L)-[\psi^H((q^*,p^*)(H,L))]^+\\
&\quad-[\psi^{HL}((q^*,p^*)(H,L))]^++\Gamma_{LL}^{HL}(L,L),\\
X^*(H,H)&=p^*(H,H)q^*(H,H)-[\psi^H((q^*,p^*)(H,H))]^+\\
&\quad-[\psi^{HH}((q^*,p^*)(H,H))]^++\Gamma_{HL}^{HH}(H,L)\\
&\quad+\Gamma_{LL}^{HL}(L,L),
\end{aligned} \tag{A1}$$

where $\Gamma_{LL}^{HL}(L,L)\overset{\text{def}}{=}\Gamma_{LL}^{HL}((q^*,p^*)(L,L))$ and $\Gamma_{HL}^{HH}(H,L)\overset{\text{def}}{=}\Gamma_{HL}^{HH}((q^*,p^*)(H,L))$.

Appendix B. Technical Results

Lemma 5. *Given that $c^L/l>c^H/h$ and $h>l$, the following inequalities are true*:

$$\begin{aligned}
&\frac{c^L}{l(1-h)}>\frac{c^H}{h(1-h)}>\frac{c^H}{h}\quad \textit{and}\\
&\frac{c^L}{l(1-h)}>\frac{c^L}{l(1-l)}>\frac{c^L}{l}>\frac{c^H}{h}.
\end{aligned} \tag{B1}$$

Proof. The results follow from the inequalities $c^L/l>c^H/h$ and $h>l$. □

Lemma 6. *Under order quantity q and shortfall penalty p the (H,H) PSP type's reliability advantage over the (H,L) type is*

$$\Gamma_{HL}^{HH}(q,p)=\begin{cases}0 & \text{if } p<\dfrac{c^H}{h(1-h)},\\[2mm] [h(1-h)p-c^H]q & \text{if } \dfrac{c^H}{h(1-h)}\leq p<\dfrac{c^L}{l(1-h)},\\[2mm] [(h-l)(1-h)p-(c^H-c^L)]q & \text{if } p\geq\dfrac{c^L}{l(1-h)}\end{cases} \tag{B2}$$

The (H, L) PSP type's reliability advantage over the (L, L) type is

$$\Gamma^{HL}_{LL}(q,p) = \begin{cases} 0 & \text{if } p < \frac{c^H}{h}, \\ (hp - c^H)q & \text{if } \frac{c^H}{h} \le p < \frac{c^L}{l}, \\ [(h-l)p - (c^H - c^L)]q & \text{if } \frac{c^L}{l} \le p < \frac{c^L}{l(1-l)}, \\ \{[(1-l)^2 - (1-h)]p - c^H + 2c^L\}q & \text{if } \frac{c^L}{l(1-l)} \le p < \frac{c^L}{l(1-h)}, \\ [(h-l)(1-l)p - (c^H - c^L)]q & \text{if } p \ge \frac{c^L}{l(1-h)}. \end{cases} \tag{B3}$$

Both $\Gamma^{HL}_{LL}(q,p)$ and $\Gamma^{HH}_{HL}(q,p)$ are nonnegative and continuous in q and p, and are linearly increasing in q. Function $\Gamma^{HH}_{HL}(q,p)$ is monotonic increasing in the penalty p. Function $\Gamma^{HL}_{LL}(q,p)$ is monotonic increasing in p if and only if $(1-l)^2 - (1-h) \ge 0$. Under $(1-l)^2 - (1-h) < 0$, $\Gamma^{HL}_{LL}(q,p)$ decreases in $p \in [c^L/(l(1-l)), c^L/(l(1-h)))$.

Proof. To derive the expressions in (B2) and (B3), one can apply the expressions for $\psi^H(q,p)$, $\psi^L(q,p)$ (defined in (2)), $\psi^{H,H}(q,p)$, $\psi^{H,L}(q,p)$, and $\psi^{L,L}(q,p)$ (defined in (3)) to (6a) and (6b). Details are omitted. □

Lemma 7. *The following inequalities are true*:

$$\tilde{r}^{HL} > \tilde{r}^{LL} > \tilde{r}^L; \tag{B4a}$$

$$r^L > \tilde{r}^L, \quad \tilde{r}^{HL} > r^{HL}; \quad \text{and} \quad r^{HL} > \tilde{r}^L \quad \text{under } h \ge \tfrac{1}{2}. \tag{B4b}$$

Proof. The inequalities in (B4a) follow from the definitions of $\tilde{r}^{HL}$, $\tilde{r}^{LL}$, and $\tilde{r}^L$ (see (15a), (15c), and (15b)). In (B4b), inequality $r^L > \tilde{r}^L$ follows from the definitions of r^L (see (11b)) and $\tilde{r}^L$, and inequality $\tilde{r}^{HL} > r^{HL}$ follows from the definitions of $\tilde{r}^{HL}$ and r^{HL} (see (11a)).

Now, we prove $r^{HL} > \tilde{r}^L$ under $h \ge 1/2$. We shall show that if $(\alpha^L)^2\psi^L - (\alpha^L\alpha^H)\phi \le 0$ (i.e., $r \le \tilde{r}^L$), then $2(\alpha^H\alpha^L)\psi^{HL} - (\alpha^H)^2\phi < 0$ (i.e., $r < r^{HL}$). Recall the definitions $\psi^L = lr - c^L$ and $\psi^{HL} = l(1-h)r - c^L$. One can verify that $\psi^L > 2\psi^{HL}$ under $h \ge 1/2$. Therefore, $2(\alpha^H\alpha^L)\psi^{HL} - (\alpha^H)^2\phi < (\alpha^H/\alpha^L)[(\alpha^L)^2\psi^L - (\alpha^L\alpha^H)\phi] \le 0$. The result follows. □

Appendix C. The PSP Value from the (L, L) Contract Under $r^L < r^{LL} < \tilde{r}^{LL}$

In §5.2, we assumed $r^L > r^{LL} > \tilde{r}^{LL}$. To reveal additional effects of implicit supplier collusion and the change of control, we assume $r^L < r^{LL} < \tilde{r}^{LL}$. Other scenarios are possible, but we choose to present these two scenarios because they together are representative of the effects of implicit supplier collusion and the change of control.

Following the structure of Table 2, we present the procurements actions and the buyer's profits from the two models and the PSP value in Table C.1.

Under large and small revenues in Table C.1 (the rightmost and the leftmost columns), the effects of implicit supplier collusion and the change of control are identical to the respective cases in Table 2 (under $r^L > r^{LL} > \tilde{r}^{LL}$). Therefore, we focus on the cases of medium revenues in Table C.1, $r \in [r^{LL}, \tilde{r}^{LL})$ and $r \in [r^L, r^{LL})$, which did not appear in Table 2.

Consider the case of $r \in [r^{LL}, \tilde{r}^{LL})$. Diversification is employed under PSP procurement, but not under direct procurement. The expected benefit from increased supply availability is $(\alpha^L)^2\psi^{LL}$. However, diversification under PSP procurement increases the buyer's informational costs. When sole sourcing from the low-type supplier 1 under direct procurement, the buyer pays the (H, L) pair expected informational rent $(\alpha^H\alpha^L)\phi$. Under PSP procurement, the buyer incurs the informational cost ω for using diversification with the (L, L) PSP type. Compared to direct procurement, the (H, L) type earns an extra informational rent $(\alpha^H\alpha^L)(\omega - \phi)$, and the (L, H) type earns an expected informational rent $(\alpha^L\alpha^H)\omega$. The net effect from the change of control, $(\alpha^L)^2\psi^{LL} - (\alpha^L\alpha^H)\omega - (\alpha^H\alpha^L)(\omega - \phi)$, is negative.

The reason for why there is more diversification under PSP procurement is not obvious. On one hand, the PSP is privy to the suppliers' information, and the PSP can order from the second supplier without paying informational cost that the buyer would have to pay in the same situation. On the other hand, we are looking at the optimal contracts designed by the buyer, and, for the buyer, diversification through the PSP comes with costs due to the change of control and implicit supplier collusion. The following is an explanation of this result.

The buyer's benefit of ordering from the second supplier, in addition to ordering from the first one, is $(\alpha^L)^2\psi^{LL}$, and it is the same in both the direct-procurement and PSP-procurement models. However, the expected informational costs of ordering from the second supplier vary. Under direct procurement, this cost of the second supplier is $(\alpha^L\alpha^H)\phi$. It is due to the incremental informational cost the buyer must pay to prevent the second supplier, if it is the high type, from pretending to be the low type. (Because there are two suppliers, there is also an informational cost attributed to the first supplier, but we are only concerned with the incremental effects of diversification.) Under PSP procurement, the incremental informational cost of ordering from the second supplier is $[1 - (\alpha^L)^2](\omega - \phi)$. It is due to the possibility of the PSP of types (H, H), (H, L), and (L, H) pretending to do be (L, L) type. If $(\alpha^L\alpha^H)\phi > [1 - (\alpha^L)^2](\omega - \phi)$, then the diversification is more likely to be employed under PSP procurement.

For the case of $r \in [r^L, r^{LL})$, there is no difference in the supply availability between the two models. It turns out that the change of control has no effect on the buyer's informational costs either. As we discussed in §5.1, intuitively, the buyer is indifferent between dealing with one supplier directly and dealing with a coordinated subsystem of the PSP and one supplier.

The only PSP value comes from implicit supplier collusion. Under direct procurement, the high-type supplier 1 has an incentive to pretend to be the low type. (The high-type supplier 2 does not, because it would not win an order by pretending to be the low type.) The buyer pays the expected informational cost of $(\alpha^H\alpha^L)\phi$ to prevent that. Under PSP procurement, not only the (H, L) PSP type, but also the (L, H) and (H, H) PSP types can pretend to be (L, L). In expectation, the buyer pays extra expected informational costs of $[(\alpha^L\alpha^H) + (\alpha^H)^2]\phi$.

Table C.1 The Optimal Procurement Actions, the Buyer's Profits, and the Buyer's Value from PSP, by Cause, Attributable to the (L, L) Type vs. the Revenue per Unit r

Revenue per unit, $r \in$	$[\tilde{r}^L, r^L)$	$[r^L, r^{LL})$	$[r^{LL}, \tilde{r}^{LL})$	$[\tilde{r}^{LL}, \infty)$
PSP procurement				
$(z_1^*, z_2^*)(L, L)$ Profit	$(0, 0)$ 0	$(1, 0)$ $(\alpha^L)^2\psi^L - [1-(\alpha^L)^2]\phi$	$(1, 1)$ $(\alpha^L)^2(\psi^L+\psi^{LL}) - [1-(\alpha^L)^2]\omega$	
Direct procurement				
(z_1^L, z_2^L) Profit	$(1, 0)$ $(\alpha^L)^2\psi^L - (\alpha^H\alpha^L)\phi$			$(1, 1)$ $(\alpha^L)^2(\psi^L+\psi^{LL}) - 2(\alpha^H\alpha^L)\phi$
PSP value $=$ PSP profit $-$ direct profit				
Change of control				
Supply availability Informational cost	$-(\alpha^L)^2\psi^L$ $(\alpha^H\alpha^L)\phi$	0 0	$(\alpha^L)^2\psi^{LL}$ $-[(\alpha^L\alpha^H)\omega + (\alpha^H\alpha^L)(\omega-\phi)]$	0 $-2(\alpha^H\alpha^L)(\omega-\phi)$
Implicit supplier collusion	0	$-[(\alpha^L\alpha^H)+(\alpha^H)^2]\phi$	$-(\alpha^H)^2\omega$	
Total	$-[(\alpha^L)^2\psi^L - (\alpha^H\alpha^L)\phi]$	$-[(\alpha^L\alpha^H)+(\alpha^H)^2]\phi$	$(\alpha^L)^2\psi^{LL} - (\alpha^L\alpha^H)\omega - (\alpha^H\alpha^L)(\omega-\phi) - (\alpha^H)^2\omega$	$-2(\alpha^H\alpha^L)(\omega-\phi) - (\alpha^H)^2\omega$

Note. Assumption on parameter values: $r^L < r^{LL} < \tilde{r}^{LL}$.

Appendix D. List of Definitions

Term	Definition	Reference
$\theta = h, l$	The probability of successful production run by the high- and low-reliability supplier types	§2
α^H, α^L	The probability of drawing the high and low supplier types; $\alpha^H + \alpha^L = 1$	§2
c^H, c^L	The unit cost of running production by the high and low supplier types	§2
D	The buyer's market demand; we assume $D = 1$	§2
r	Revenue per unit of market demand satisfied	§2
X, q, p	Payment, required quantity and penalty per unit of shortfall	§3.1
$(X, q, p)(t_1, t_2)$	The contract intended for the (t_1, t_2) PSP type in the contract menu	§3.1
$\pi^{t_1, t_2}(X, q, p)$	Optimal expected profit of the (t_1, t_2) PSP type, under contract (X, q, p)	(1)
$(z_1^*, z_2^*)(q, p)$	The PSP's production assignments to the suppliers under (q, p)	§3.2
$\psi^t(q, p)$	$\stackrel{\text{def}}{=} (\theta^t p - c^t)q$, the PSP's benefit of sole sourcing from a supplier of type t, under given (q, p)	(2)
$\psi^{t_1, t_2}(q, p)$	$\stackrel{\text{def}}{=} [\theta^{t_2}(1-\theta^{t_1})p - c^{t_2}]q$, the PSP's benefit of diversification with a pair of suppliers of types (t_1, t_2), under given (q, p)	(3)
$\Gamma_{HL}^{HH}(q, p)$	$\stackrel{\text{def}}{=} \pi^{HH}(X, q, p) - \pi^{HL}(X, q, p)$, the reliability advantage of the (H, H) PSP type over the (H, L) type, under given (q, p)	(5a)
$\Gamma_{LL}^{HL}(q, p)$	$\stackrel{\text{def}}{=} \pi^{HL}(X, q, p) - \pi^{LL}(X, q, p)$, the reliability advantage of the (H, L) PSP type over the (L, L) type, under given (q, p)	(5b)
$\pi^{t_1, t_2}(s_1, s_2)$	$\stackrel{\text{def}}{=} \pi^{t_1, t_2}((X, q, p)(s_1, s_2))$, the optimal profit of the (t_1, t_2) PSP type under the contract intended for the (s_1, s_2) type	§3.4
$(z_1^*, z_2^*)(t_1, t_2)$	$(z_1^*, z_2^*)((q, p)(t_1, t_2))$	§3.4
$\Gamma_{HL}^{HH}(t_1, t_2)$	$\stackrel{\text{def}}{=} \Gamma_{HL}^{HH}((q, p)(t_1, t_2))$	
$\Gamma_{LL}^{HL}(t_1, t_2)$	$\stackrel{\text{def}}{=} \Gamma_{LL}^{HL}((q, p)(t_1, t_2))$	
ψ^t	$\stackrel{\text{def}}{=} \psi^t(q, p)$ at $(q, p) = (1, r)$	(8a)
ψ^{t_1, t_2}	$\stackrel{\text{def}}{=} \psi^{t_1, t_2}(q, p)$ at $(q, p) = (1, r)$	(8b)
$\tilde{p}$	The optimal penalty $p^*(L, L)$ that induces the (L, L) PSP type to diversify	(9a)
ϕ	$\stackrel{\text{def}}{=} \Gamma_{LL}^{HL}\left(1, \dfrac{c^L}{l}\right)$, informational cost, the (L, L) PSP type sole sources	(9b)
	$\stackrel{\text{def}}{=} \Gamma_{HL}^{HH}\left(1, \dfrac{c^L}{l(1-h)}\right)$, informational cost, the (H, L) PSP type diversifies	(9b)
	$\stackrel{\text{def}}{=} \Gamma_{L}^{H}\left(1, \dfrac{c^L}{l}\right)$, informational cost of a low-type supplier, direct procurement	(12)
ω	$\stackrel{\text{def}}{=} \Gamma_{LL}^{HL}(1, \tilde{p})$, informational cost, the (L, L) PSP type diversifies	(9c)
r^{HL}	The value of per-unit revenue, above which it is optimal for the buyer to induce the (H, L) PSP type to diversify	(11a)
r^L	The value of per-unit revenue, above which it is optimal for the buyer to induce the (L, L) PSP type to sole source	(11b)
r^{LL}	The value of per-unit revenue, above which it is optimal for the buyer to induce the (L, L) PSP type to diversify	(11c)
$\tilde{r}^{HL}$	The value of per-unit revenue, above which it is optimal for the buyer to diversify with the (H, L) supplier pair in the direct procurement model	(15a)
$\tilde{r}^L$	The value of per-unit revenue, above which it is optimal for the buyer to sole source from a low-type supplier in the direct procurement model	(15b)
$\tilde{r}^{LL}$	The value of per-unit revenue, above which it is optimal for the buyer to diversify with the (L, L) supplier pair in the direct procurement model	(15c)

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