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OPTIMAL PROCUREMENT STRATEGY UNDER SUPPLY RISK

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With the rapid expansion of global business, newer suppliers with cheaper but possibly unreliable technologies have entered the marketplace to win orders from buyer firms by beating the price of their perfectly reliable (but expensive) competitors. We model the procurement problem as a Nash game where the buyer has to allocate its purchases between an expensive but reliable supplier, and a cheaper but unreliable supplier. The suppliers specify prices for different proportions of the order awarded to them. Our analysis shows that, when perfect information is available about the reliability level of the unreliable supplier, the Nash equilibrium is a sole-sourcing allocation and that the supplier selection decision depends on the reliability and cost differentials between the two suppliers. In addition, we model the case when the buyer and the reliable supplier have limited information about the reliability of the unreliable supplier. Even in such an asymmetric scenario, the buyer's equilibrium allocation is a sole-sourcing outcome, but depending on system conditions either a separating or a pooling equilibrium is possible. An interesting insight into the effect of information asymmetry is that it can result in higher or lower profits/costs for the channel partners (compared to the perfect information case). As such, the buyer may even benefit from information asymmetry regarding unreliable supplier due to its impact on the degree of competition between the two suppliers.

Keywords: Procurement; supply risk management; asymmetric information.

1. Introduction and Related Literature

One of the most important characteristics of the "new" economy is its growing dependence on outsourcing, and resulting fragmentation of monolithic organizations. Survival in this atmosphere depends on a firm's ability to effectively manage its own operations, as well as to intelligently collaborate with its supply chain partners who are involved in the process of product/service generation. The increasing globalization of supply base, fuelled partly by the ease of B2B transactions through internet, only exacerbates the complexity of supply chain management (SCM). This phenomenon is changing the way firms from emerging economies trade with the rest of the world by allowing small and mid-sized companies to access a whole new set of buyers, and vice versa. The growing amount of offshore outsourcing by North American (NA) firms to Asian suppliers in low-cost countries (LCCs) is a testament to this fact (Deloitte Research, 2003a; Ray *et al.*, 2005). Actually, more than 25% NA companies do not produce anything in their home base; China, on the other hand, produces more than 50% of the world's cameras, 30% of the televisions and 20% of the refrigerators (Deloitte Research, 2003a).

However, although such actions have opened more opportunities for trade, any outsourcing decision must keep the following caveat in mind: The reliability and trustworthiness of many of the low-cost suppliers might not be worth the risk (Economist, 2001). This puts the buyers in a dilemma.

" *...Sure, they may save a ton of money by holding a reverse auction, but how can they be sure that the low-bidding suppliers can actually fill their orders.*" (Feuerstein, 2000).

This issue has recently come to the forefront as a result of huge recalls of products produced by offshore suppliers, especially the ones by Mattel and Purina (CNN Money, 2007a; CNN Money, 2007b). Offshore supplier quality is now one of the primary causes of concern for most supply chain managers, and significantly increases the risk of supply chain failures/disruptions (Deloitte Research, 2003b). In fact, supply-demand mismatches, caused partly by such risks, results in significantly lower shareholder wealth (Hendricks and Singhal, 2003). Rather, reliable supply of quality products by local, but perhaps more expensive, suppliers has often proved crucial for effective SCM. It is then important that managers take this trade-off into account while making procurement decisions. Another consequence of the fragmentation of supply chains is the lack of visibility regarding supplier risk/reliability. Indeed, only 15% of the buyers may have good information about their suppliers (Deloitte Research, 2003b). Information asymmetry (that is, lack of full information) regarding supplier reliability, has been attributed as being a key factor behind recent problems in toy, textiles, and electronics industries (USA Today, 2008; Midler, 2009). On the other hand, empirical studies have shown that effective supplier management strategy improves both the suppliers' and buyers' performance (Shin *et al.* 2000). The motivation of our paper stems from addressing the procurement problem for a buyer in this context of supply risk and information asymmetry. Specifically, we consider a single buyer who has to allocate an order between an expensive, but reliable, supplier and a cheaper, but unreliable, supplier where the degree of reliability of the latter supplier might not be exactly known to the other two channel partners. This might, for example, represent a scenario where a NA buyer has a trusted local supplier, but would like to explore business opportunities with cheaper suppliers from LCCs who have just entered the marketplace and not much information is available about their reliability.

While the complexity of managerial decision-making can be due to demand and/or supply side risks/uncertainties, in this paper we focus on the supply side. The sources of supply risks may be specific to the product, or to the supplier, or both. Supplier-specific risk (i.e., the ability of a supplier to meet the buyer's specifications) depends on a variety of factors like the technology used, manufacturing capability, available capacity, maintenance/quality programs, political risks, infrastructure, trade-policies. For example, the technology used by a supplier might not meet the strict quality requirements of the buyer, or problems in the distribution infrastructure/custom requirements might prohibit a supplier from satisfying the due date requirement of the buyer. Such supply problems are most challenging if the buyer and the supplier are interacting for the first-time and/or if the buyer does not have previous experience dealing with other suppliers in that region.

The general concept of supply uncertainty has been analyzed before in operations management (OM) literature. In these models supply uncertainty is usually in terms of quantity of acceptable goods available to the buyer for sale at the right place and at the right time. The related models can be categorized primarily into three streams. In the first stream, commonly referred to as the random yield literature, the quantity of good units delivered by the supplier is a random fraction of the quantity ordered by the buyer (see Anupindi and Akella, 1993; Gerchak *et al.*, 1994; Gurnani *et al.*, 2000; Gurnani and Gerchak, 2007; Huh and Nagarajan, 2010). Our paper, on the other hand, follows the second stream in which the supply uncertainty is of the "all-or-nothing" kind (Turnbull, 1986; Anupindi and Akella, 1993; Gurnani *et al.*, 1996). In this case, the supplier is either able to deliver the entire amount ordered (of acceptable quality) or nothing at all. The second type of supply uncertainty usually arises due to the supplier missing the due-date for delivery or because of quality problems. For example, if the buyer is facing a concentrated selling season (e.g., Christmas season) or a project due date, then unless the supplier delivers by a certain time it might not be acceptable to the buyer. According to a Reuters article, manufacturing problems from a new technology used at IBM's East Fishkill, New York, plant led to production shortages which drew complaints from Apple Computer that IBM's inability to deliver chips on time is the reason for its inability to put Xserve G5 computers on the retail shelf (Sorrid, 2004). Finally, the third stream considers supply uncertainty due to (exogenous) randomness in terms of capacity (Ciarallo *et al.*, 1994; Dada *et al.*, 2007; Gümüş *et al.*, 2012).

While most of the above literature focus on optimal procurement policy from a single unreliable supplier, in a recent paper Tomlin (2006) studies the optimal allocation between two different suppliers, one of which is unreliable but cheap, while the other is reliable but more expensive (like in our setting). The two suppliers are constrained in terms of capacity, but the reliable supplier may improve its volume flexibility at a cost. It is shown that in the special case in which the reliable supplier has no flexibility and the unreliable supplier has infinite capacity, a risk-neutral firm will pursue one of the following disruption-management strategy: Carry inventory, single-source from the reliable supplier, or passive acceptance. In a recent paper, Babich *et al.* (2007) extended this stream of research by considering exogenous supplier risk in a decentralized setting. In their paper, multiple suppliers compete for the buyer's order but there is no information asymmetry about supplier reliability. In the supply risk contracting literature with information asymmetry, some recent papers include Gurnani and Shi (2006), Yang *et al.* (2009), Gümüş *et al.* (2009). While Gurnani and Shi (2006) consider a bargaining approach where the decentralized supply chain partners have different estimates about supply reliability, in Yang *et al.* (2009), the buyer designs a menu contract whereby private information about supplier reliability is revealed through contract choices made by the supplier. Using a different approach, Gümüş *et al.* (2009) study supplier-initiated contracts, more specifically, *guarantee contracts* in a decentralized supply chain with asymmetric information about supplier reliability and analyze their effects on profits and equilibrium decisions on supply chain partners. Moreover, supply uncertainty in their model stems from randomness in supplier capacity as opposed to randomness of yield in our paper.

Finally, our paper is related to papers in the economics/OM literature that deal with procurement allocation in an auction setup. The most noteworthy from our perspective is the paper by Anton and Yao (1989) who consider a procurement auction model and derive a continuum of Nash equilibrium outcomes for the case of two reliable suppliers who are asymmetric in terms of cost. For each outcome, the orders are exact split awards, in that the total award size is *fixed* and the allocation decision is to determine the proportion to be awarded to each supplier. Since the auction-related OM literature is not directly related to our paper, for a detailed review of this stream we refer the readers to Elmaghraby (2000) and Keskinocak and Tayur (2001).

The objective of our paper is to model the profit-maximizing procurement decisions of a firm (buyer) that has to satisfy a fixed amount of end-customer demand at a given price. The buyer can allocate the demand between two suppliers. One of the suppliers is a reliable one, who can ensure that the supply process is not disrupted. However, she also charges a price premium for guaranteeing quality and timely delivery. On the contrary, the second supplier is cheaper, but less reliable. Furthermore, we also assume that in case the unreliable supplier is not able to make the delivery, the buyer can meet the shortfall through an alternative arrangement, but at a cost even higher than that of the reliable supplier. This arrangement might be either using in-house production or emergency procurement from an alternative supplier or penalty payment to the end customer (henceforth, we will term this arrangement as the in-house option). We model the problem as a Nash game between the two suppliers. These suppliers submit their profit-maximizing offers, based on the information available, that specifies prices for different proportions of the order awarded to them. Obviously, each supplier needs to take into account the response of its competitor, and the decision-making process of the buyer while deciding on its offer.[1] The buyer then evaluates the offers and determines: (i) how much to procure, and (ii) how to allocate the total order among three supply sources (two different suppliers of varying costs and reliabilities, and the reliable in-house production), with the objective of maximizing its profit. Some of the issues, we address are:

- What is the equilibrium allocation for the buyer as well as the costs/profits for the three channel partners under two information scenarios:
  - — When all the parties involved have *perfect* (*symmetric*) *information* about the reliability of the cheaper (and less reliable) supplier;
  - — When there is *information asymmetry* between the parties about the reliability level of the cheaper supplier?
- What are the effects of degree of supply reliability and cost parameters on the equilibrium allocation outcome and costs/profits of the associated parties under the two information scenarios?
- How does the asymmetry in terms of reliability information affects the equilibrium allocation and costs/profits of the channel partners? That is, how does the equilibrium allocation, buyer's procurement costs and the profits of the two suppliers compare under the two information scenarios?

We show that for the perfect information case, the Nash equilbrium allocation is a sole-sourcing outcome which depends on the reliability and cost parameters of the two suppliers. The unreliable supplier (respectively, reliable supplier) is more likely to get the allocation if its reliability is high (low), cost differential with reliable (unreliable) supplier is high (low) and when the buyer's in-house production cost is low (high). For the asymmetric information case, the allocation outcome is still sole-sourcing, but now the equilibrium can be of separating or pooling type. Under the pooling type equilibrium, the reliable supplier gets the allocation, whereas under the separating type, either the relatively less risky unreliable supplier or the reliable supplier gets the order. In contrast to conventional wisdom, lack of perfect information regarding supplier reliability may lead to higher or lower profits/costs for the channel partners (as compared to the perfect information case). The reliable supplier is weakly better off under the imperfect information scenario when the unreliable supplier is not too risky (h-type) as it leads to less intense competition between the suppliers. For the unreliable supplier, the results are mixed. If the

[1] The in-house production cost is known and the buyer can call upon it at anytime. However, since this option is the most expensive, it may be used as a last-resort option.

unreliable supplier is indeed very risky (l-type), as expected, it is weakly better off under imperfect information as the reliable supplier then faces more competition for order allocation. However, if the unreliable supplier is of the h-type, the separating equilibrium allows it to differentiate from the more uncertain l-type and compete more effectively with the reliable supplier resulting in higher prices being charged by both suppliers. This has interesting implications for the buyer. When the unreliable supplier is of l-type, the buyer mostly prefers asymmetric information setting since the reliable supplier has to compete based on imperfect information. However, when there is a pooling equilibrium, the buyer prefers perfect information since the unreliable supplier in that case cannot compete effectively under imperfect information and the reliable supplier is able to increase costs for the buyer under imperfect information scenario.

The rest of the paper is organized as follows. In the next section, we discuss the model framework and formulate the offers to be submitted by the two suppliers and the procurement problem for the buyer in the perfect information scenario. In Sec. 3, we characterize the Nash equilibrium outcome for the perfect information scenario, and subsequently, in Sec. 4, we analyze the case when there is information asymmetry about the reliability of the cheaper supplier. We also compare the costs/profits under the two information scenarios in this section. Finally, in Sec. 5, we present the conclusions of our study and identify potential future research issues.

2. Model Formulation

We consider the case of a buyer who has committed to delivering x units (fixed) of a product to his customers and has to make procurement allocation decisions between two potential suppliers.[2] The model setting is based on a reverse auction studied by Anton and Yao (1989) with two reliable suppliers. Supplier R is the long-time trusted and reliable supplier, whereas supplier U, relatively new in business, is unreliable in terms of its delivery commitment. Following Turnbull (1986), Gurnani *et al.* (1996), Babich *et al.* (2007) and Yang *et al.* (2009), we assume that delivery by the unreliable supplier U is dichotomous — either she delivers 100% of the order, or delivers nothing at all. Suppose that she receives payment only upon successful delivery of the order, and let $\beta \in (0, 1]$ be the probability that U can fulfill her order.

In this paper, we model a setting where each supplier submits an offer to supply the product to the buyer that specifies prices for different proportions of x that is awarded to her. If αx and γx units are awarded to suppliers U and R, respectively,[3] $\alpha \in [0, 1]$ and $\gamma \in [0, 1]$, the offers are functions $P_U(\alpha)$ for supplier U and $P_R(\gamma)$ for supplier R, where $P_i : [0, 1] \rightarrow \Re$, $i = U, R$, with $P_U(0) = 0 = P_R(0)$. Note

[2]We assume that the two suppliers have already been identified. For discussion about single versus multi-sourcing strategies refer to Treleven and Schweikhart (1988).

[3]Throughout the paper we follow the notation that an order (α, γ) indicates that αx units are awarded to supplier U and γx units to supplier R.

that we do not restrict α and γ to add up to unity, i.e., awards are not necessarily *split-awards*. The reason for this is intuitive in the face of supplier unreliability. For instance, even if the full contract is awarded to supplier U (i.e., $\alpha = 1$), she might default on delivery. It is then quite natural for the buyer to err on the side of caution, and to order some share from the reliable supplier. Thus, $\alpha + \gamma > 1$ (*over-ordering*) is a natural possibility in our framework. We also allow $\alpha + \gamma < 1$ (*under-ordering*) to add up to less than unity to capture the fact that the buyer can use in-house production to satisfy the shortfall.

Suppliers U and R face the costs of production $C_U(\alpha)$ and $C_R(\gamma)$, respectively, where $C_i : [0,1] \to \Re$, $i = U, R$, with $C_U(0) = 0 = C_R(0)$. Supplier U is unreliable because, presumably, she is using an inferior (and cheaper) technology. So, we assume that $C_U(\alpha) < C_R(\alpha)$ for all $\alpha \in (0,1]$. Furthermore, suppose that the suppliers have complete information about each other's costs when they bid.

Recall that deliveries are "all or nothing" in nature. If a share $\eta \in [0,1]$ of x remains undelivered, the buyer incurs a cost of $K(\eta)$, where $K : [0,1] \to \Re$, with $K(0) = 0$, to fulfill its obligation. As discussed before, this cost can have the following alternative interpretations although we term it as in-house production cost (similar assumption is common in the operations literature, e.g., Rao *et al.*, 2005): The buyer can produce in-house[4] at a high cost, or the buyer pays the penalty for nondelivery to his own customers, or the buyer procures the deficit from an alternative source incurring an expediting fee. It is natural to assume that $K(\eta) > C_R(\eta) > C_U(\eta)$, for all $\eta \in (0,1]$.

For now assume that the buyer and the reliable supplier have perfect information about the reliability level of the unreliable supplier (i.e., all three channel partners exactly know β). In that case, when the buyer places an order (α, γ), the total cost to the system has three components — production costs of suppliers U and R, and the expected in-house production cost of the buyer. Given any order (α, γ), let us define the total system cost as

$$TSC(\alpha, \gamma) = C_U(\alpha) + C_R(\gamma) + \beta K(\{1 - (\alpha + \gamma)\}^+) + (1 - \beta)K(1 - \gamma),$$

where $\{1 - (\alpha + \gamma)\}^+ = \left\{\begin{smallmatrix} 0, & \text{if } (\alpha+\gamma) \geq 1, \\ 1 - (\alpha + \gamma), & \text{if } (\alpha+\gamma) < 1. \end{smallmatrix}\right\}$.

If the suppliers submit the offers $P_U(\cdot)$ and $P_R(\cdot)$ and the buyer places the order (α, γ), supplier R earns the profit $\pi_R(\gamma) = P_R(\gamma) - C_R(\gamma)$, while supplier U's expected profit is $\pi_U(\alpha) = \beta P_U(\alpha) - C_U(\alpha)$. Note that supplier U receives the payment $P_U(\alpha)$ only when she delivers the promised amount αx. However, as is a standard assumption in the literature, we assume that since production cost is sunk, in case of nondelivery, the supplier is not paid at all but has to bear the production cost $C_U(\alpha)$, irrespective of the supply situation. The suppliers maximize expected profits, and their participation is ensured by restricting our attention to bids for which $\pi_U(\alpha) \geq 0$ and $\pi_R(\gamma) \geq 0$.

[4]For example, in the defense sector it is quite common for the government to use outside suppliers, but also retain the government-owned production option (Dana and Spier, 1994).

The buyer's expected procurement cost is

$$G(\alpha,\gamma)=\beta P_U(\alpha)+P_R(\gamma)+\beta K(\{1-(\alpha+\gamma)\}^+)+(1-\beta)K(1-\gamma), \tag{1}$$

and the buyer places the order $(\alpha,\,\gamma)$ to maximize his profit. However, since the buyer's selling price is exogenous to the model (determined independently when the commitment of x units was made), the profit maximization problem is equivalent to cost minimization. That is, the buyer's objective is to solve the following problem:

$$(\alpha,\gamma)\in\arg\min_{(\alpha,\gamma)\in[0,1]\times[0,1]}\{G(\alpha,\gamma)\}. \tag{2}$$

We formulate the above problem as a *two-stage Nash* game. The sequence of the game is as follows. In stage 1, the two suppliers play a Nash game by simultaneously (and noncooperatively) submitting their profit-maximizing offers $P_U(\cdot)$ and $P_R(\cdot)$ to the buyer. Based on those offers, in stage 2, the buyer chooses the order $(\alpha,\,\gamma)$ that minimizes the expected procurement cost. A Nash equilibrium involves a pair of bids submitted by the suppliers, $(P_U^*(\alpha),P_R^*(\gamma))$, such that the bids are mutually best responses for them. Given the equilibrium bids, if an order (α^*,γ^*) minimizes the buyer's expected procurement cost [i.e., satisfies (2)], then (α^*,γ^*) is an equilibrium outcome. The equilibrium procurement price is denoted by $g^*=G(\alpha^*,\gamma^*)=\beta P_U^*(\alpha^*)+P_R^*(\gamma^*)+\beta K(\{1-(\alpha^*+\gamma^*)\}^+)+(1-\beta)K(1-\gamma^*)$. Note that a *sole-source outcome* is an order (α,γ) such that either $\alpha=0$ or $\gamma=0$, whereas a *dual-source outcome* is an order (α,γ), where $0<\alpha\le 1$ and $0<\gamma<1$.

2.1. *Solution approach*

The objective for the buyer is to choose an allocation scheme that minimizes his total expected procurement costs, whereas for the suppliers the objective is to structure their offers in order to maximize their individual expected profits. To analyze the above two-stage game, in this section we first derive the deviation conditions to characterize the Nash Equilibrium (NE) offers for the suppliers. The deviation conditions essentially *eliminate* orders that cannot be supported in equilibrium — one or more parties would be better off with a different allocation scheme.

Deviation Conditions: Suppose that the suppliers submit the offers (P_U,P_R) and the buyer places the order (α,γ). Supplier U can induce the buyer to switch from the order (α,γ) to $(\widehat{\alpha},\widehat{\gamma})$ if U can find a price $\widehat{p}$ for $\widehat{\alpha}$ such that U's expected profit is greater $(\pi_U(\widehat{\alpha})>\pi_U(\alpha))$ *and* the buyer incurs a lower expected procurement cost $(G(\widehat{\alpha},\widehat{\gamma})<G(\alpha,\gamma))$. This will happen if $\beta\widehat{p}-C_U(\widehat{\alpha})>\beta P_U(\alpha)-C_U(\alpha)$, and $\beta\widehat{p}+P_R(\widehat{\gamma})+\beta K(\{1-(\widehat{\alpha}+\widehat{\gamma})\}^+)+(1-\beta)K(1-\widehat{\gamma})<\beta P_U(\alpha)+P_R(\gamma)+\beta K(\{1-(\alpha+\gamma)\}^+)+(1-\beta)K(1-\gamma)$. After some simplification (using $\pi_R(\gamma)=P_R(\gamma)-C_R(\gamma)$) we conclude that supplier U can profitably induce the buyer to switch from (α,γ) to $(\widehat{\alpha},\widehat{\gamma})$ if

$$\begin{aligned}&\pi_R(\gamma)+C_U(\alpha)+C_R(\gamma)+\beta K(\{1-(\alpha+\gamma)\}^+)+(1-\beta)K(1-\gamma)\\&\quad>\pi_R(\widehat{\gamma})+C_U(\widehat{\alpha})+C_R(\widehat{\gamma})+\beta K(\{1-(\widehat{\alpha}+\widehat{\gamma})\}^+)+(1-\beta)K(1-\widehat{\gamma}).\end{aligned} \tag{3}$$

Similarly, supplier R can induce the buyer to switch from the order (α, γ) to $(\widehat{\alpha}, \widehat{\gamma})$ if

$$\begin{aligned}&\pi_U(\alpha) + C_U(\alpha) + C_R(\gamma) + \beta K(\{1-(\alpha+\gamma)\}^+) + (1-\beta)K(1-\gamma)\\&\quad > \pi_U(\widehat{\alpha}) + C_U(\widehat{\alpha}) + C_R(\widehat{\gamma}) + \beta K(\{1-(\widehat{\alpha}+\widehat{\gamma})\}^+) + (1-\beta)K(1-\widehat{\gamma}). \qquad (4)\end{aligned}$$

In what follows, we use the above two deviation conditions in order to determine the Nash equilibrium outcome(s) of the game. Note that these conditions are necessary, but not sufficient. As such, we use them to eliminate allocations that cannot be sustained under equilibrium. Once we have eliminated these allocations, we use the original conditions to develop the supplier offers.

In the next section, we analyze the problem formulated in (2), i.e., when the buyer and the reliable supplier R have perfect information about the reliability level of supplier U, i.e., β, to determine the optimal procurement allocation, as well as the associated costs/profits for all the channel partners.

3. Perfect (Symmetric) Information Scenario

Let us suppose that the buyer and the reliable supplier have exact knowledge about β, which implies that there is no asymmetry in terms of information among the three channel partners. We also assume that the marginal costs of production for the suppliers and the in-house option are linear functions. Specifically, $C_U(\alpha) = U\alpha$, $C_R(\gamma) = R\gamma$, and $K(\delta) = K\delta$, where, $U < R < K$. So, the reliable supplier is more expensive than the unreliable supplier, and the in-house production option is the most expensive. Note that $(R-U)$ can be thought of as the *reliability premium*, i.e., a measure of increase in production cost for the reliable supplier to guarantee delivery. In order to determine the Nash equilibrium allocation outcome for this information scenario, we have to consider the two possible cases of multi-source and sole-source outcomes. The next proposition presents the equilibrium allocation for this scenario.[5]

Proposition 1. *The following are true*:

- *Over-ordering, under-ordering or multi-sourcing cannot be equilibrium outcomes.*
- $(0, 1)$ *is the unique equilibrium allocation if* $\beta < 1 - \frac{R-U}{K}$, *whereas* $(1, 0)$ *is the unique equilibrium allocation when* $\beta > 1 - \frac{R-U}{K}$.

The above proposition implies that only one of the two suppliers will get an allocation, and that the particular supplier would set its offer such that it is optimal for the buyer to order exactly equal to its demand[6]. Clearly, the way to manage supply risk in this setting is to *allocate the whole order to one of the suppliers*, where the choice of the supplier depends on the reliability premium $R-U$, reliability

[5]The proofs for all propositions are provided in the Appendix.

[6]Note that if $\beta = 1 - \frac{R-U}{K}$, the buyer would be indifferent between ordering from the reliable or unreliable supplier.

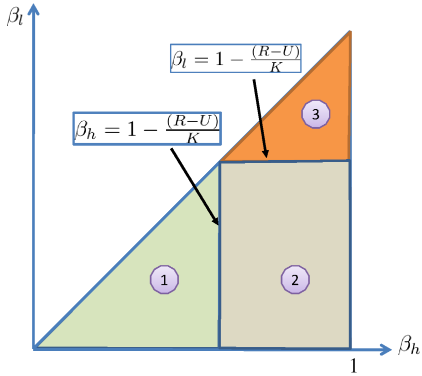
level of the cheaper supplier β, and the cost of producing in-house K. This also means that it is *never optimal* for the buyer to allocate anything to the in-house production facility, although the in-house cost affects the offers from both suppliers and the allocation policy for the buyer (see below). Note that the above proposition is a *generalization* of Anton and Yao's (1989) result about split-award being the optimal procurement strategy for the buyer. While Anton and Yao established it for the case when there are no supply problems, we show that it continues to be the optimal policy even when one of the suppliers has less than perfect reliability.

While the above proposition demonstrates the optimal procurement strategy for the buyer, in the following proposition we present the optimal cost for the buyer and the optimal profits of the two suppliers, under the equilibrium outcome. Figure 1 depicts the results of the proposition.

Proposition 2. *The optimal allocation and optimal costs/profits for the associated parties, under the condition that the buyer and the reliable supplier have perfect information about the reliability level of the unreliable supplier, are as follows*:

- *Supplier* U: *If* $\beta < 1-\frac{R-U}{K}$, *then the unreliable supplier is not allocated any order, and so her profit is zero. On the other hand, if* $\beta > 1-\frac{R-U}{K}$, *then the unreliable supplier receives the full order, and her profit is* $\pi_U = \beta p_U - U = [R-(1-\beta)K]-U$.
- *Supplier* R: *If* $\beta < 1-\frac{R-U}{K}$, *then the reliable supplier is allocated the whole order, and her profit is* $\pi_R = p_R - R = \beta\min(\frac{U}{\beta}, K) + (1-\beta)K - R$; *for* $\beta > 1-\frac{R-U}{K}$, *the reliable supplier's allocation and profits are zero.*
- *The buyer's procurement cost is*:

$$g^* = \left\{\begin{array}{ll} \beta\min\left(\dfrac{U}{\beta}, K\right) + (1-\beta)K, & \text{if } \beta < 1-\dfrac{R-U}{K}, \\ R, & \text{if } \beta > 1-\dfrac{R-U}{K}. \end{array}\right\}.$$



Regions	l-type	h-type	Supplier R
1	0	0	Q
2	0	Q	Q if l-type; 0 otherwise
3	Q	Q	0

Note: [a]The figure assumes that β can be β_h or β_l, but whether $\beta = \beta_h$ or $\beta = \beta_l$ is exactly known to all three channel partners (the buyer and the two suppliers). This helps us to better compare this model in this section to the asymmetric information setting in Sec. 4.

Fig. 1. Equilibrium allocation in the perfect information scenario.[a]

Table 1. Equilibrium cost for the buyer and profits for suppliers R and U.

		$\beta > 1 - \frac{(R-U)}{K}$	$\beta < 1 - \frac{(R-U)}{K}$
Alloc		$R = 0, U = Q$	$R = Q, U = 0$
Prices	p_U	$[\frac{R-(1-\beta)K}{\beta}]^{(-)}$	$\frac{U}{\beta}$
	p_R	R	$[\beta \min(\frac{U}{\beta}, K) + (1-\beta)K]^{(-)}$
Profits	Supplier U	$R - (1-\beta)K - U$	0
	Supplier R	0	$\beta \min(\frac{U}{\beta}, K) + (1-\beta)K - R$
Cost	Buyer	R	$\beta \min(\frac{U}{\beta}, K) + (1-\beta)K$

Using the results above we can then determine the optimal expected cost for the buyer and profits for the two suppliers as shown in Table 1. Define $[M]^- = M - \epsilon$, where $\epsilon \to 0$.

Next we discuss the effects of reliability level β, and cost parameters K, R, and U on the expected allocation, profits of the two suppliers and the buyer's cost below.

We start by discussing the effects of β which is shown in Fig. 2. Interestingly, for high levels of supply reliability ($\beta > U/K$), the buyer actually *benefits* from the competition between the suppliers since his cost is less than the buyer's in-house cost K. Note that the buyer's procurement cost decreases with the reliability of

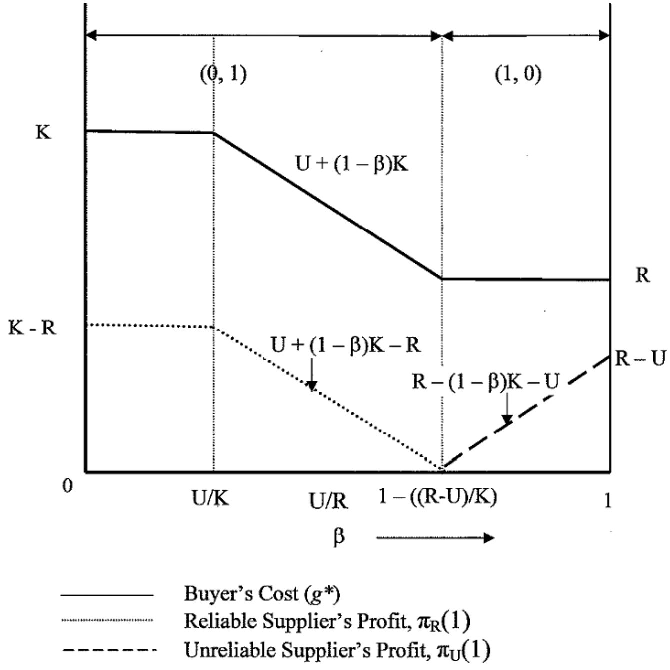


Fig. 2. Effects of β on supply chain partners' profit/costs in the perfect information scenario.

Table 2. Effects of increase in parameter values.

Increase in	Optimal allocation	Buyer's cost $[g^*]$	Supplier R's profit $[\pi_R]$	Supplier U's profit $[\pi_U]$
β	Unreliable	Decrease	Decrease	Increase
K	Reliable	Increase	Increase	Decrease
R	Unreliable	Increase	Decrease	Increase
U	Reliable	Increase	Increase	Decrease

U, but increases as the marginal production cost of either supplier or the marginal cost of in-house production increases. However, for $\beta < U/K$, there is no benefit to the buyer from suppliers competing with each other as the reliable supplier is able to take advantage of the low reliability of supplier U and increase its offer such that the buyer's cost is equal to the in-house option, i.e., K. The effects of *increase* of various parameters on the optimal allocation scheme, as well as on the buyer's cost (g^*) and the suppliers' profits ($\pi_R(1)$ and $\pi_U(1)$) are also summarized below in Table 2.[7] The allocation column suggests which supplier is *more likely* to be used with the increase of the particular parameter value.

Note that as K increases, the unreliable supplier is worse off since the range of β over which the unreliable supplier gets the order is lower. Further, as K increases, so does the unreliable supplier's offer (equal to $\frac{1}{\beta}[R-(1-\beta)K]$). In fact, if $K \to \infty$ (e.g., if the buyer has no in-house production option), then the reliable supplier will get the full order. This implies that the option of in-house production at a reasonable cost benefits the unreliable supplier as the buyer is able to hedge against the uncertainty in delivery from the unreliable supplier. Consistent with intuition, as the reliability premium $(R-U)$ decreases, it becomes more likely that the reliable supplier will be allocated the entire order and will make higher profit at the expense of the unreliable one. However, the effect of reliability premium on the buyer's procurement cost depends on the value of β and whether the decrease in $(R-U)$ is due to decrease in R or increase in U. For example, if β is sufficiently high, i.e., (1, 0) allocation, the buyer benefits if R decreases (the cost advantage for the unreliable supplier is small in that case, which promotes more competition between the suppliers and so, results in lower costs for the buyer), but is unaffected if U changes. For low values of β, i.e., (0, 1) allocation, any increase in U adversely affects the buyer, but his cost does not change with R.

4. Asymmetric Information Scenario

While the perfect information scenario analyzed in the last section generates relevant managerial insights, in reality, it is rare that the buyer or the reliable supplier will have perfect information about β. Normally, they will only have some limited

[7]Throughout the paper, we use increasing/decreasing in the weak sense unless otherwise specified.

information about the reliability levels of the suppliers from the region. This may be due to prior interactions with other suppliers in that region or due to some publicly available information. So, it is more realistic to assume that only partial information about the reliability level of U is available to the buyer or supplier R, but not the exact value of β. In order to capture this scenario, in this section we analyze a model where β can either be β_h (high value) or β_l (low value, $\beta_h > \beta_l$). The actual value is private information for supplier U. However, both the buyer and R know the following: β can be β_l with probability p, and β_h with probability $(1-p)$; that is, their expectation regarding the delivery reliability of U is $\overline{\beta} = p\beta_l + (1-p)\beta_h$. Note that nowadays there are a lot of historical information is available about general reliability of Asian suppliers, especially from countries like China, Taiwan and South Korea, from which such data can be generated (e.g., Alibaba.com). However, the *supplier-specific* information may still be private information.

It turns out that the first part of Proposition 1 — over-ordering, under-ordering or multi-source outcome cannot be equilibrium outcomes — holds true for this case also.[8] However, the lack of perfect information about the reliability level of U will significantly affect the equilibrium allocation. We can then show that:

Proposition 3. *Let* $U^l = \min(\frac{U}{\beta_l}, K)$ *and* $U^h = \min(\frac{U}{\beta_h}, K)$. *Then, the following are true*:

- *Region* 1: *If* $\beta_l \leq \frac{U\beta_h}{R-(1-\beta_h)K}$ *but* $p \leq \frac{\frac{U}{\beta_h} - \frac{R-(1-\beta_h)K}{\beta_h}}{U^l - \frac{R-(1-\beta_h)K}{\beta_h}}$, *then supplier* R *will submit the offer* $P_R = \beta_h U^h + (1-\beta_h)K$ *and will get the order.*
- *Region* 2: *If* $\beta_l \leq \frac{U\beta_h}{R-(1-\beta_h)K}$ *and* $p > \frac{\frac{U}{\beta_h} - \frac{R-(1-\beta_h)K}{\beta_h}}{U^l - \frac{R-(1-\beta_h)K}{\beta_h}}$, *then* l*-type supplier* U *will submit the offer* $\frac{U}{\beta_l}$, *and will not get the order.* h*-type supplier* U *and supplier* R *offer any bid within the intervals* $[pU^l + (1-p)\frac{R-(1-\beta_h)K}{\beta_h}, U^l]$ *and* $[p(\beta_h U^l + (1-\beta_h)K) + (1-p)R, \beta_h U^l + (1-\beta_h)K]$ *with probability distributions* G_1 *and* G_2, *respectively, where* $G_1(x) = \mathrm{Prob}(P_U^h \leq x) = \frac{1}{1-p}(1 - p\frac{\beta^h U^l + (1-\beta_h)K - R}{\beta^h x + (1-\beta_h)K - R})$, *and* $G_2(x) = \mathrm{Prob}(P_R \leq x) = 1 - \beta_h \frac{pU^l + (1-p)\frac{R-(1-\beta_h)K}{\beta_h} - U}{x - (1-\beta_h)K - U}$, *with probability mass of* $1 - G_2(\beta_h U^l + (1-\beta_h)K)$ *at* $\beta_h U^l + (1-\beta_h)K$. *Either* h *type supplier* U *or* R *gets the order depending on whether* $\beta_h P_U^h + (1-\beta_h)K < P_R$ *or not.*
- *Region* 3: *If* $\frac{U\beta_h}{R-(1-\beta_h)K} < \beta_l \leq 1 - \frac{(R-U)}{K}$, *then only* h *type supplier* U *gets the order by submitting* $P_U^h = \frac{R-(1-\beta_h)K}{\beta_h}$.
- *Region* 4: *If* $\beta_l > 1 - \frac{(R-U)}{K}$, *then both* h *and* l *type supplier* U *will submit the same offer* $P_U^h = P_U^l = \frac{R-(1-\overline{\beta})K}{\overline{\beta}}$, *and will get the order.*

[8]Keeping in mind the space constraint we do not include proofs of the results which are similar to the last section; however, they are available from the authors on request.

Using the results above we can then determine the optimal expected (ex-ante) cost for the buyer and profits for the two suppliers as shown in Table 3 (also refer to Fig. 3 .[9])

First of all, note from above that in most circumstances (in all regions of Fig. 3, except region 4) indeed the h-type supplier can signal its low risk and separate itself from the l-type one through a separating equilibrium. So, in those cases, the contract from supplier U can indeed eliminate the information asymmetry for the buyer (this benefit might have a cost associated with it, as we discuss below).[10] However, if both β_h and β_l are quite high, then the equilibrium is of the pooling type, that is, the h-type in that case cannot effectively signal its low risk and consequently both supplier R and the buyer then need to make their decisions based on an "average" supplier U, i.e., based on $\bar{\beta}$.

It is also quite interesting to understand the effects of the distribution about supplier U's reliability on the above costs/profits. We specifically focus on the following effects which are pictorially represented in Fig. 4.

- If β_l increases, while β_h and p remains constant (i.e., $\overline{\beta}$ increases): See Fig. 4(a).
- If β_h increases, while p and β_l remains constant (i.e., $\overline{\beta}$ increases): See Fig. 4(b).
- If $\overline{\beta}$ remains constant, while β_h increases and β_l decreases by the same amount, say δ (assuming $p = 0.5$ this implies that variance increases in δ): See Fig. 4(c).

β_l increases: It is evident from Fig. 3 that, given β_h is sufficiently high, as β_l increases, we move from region 2 to region 3 and finally to region 4 (from Table 3 note that the costs and profits are independent of β_l in Region 1). Such an increase implies a decrease in the difference between reliability levels of h and l types, i.e., the two supplier U types become similar. Consequently, as β_l increases, the premium that h-type supplier U or supplier R can extract from the buyer by separating themselves from l-type supplier U decreases, which explains the reduction in profits for those two suppliers as well as the cost for the buyer in regions 2 and 3. Evidently, l-type supplier U does not get any allocation in those two regions, and so its profit is always zero there. As for region 4, supplier R does not get any allocation in that region and the buyer's cost remains constant there ($= R$). However, interestingly, the profits of both supplier U types now increase in β_l. Since there is a pooling equilibrium in region 4, the buyer's decision is based on $\overline{\beta}$ in that region; increase in β_l increases $\overline{\beta}$, allowing the two supplier U types to charge a premium and increase their profits.

β_h increases: Given β_l is in the medium range, as β_h increases, we move from region 1 to region 2 and finally to region 3. Clearly, increase in β_h makes h-type supplier U better and at the same time provides more competition to supplier R. So, we

[9]Actually profits/costs would be infinitesimally less than what we indicate.
[10]Note that supplier R still faces information asymmetry since it submits its bid simultaneously with supplier U.

Table 3. Equilibrium prices and profits for supplier R and U and cost for buyer.

		$\beta_l \le \frac{U\beta_h}{R-(1-\beta_h)K}$		$\beta_l > \frac{U\beta_h}{R-(1-\beta_h)K}$ and $\beta_l \le 1-\frac{(R-U)}{K}$ (Region 3) Separating	$\beta_l > 1-\frac{(R-U)}{K}$ (Region 4) Pooling
		$p \le \frac{\frac{U}{\beta_h}-\frac{R-(1-\beta_h)K}{\beta_h}}{U^l-\frac{R-(1-\beta_h)K}{\beta_h}}$ (Region 1) Separating	$p > \frac{\frac{U}{\beta_h}-\frac{R-(1-\beta_h)K}{\beta_h}}{U^l-\frac{R-(1-\beta_h)K}{\beta_h}}$ (Region 2) Separating		
	Alloc	$R = Q$, $U = 0$	$R = Q$, $U = 0$, if $P_U^h > P_R$ $R = 0$, $U = Q$, otherwise	$R = 0$, $U = Q$	$R = 0$, $U = Q$
Prices	P_U^l	$\frac{U}{\beta_l}$	$\frac{U}{\beta_l}$	$\frac{U}{\beta_l}$	$\frac{R-(1-\bar{\beta})K}{\bar{\beta}}$
	P_U^h	$\frac{U}{\beta_h}$	$P_U^h \sim G_1(x)$	$\frac{R-(1-\beta_h)K}{\beta_h}$	$\frac{R-(1-\bar{\beta})K}{\bar{\beta}}$
	P_R	$\beta_h U^h + (1-\beta_h)K$	$P_R \sim G_2(x)$	R	R
Profits	l-type supplier U	0	0	0	$\beta_l(\frac{R-(1-\bar{\beta})K}{\bar{\beta}}) - U$
	h-type supplier U	0	$\beta_h(pU^l + (1-p)\frac{R-(1-\beta_h)K}{\beta_h}) - U$	$R-(1-\beta_h)K-U$	$\beta_h(\frac{R-(1-\bar{\beta})K}{\bar{\beta}}) - U$
	Supplier R	$\beta_h U^h + (1-\beta_h)K - R$	$p(\beta_h U^l + (1-\beta_h)K - R)$	0	0
Cost	Buyer	$\beta_h U^h + (1-\beta_h)K$	$E\min(P_R, \beta_h P_U^h + (1-\beta_h)K)$	R	R

$\bar{\beta} = p\beta_l + (1-p)\beta_h$; $U^l = \min(\frac{U}{\beta_l}, K)$ and $U^h = \min(\frac{U}{\beta_h}, K)$.

Regions referred in this table correspond to the regions shown in Fig. 3.

$G_1(x) = \mathrm{Prob}(P_U^h \le x) = \frac{1}{1-p}(1 - p\frac{\beta^h U^l + (1-\beta_h)K - R}{\beta^h x + (1-\beta_h)K - R})$ is a c.d.f., where $x \in [pU^l + (1-p)\frac{R-(1-\beta_h)K}{\beta_h}, U^l]$

$G_2(x) = \mathrm{Prob}(P_R \le x) = 1 - \beta_h \frac{pU^l + (1-p)\frac{R-(1-\beta_h)K}{\beta_h} - U}{x - (1-\beta_h)K - U}$ is a c.d.f., where $x \in [p(\beta_h U^l + (1-\beta_h)K) + (1-p)R, \beta_h U^l + (1-\beta_h)K]$.

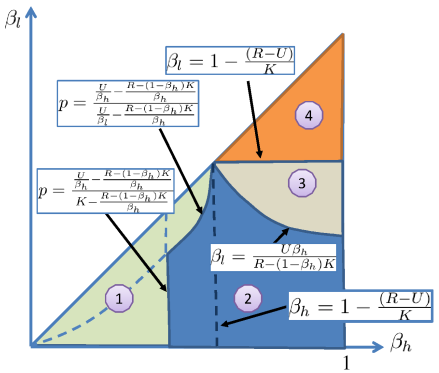
notice that the profit of h-type increases in β_h while that of R decreases (h-type does not get any allocation in region 3, while R does not get any allocation in region 1). The above also explains the behavior of the buyer's cost in region 1 (the buyer's cost is constant in region 3). More interesting is the effect of β_h on the buyer's cost in region 2, where there are two counteracting forces. On the one hand, higher β_h (compared to a fixed β_l) enables h-type supplier U to better separate itself from l-type and charge a higher premium from the buyer. On the other hand, the higher level of reliability reduces the buyer's cost since it has to depend less on using the emergency option. Depending on the strength of the two forces, the buyer's cost can increase or decrease in β_h or can even be nonmonotone as we see in Fig. 4(b). Note that in region 4 with pooling equilibrium, as we discussed before, increase in β_h increases $\overline{\beta}$, allowing the two supplier U types to charge a premium and increase their profits.

δ increases: Lastly, if we keep $\overline{\beta}$ constant, while increasing β_h and decreasing β_l by the same amount δ, then an increase in δ implies moving perpendicular to the diagonal line in Fig. 3, first over region 1 and then over region 2. The effects of increasing δ is somewhat different from what we discussed before for increase in β_h because in this case β_l also decreases (before we just increased β_h without changing β_l). Specifically, while the behavior in region 1 remains the same as in the case of increasing β_h, it changes for region 2. Lowering of β_l allows h-type supplier U and supplier R now to more effectively separate themselves against l-type supplier U and extract a significant premium from the buyer. Moreover, it also reduces the positive effect of higher reliability due to higher β_h on buyer's cost. Consequently, the profits of both h-type and R as well as the buyer's cost increase in δ as shown in Fig. 4(c) [recall that the buyer's cost can decrease in Fig. 4(b)]. As far as regions 3 and 4 are concerned, it is clear from Table 3 that an increase in δ will not affect buyer's cost or R's profit, the only effect would be that it will increase h-type's profit while decreasing l-type's.

In summary, we note that the effects of any change in reliability distribution depend on the relative strength of how such a change affects the buyer's cost of using emergency option, the competition between the two suppliers and the ability of h-type and supplier R to effectively separate themselves from l-type. Indeed, depending on the parameter values, such a change might increase or decrease or might have a non-monotone effect on the buyer's cost and the suppliers' profits.

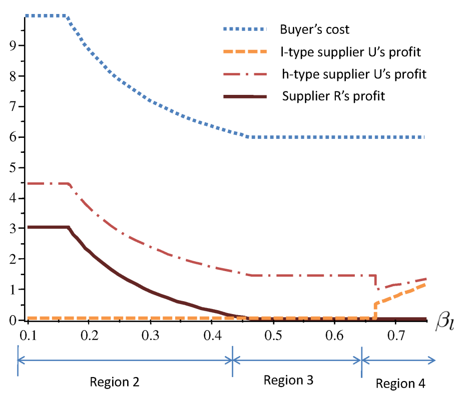
4.1. *Comparison of perfect and asymmetric information scenarios*

Until now we have focussed on studying the behavior of the imperfect information scenario. In what follows, we compare the allocation scheme as well as the profits/costs under asymmetric information scenario to those of the perfect (symmetric) information scenario of the last section to establish the effects of information asymmetry. Note that since the allocation regions in the two models do not match (refer to Figs. 1 and 3), when we overlap them, the resulting figure would have five

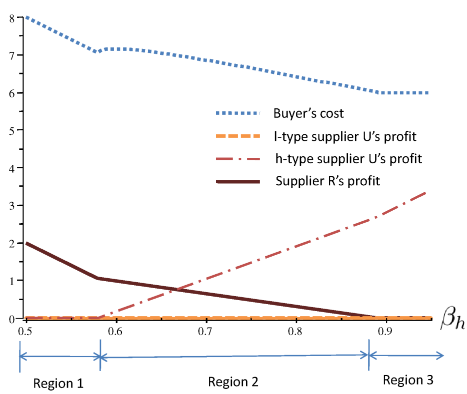


Regions	l-type	h-type	Supplier R	Eq.Type
1	0	0	Q	Separating
2	0	mixed	mixed	Separating
3	0	Q	0	Separating
4	Q	Q	0	Pooling

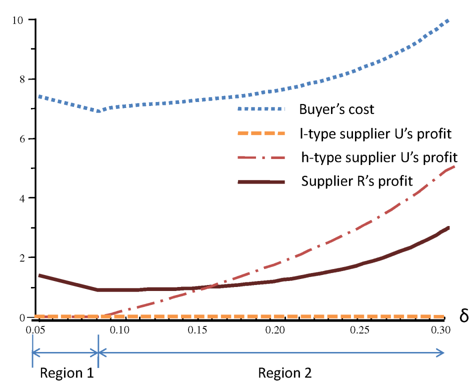
Fig. 3. Equilibrium allocation for the asymmetric information scenario.



(a) Sensitivity of payoffs with respect to β_l



(b) Sensitivity of payoffs with respect to β_h



(c) Sensitivity of payoffs with respect to δ

Note: In Fig. 4(c), we let $\beta_h = 0.5 + \delta$ and $\beta_l = 0.5 - \delta$, and change δ from 0.05 and 0.30.

Fig. 4. Effects of β_l, β_h, and δ on supply chain partners' profit/costs when there is information asymmetry.

comparison regions. Obviously, such comparison would depend on whether the true reliability of supplier U is β_h or β_l.

First of all, note that, as far as the equilibrium order allocation is concerned, the share of the two suppliers might increase or decrease depending on the parameter values. Lack of perfect information helps supplier U in the sense that it is under consideration for allocation in a greater parameter range under asymmetric information setting. For example, supplier U never receives any allocation in region 1 of Fig. 1 (perfect information). However, in the corresponding region of Fig. 3 (asymmetric information), it might get some allocation if it is of h-type.[11] On the other hand, information asymmetry might also help supplier R by providing it a chance for allocation in a region where it was surely not getting any order when the buyer has perfect information about the reliability of supplier U (e.g., in region 2 of Fig. 1, supplier R will not receive any allocation if $\beta = \beta_h$, but it has a chance of receiving allocation in the corresponding region of Fig. 3). As regards the effects of information asymmetry on profits/costs of the channel partners, we establish them in the following proposition.

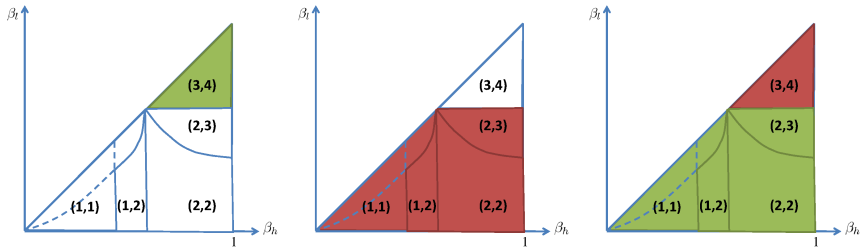
Proposition 4. *The comparison between the chain partners' profits and costs under perfect* (*symmetric*) *and asymmetric information scenarios is fully characterized in Fig.* 5.

One of the interesting insights of the above proposition is that the effects of information asymmetry about reliability of supplier U is not monotone, it can indeed result in higher or lower profits/costs for the channel partners (compared to symmetric information scenario) depending on the system parameters. Let us discuss the above proposition in more details from the perspective of the individual channel partners.

Supplier R: The effects of information asymmetry on supplier R's profits are rather intuitive. When the true reliability of the unreliable supplier is low, supplier R (weakly) prefers that the buyer knows about it (i.e., prefers symmetric information scenario) so that R can get more allocation and/or can charge a premium for its higher reliability. On the other hand, if the true reliability of the unreliable supplier is high, supplier R (weakly) prefers that the buyer does not know about it (i.e., prefers asymmetric information scenario) so that there is less competition for R.

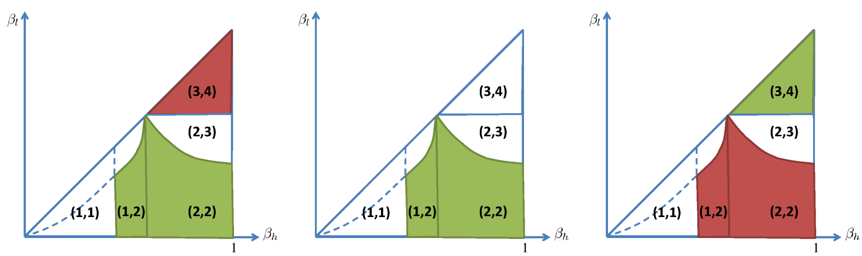
Supplier U: As for supplier U, the intuition is that it will, at least weakly, prefer asymmetric information scenario when its true reliability is low (so that the buyer does not exactly know about its poor reliability) and vice versa when the true reliability is high (so that the buyer knows it is highly reliable). Although the intuition is valid when supplier U is actually l-type, this might not be so when supplier U is actually h-type [e.g., regions (1, 2) and (2, 2)]. The underlying reason behind this is

[11] Whenever U is under consideration for allocation in Fig. 1, it is also seen in Fig. 3.



Regions	l-type's profit	Supplier R's profit	Buyer's cost
(1,1)	$PI = AI$	$PI > AI$	$PI > AI$
(1,2)	$PI = AI$	$PI > AI$	$PI > AI$
(2,2)	$PI = AI$	$PI > AI$	$PI > AI$
(2,3)	$PI = AI$	$PI > AI$	$PI > AI$
(3,4)	$PI < AI$	$PI = AI$	$PI < AI$

(a) The impact of information asymmetry on supply chain partners' profits/costs if true reliability is low



Regions	h-type's profit	Supplier R's profit	Buyer's cost
(1,1)	$PI = AI$	$PI = AI$	$PI = AI$
(1,2)	$PI < AI$	$PI < AI$	$PI < AI$
(2,2)	$PI < AI$	$PI < AI$	$PI < AI$
(2,3)	$PI = AI$	$PI = AI$	$PI = AI$
(3,4)	$PI > AI$	$PI = AI$	$PI > AI$

(b) The impact of information asymmetry on supply chain partners' profits/costs if true reliability is high

Note: The different colored regions in the above figure denote the following preference between perfect (symmetric) information (PI) and asymmetric information (AI) scenarios for each supply chain partner: green (light shaded) regions, prefers AI over PI; red (dark shaded) regions, prefers PI over AI; and, white regions, indifferent between AI and PI. In the "Regions" column, the first and second elements refer to the regions in Figs. 1 and 3, respectively.

Fig. 5. Effects of information asymmetry on supply chain partners' profit/costs.

that in those regions there is a separating equilibrium in the asymmetric information setting. This allows h-type supplier U to separate itself from l-type and more effectively compete with R, resulting in it charging higher prices and/or increasing its chances of getting an allocation (compared to symmetric information setting).

Buyer: The effects of lack of perfect information is perhaps most interesting when seen from the buyer's viewpoint. When supplier U is actually of l-type, the buyer mostly prefers the asymmetric information setting (i.e., its costs are less under that scenario). The reason is that when supplier R exactly knows that supplier U is of l-type, it can use that information to extract a premium from the buyer; however, when there is information asymmetry, R has to hedge its bid against the possibility that U is of h-type and consequently charges less. This allows the buyer to lower its cost at the expense of supplier R's profits. However, in region (3, 4) of Fig. 4(a), when there is a pooling equilibrium under asymmetric information, the buyer prefers the perfect information scenario since supplier U in that case cannot use the buyer's lack of perfect information about its low reliability and charge a higher price. In contrast, the buyer mostly prefers the perfect information setting when supplier U is actually of h-type since in the asymmetric information setting both supplier U (h-type) and supplier R can take advantage of effectively separating themselves from l-type and charge a premium to the buyer. The only exception is again region (3,4) of Fig. 4(b), when there is a pooling equilibrium under asymmetric information; the buyer in that case prefers the asymmetric information scenario since supplier U then cannot use its higher reliability to to charge a high price (recall that under pooling equilibrium the bids would be based on $\overline{\beta}$, not β_h).

5. Concluding Discussion and Future Research Opportunities

Rise of electronic commerce have allowed a multitude of new firms to join the marketplace, offering expanded choices for buyers and suppliers. Many of these new entrants are low cost suppliers from Asia. These firms may have uncertain reliability, and oftentimes not much supplier-specific information about their capabilities might be available. However, because of their low costs, they provide an attractive alternative to reliable but expensive local suppliers. An important consideration for any firm then is the level of risk they are willing to take when making allocation decisions across unreliable and reliable suppliers. In this paper, we addressed the issue of optimal procurement strategy for a buyer receiving offers from a reliable but expensive supplier R and a cheaper but unreliable supplier U, where the two suppliers play a Nash game between themselves.

We first proved that for linear costs and when *perfect information* about the reliability of supplier U is available to all parties, the optimal allocation scheme is to *award the order to a single supplier* with the selection depending on factors such as reliability of the cheaper supplier, cost differential between the two suppliers, and the presence of an in-house production option. The cost of in-house production acts as an upper limit on the bids by the two suppliers even though the in-house option is never used. We then generalized the model to consider the *asymmetric information* scenario, where the buyer and the reliable supplier have *a-priori* beliefs about the probability that supplier U will be more or less reliable (i.e., of type h or l, respectively) but they do not exactly know supplier U's reliability level. Although the order is still allocated to a single supplier, characterization of the equilibrium allocation and costs/profits under this scenario is considerably more complicated. However, we are able to analytically establish the full equilibrium characterization and show that such a scenario might result in either pooling or separating equilibrium depending on the parameter values. Specifically, a more reliable h-type supplier U can mostly separate itself from a less reliable l-type supplier U, except when the *a-priori* beliefs are that supplier U can be highly reliable or highly unreliable. We then compare the costs/profits of the channel partners under the two information scenarios and demonstrate the effects of informational asymmetry on the performance of the channel partners. Interestingly, lack of perfect information can indeed either benefit or hurt the channel partners depending on parameter values. It is especially noteworthy that perfect information about supplier U's reliability level does not necessarily reduce the cost for the buyer or lack of such information does not necessarily increase the profit of supplier U.

Our analysis seems to suggest that NA buyers need to be careful in their effort to gain more information about the true reliability level of suppliers from LCCs. While such a strategy might be beneficial if the supplier indeed turns out to be good, the reverse scenario might be harmful for the buyer. Moreover, the buyers should always keep a relatively efficient in-house option available even if they do not use it in order to use it as a constraint for the supplier's offers. But, from the reliable supplier's perspective the incentive is just the opposite — it wants the exact reliability information to be public knowledge if and only if the cheaper supplier is indeed not so good. What about the perspective of the low-cost suppliers? Obviously, their first priority would be to improve their reliability in an efficient fashion (i.e., so that their costs do not increase substantially). However, anecdotal evidences suggest that the move towards local suppliers may get a further boost due to the rising in the wage level in LCCs. In fact, there seems to be already a growing push towards selecting known suppliers (Deloitte Research, 2003a). These suppliers should also carefully think about making their reliability information to be public information — if they can indeed improve their reliability level such a strategy can indeed be beneficial; otherwise, it might be better for them that the other chain partners do not exactly know about their reliability levels. It would be very interesting to see how these conflicting incentives play out in the future in terms of information asymmetry (obviously, advances in information technologies might reduce information asymmetry over time).

There are a number of possible future extensions of our framework. One possibility would be to study the effect of information sharing between one or more parties on the optimal allocation (see Gavirneni, 2002). The issue of information sharing also raises the issue of truthfulness of the information being shared (Yao *et al.*, 2005), and about the asymmetry in the initial information available to the parties (Gurnani and Shi, 2006). For example, in many settings — especially for the case of first-time interactions — the buyer and the unreliable supplier may have different beliefs on the extent of supply unreliability in the supply chain. How would the beliefs on supply unreliability affect the buyer's relationship with its reliable suppliers? Also note that we focus on an "all or nothing" delivery model. It might be worthwhile to analyze the impact of different supply models in which the unreliable supplier delivers a random fraction of the order quantity. Finally, another interesting extension may be to analyze the problem in an auction framework where there is information asymmetry about production costs in addition to the reliability level, and understand the interaction between the two asymmetries.

The primary contribution of our paper is in bridging the gap between the research stream focusing on procurement games with perfectly reliable suppliers, and the stream which deals with supply unreliability but with fixed prices. We hope that our paper will spur a new stream of research in the operations management community which will serve to provide guidance on supplier selection and allocation strategies for purchasing managers operating in an environment of supply risk and information asymmetry.

Appendix A. Proofs of Propositions

Proof of Proposition 1. Note that in a multi-source award, each supplier gets some order, i.e., it involves an order (α, γ) such that $0 < \alpha \leq 1$, and $0 < \gamma \leq 1$. There are three possible candidates for multi-source outcomes: (1) $\alpha + \gamma > 1$, (2) $\alpha + \gamma = 1$, and (3) $\alpha + \gamma < 1$. We consider each candidate outcome below.

(1) $\alpha+\gamma > 1$: It is easy to see from (3) that supplier U can induce a deviation from (α, γ) such that $\alpha + \gamma > 1$ to $(\widehat{\alpha}, \gamma)$ such that $\widehat{\alpha} + \gamma = 1$. Therefore, $\alpha + \gamma > 1$ cannot be an equilibrium outcome.

(2) $\alpha+\gamma < 1$: Again, it is easy to see from (4) that supplier R can induce a deviation from (α, γ) such that $\alpha + \gamma < 1$ to $(\alpha, \widehat{\gamma})$ such that $\alpha + \widehat{\gamma} = 1$, that is, $\alpha + \gamma < 1$ cannot be an equilibrium outcome.

(3) Finally, consider the case when $\alpha + \gamma = 1$:

- Using (3) we can see that supplier U can induce a deviation from (α, γ) such that $\alpha + \gamma = 1$ to $(1, 0)$ if

$$\pi_R(\gamma) + U\alpha + R\gamma + (1-\beta)K(1-\gamma) > \pi_R(0) + U + (1-\beta)K,$$
$$\text{i.e., if } \pi_R(\gamma) + \gamma[R - U - (1-\beta)K] > 0 \text{ [using } \pi_R(0) = 0 \text{ and } \alpha = 1-\gamma].$$

  Since $\pi_R(\gamma) \geq 0$, this will happen when $R > U + (1-\beta)K$, i.e., when $\beta > 1 - \frac{R-U}{K}$.

- Similarly, using (4) we can see that supplier R can induce a deviation from (α, γ) such that $\alpha + \gamma = 1$ to $(0, 1)$ if

$$\pi_U(\alpha) + U\alpha + R\gamma + (1-\beta)K(1-\gamma) > \pi_U(0) + R,$$
$$\text{i.e., if } \pi_U(\alpha) + (1-\gamma)[U + (1-\beta)K - R] > 0$$
$$[\text{using } \pi_U(0) = 0 \text{ and } \alpha = 1-\gamma].$$

  Since $\pi_U(\alpha) \geq 0$, this will ensue when $R < U + (1-\beta)K$, i.e., when $\beta < 1 - \frac{R-U}{K}$.

Hence, $\alpha + \gamma = 1$ with $\alpha > 0$ and $\gamma > 0$ cannot be an equilibrium outcome. The above three cases jointly prove the first part of the proposition.

As far as the second part is concerned, recall that a sole-source outcome is an order (α, γ) such that either $\alpha = 0$ or $\gamma = 0$. There are four possible candidates for sole-source outcomes: (1) (1, 0), (2) (0, 1), (3) (α, 0), where $0 < \alpha < 1$, and (4) (0, γ), where $0 < \gamma < 1$. We consider them one-by-one.

(1) $(0, \gamma)$: It is easy to see from (4) that supplier R can induce a deviation from $(0, \gamma)$ to $(0, 1) \Rightarrow (0, \gamma)$ cannot be an equilibrium outcome.

(2) $(\alpha, 0)$: From (4), we can show that supplier R can induce a deviation from $(\alpha, 0)$ to $(\alpha, \widehat{\gamma})$ such that $\alpha + \widehat{\gamma} = 1$, implying that $(\alpha, 0)$ cannot be an equilibrium outcome.

The only available options are then to allocate the entire order to one of the suppliers. We analyze these cases next.

(3) $(1, 0)$: Using (4) we get that supplier R can induce a deviation from $(1, 0)$ to $(0, 1)$ if

$$\pi_U(1) + U + (1-\beta)K > \pi_U(0) + R, \text{ i.e., if } \pi_U(1) + U + (1-\beta)K > R \quad [\text{using } \pi_U(0) = 0].$$

Since $\pi_U(1) \geq 0$, this will definitely be the case when $R < U + (1-\beta)K$, i.e., when $\beta < 1 - \frac{R-U}{K}$. Thus, $(1, 0)$ is not an equilibrium allocation if $\beta < 1 - \frac{R-U}{K}$.

(4) $(0, 1)$: Using (3), we get that supplier U can induce a deviation from $(0, 1)$ to $(1, 0)$ if

$$\pi_R(1) + R > \pi_R(0) + U + (1-\beta)K, \quad \text{i.e., if } \pi_R(1) + R > U + (1-\beta)K \quad [\text{using } \pi_R(0) = 0].$$

Since $\pi_R(1) \geq 0$, this will occur when $R > U + (1-\beta)K$, i.e., when $\beta > 1 - \frac{R-U}{K}$. Thus, $(0, 1)$ is not an equilibrium allocation if $\beta > 1 - \frac{R-U}{K}$. $\square$

Proof of Proposition 2. $\beta < 1 - \frac{R-U}{K} \Rightarrow (0, 1)$ outcome. In this case, since the reliability in delivery from supplier U is below the threshold level, reliable supplier R gets the entire order. However, in order to ensure that the reliable supplier indeed receives the entire allocation, the price charged by supplier R must be ϵ less than the cost to the buyer from using supplier U. Therefore, we get $P_R(1) = U + (1-\beta)K$. This follows from the fact that supplier U would charge a minimum of $\frac{U}{\beta}$ in order to cover her production costs, and expected cost to the buyer comprises of two terms: Delivery by supplier U and nondelivery leading to in-house production costs. The buyer also has the option of not awarding any order to both suppliers if the expected cost exceeds K (which is the cost of producing everything in-house). Therefore, the price charged by the reliable supplier also must not exceed K, that is, we need $P_R(1) \leq K$.

$\beta > 1 - \frac{R-U}{K} \Rightarrow (1, 0)$ outcome. In this case, since the reliability in delivery from supplier U exceeds the threshold level, the unreliable supplier U gets the entire order. However, in order to guarantee that supplier U gets the entire allocation, the price charged must be ϵ less than the price charged by supplier R (if the entire order were awarded to supplier R). Therefore, we get $P_U(1) = \frac{1}{\beta}[R - (1-\beta)K]$. This follows from the fact that supplier U would charge a minimum of $\frac{U}{\beta}$ in order to cover her production costs, and the total cost to the buyer should not exceed the cost if the entire order were allocated to supplier R. Therefore, we get, $g^* = \beta P_U(1) + (1-\beta)K = R$. Note that, $\beta P_U(1)$ (as defined above) $> U$ if $\beta > 1 - \frac{R-U}{K}$ as assumed in this case. The profits for the two suppliers can be calculated based on $\pi_R(1) = P_R(1) - R$ and $\pi_U(1) = \beta P_U(1) - U$. □

Proof of Proposition 3. We prove each part in proposition one-by-one.

- If $\beta_l \geq 1 - \frac{(R-U)}{K}$, then both types of supplier U can undercut supplier R by offering a bid which costs buyer infinitesimally below supplier R's marginal cost. But since l type always mimics h type, buyer cannot separate them, hence he uses average reliability $\bar{\beta} = p\beta_l + (1-p)\beta_h$ to evaluate U's bid. Therefore, on the equilibrium supplier U offers a bid which would cost buyer infinitesimally below R when $\bar{\beta}$ is used as reliability factor, i.e., $p_U^h = p_U^L = \frac{R-(1-\bar{\beta})K}{\bar{\beta}}$.
- In this case, $\beta_l < 1 - \frac{(R-U)}{K}$ and $p > \frac{\frac{U}{\beta_h} - \frac{R-(1-\beta_h)K}{\beta_h}}{\frac{U}{\beta_l} - -\frac{R-(1-\beta_h)K}{\beta_h}}$. The first condition implies that l type cannot make a positive profit against supplier R, even if she offers her break-even price $\frac{U}{\beta_l}$. This is because she can set p_U^l at minimum $\frac{U}{\beta_l}$, but R can still undercut her offer by submitting a bid less than $U + (1-\beta_l)K$. However, h type can still compete with R by offering bids that would cost buyer less than what supplier R can offer. Hence, on the equilibrium the only sustainable price range for h type supplier U is the one which is less than $\frac{U}{\beta_l}$. This upper bound on the prices essentially expels l type out of competition. Therefore, buyer can separate between h and l. The Bertrand-type competition between h and R necessitates equilibrium strategy to be of mixed (randomized) one over a pricing interval between $\underline{p}_U$ and $\overline{p}_U$ with pricing distribution of G_U^h for h type supplier U and between $\underline{p}_R$ and $\overline{p}_R$ with pricing distribution of G_R for supplier R. We now characterize the mixed strategy. First, the upper bound for the mixed strategy interval must be set just at the break-even price of l type, i.e., $\overline{p}_U = \frac{U}{\beta_l}$ and $\overline{p}_R = \beta_h \frac{U}{\beta_l} + (1-\beta_h)K$. Mixed strategy probability distribution for R can be derived by the condition that if R mixes continuously with G_R over the interval $[\underline{p}_R, \overline{p}_R]$, h-type is indifferent between charging any price over the interval $[\underline{p}_U, \overline{p}_U]$. Similarly, l-type also mixes continuously over the interval $[\underline{p}_U, \overline{p}_U]$ to make sure that R is indifferent between undercutting both l and h types and undercutting only l-type. To express these conditions, we need to write down each firm's expected payoff first:

$$\Pi_U^h = (1 - G_R(p_R)) \left(\frac{p_R - (1-\beta_h)K}{\beta_h} - U \right)$$

and

$$\Pi_R = (1-(1-p)G_U^h(p_U^h))(\beta_h p_U^h + (1-\beta_h)K - R).$$

Recall that supplier R's profit needs to be equal to $p(\overline{p}_R - R)$ for all p_R in the support, i.e.,

$$\begin{aligned}\Pi_R &= (1-(1-p)G_U^h(p_U^h))(\beta_h p_U^h + (1-\beta_h)K - R)\\ &= p\left(\beta_h \frac{U}{\beta_l} + (1-\beta_h)K - R\right).\end{aligned}$$

Inverting the profit equation for supplier R, we obtain mixing distribution function for h-type supplier U:

$$G_U^h(p_U^h) = \frac{1}{1-p}\left(1 - p\frac{(\beta_h \frac{U}{\beta_l} + (1-\beta_h)K - R)}{(\beta_h p_U^h + (1-\beta_h)K - R)}\right).$$

From this equation, we obtain lower bound for h-type supplier U's support, i.e., $\underline{p}_U = p\frac{U}{\beta_l} + (1-p)\frac{R-(1-\beta_h)K}{\beta_h}$. Also we need to make sure that $\underline{p}_U$ must be greater than h-type's break-even price, i.e., $\frac{U}{\beta_h}$. Otherwise, by charging infinitesimally below $\frac{U}{\beta_h}$, supplier R can always undercut both l and h types and makes more profit. This condition implies that

$$\underline{p}_U = p\frac{U}{\beta_l} + (1-p)\frac{R-(1-\beta_h)K}{\beta_h} > \frac{U}{\beta_h}$$

which implies that

$$p > \frac{\frac{U}{\beta_h} - \frac{R-(1-\beta_h)K}{\beta_h}}{\frac{U}{\beta_l} - -\frac{R-(1-\beta_h)K}{\beta_h}}$$

but this is automatically satisfied because of the second condition of this case.

Note that $\lim_{p\to\underline{p}_U} G_U^h(p_U^h) = 0$ and $\lim_{p\to\overline{p}_U} G_U^h(p_U^h) = 1$. Hence, there is no mass between $\underline{p}_U$ and $\overline{p}_U$. Similarly, supplier h-type U's profit needs to be equal to $\beta_h\underline{p}_U - U$ for all p in the support, i.e.,

$$\Pi_U^l = (1-G_R(p_R))\left(\frac{p_R-(1-\beta_h)K}{\beta_h} - U\right) = \beta_h\underline{p}_U - U.$$

Inverting profit equation for h-type supplier U, we obtain mixing distribution function for supplier R, G_R:

$$G_R(p_R) = 1 - \frac{\beta_h\underline{p}_U - U}{\beta_h\frac{p_R-(1-\beta_h)K}{\beta_h} - U} = 1 - \frac{pU\frac{\beta_h}{\beta_l} + (1-p)(R-(1-\beta_h)K) - U}{p_R - (1-\beta_h)K - U}.$$

Note that $\lim_{p_R\to\underline{p}_R} G_R(p_R) = 0$ but

$$\lim_{p_R\to\overline{p}_R} G_R(p_R) = 1 - \frac{pU\frac{\beta_h}{\beta_l} + (1-p)(R-(1-\beta_h)K) - U}{\overline{p}_R - (1-\beta_h)K - U} < 1.$$

Hence, there is a mass at $\overline{p}_R$ given by

$$(1-p)U\left(\frac{\beta_h}{\beta_h-\beta_l}-\beta_l\frac{R-K(1-\beta_h)}{U(\beta_h-\beta_l)}\right).$$

- In this case, $\beta_l < 1-\frac{(R-U)}{K}$ and $p < \frac{\frac{U}{\beta_h}-\frac{R-(1-\beta_h)K}{\beta_h}}{\frac{U}{\beta_l}--\frac{R-(1-\beta_h)K}{\beta_h}}$. These two conditions imply that supplier R can and wants to undercut both l and h types. Given that $p_U^h=\frac{U}{\beta_h}$, supplier R can get the full allocation as long as $p_R < U+(1-\beta_h)K$. Since profit function of supplier R increases in p_R, on the equilibrium, she charges infinitesimally less than $U+(1-\beta_h)K$. Now, given that p_R is infinitesimally less than $U+(1-\beta_h)K$, h-type supplier U's profit will be zero if she charges more than $\frac{U}{\beta_h}$ and negative if she charges less than $\frac{U}{\beta_h}$. Hence, it implies that $p_U^h=\frac{U}{\beta_h}$ and p_R that is infinitesimally less than $U+(1-\beta_h)K$ form a Nash equilibrium. Finally, uniqueness of this equilibrium comes from the same fact that any strategy other than the above one would lead to a profitable deviation for either R, or l-type, or h-type. □

Proof of Proposition 4. We prove each case in proposition one-by-one.

- True reliability of supplier U is β_h: We compare supplier U and supplier R's profits and buyer B's cost under asymmetric information setting to full information setting.
  - Supplier R: Remember that we show in Proposition 2 that under full (perfect/symmetric) information setting, supplier R's profit is zero if $\beta_h \geq 1-\frac{(R-U)}{K}$, otherwise, it is $\beta_hU^h+(1-\beta_h)K-R$. In other words, supplier R charges $\beta_hU^h+(1-\beta_h)K$ if $\beta_h < 1-\frac{(R-U)}{K}$, otherwise, she charges R. However, under asymmetric information setting, we show in Proposition 3 that R charges exactly $\beta_hU^h+(1-\beta_h)K$ in region 1,[12] and R in regions 3 and 4. Since region 1 is subset of region characterized by the condition $\beta_h < 1-\frac{(R-U)}{K}$ and regions 3 and 4 are the subsets of the region characterized by the opposite condition $\beta_h \geq 1-\frac{(R-U)}{K}$, in those regions, supplier R earns exactly same profit under both full and asymmetric information settings. Now, we explore region 2. Note that in this region, under asymmetric information setting, supplier R charges at least $p(\beta_hU^l+(1-\beta_h)K)+(1-p)R$, whereas under full information setting, she charges $\beta_hU^h+(1-\beta_h)K$. We can show that

$$p(\beta_hU^l+(1-\beta_h)K)+(1-p)R > \beta_hU^h+(1-\beta_h)K,$$

since in Region 2,

$$p > \frac{\beta_hU^h+(1-\beta_h)K-R}{\beta_hU^l+(1-\beta_h)K-R}.$$

[12] All the regions referred in this proof correspond to the regions in Fig. 3.

Hence, supplier R weakly earns more in asymmetric information setting than she does in full information setting.

— Supplier U: In regions 1, and 3, supplier U of h type earns exactly same profit under both full and asymmetric information settings. We restrict our attention only to regions 2 and 4. In region 2, h-type supplier U earns at most $R-(1-\beta_h)K-U$ under full information setting, whereas she earns exactly $\beta_h(pU^l+(1-p)\frac{R-(1-\beta_h)K}{\beta_h})-U$ under asymmetric information setting. By comparing these two expressions, we can show that

$$R-(1-\beta_h)K-U<\beta_h\left(pU^l+(1-p)\frac{R-(1-\beta_h)K}{\beta_h}\right)-U$$

if and only if $\beta_l>\frac{U\beta_h}{R-(1-\beta_h)K}$, which holds true by definition in region 2. Now, we compare the profits in region 4. In this region, h-type supplier U charges $\frac{R-(1-\beta_h)K}{\beta_h}$ and $\frac{R-(1-\overline{\beta})K}{\overline{\beta}}$ under full and asymmetric information settings, respectively. Since by definition $K>R$ and $\beta_h>\overline{\beta}$, we can show that

$$\frac{R-(1-\beta_h)K}{\beta_h}>\frac{R-(1-\overline{\beta})K}{\overline{\beta}}.$$

Hence, in region 4, h-type supplier U earns more in full information case than she does in asymmetric information case.

— Buyer: Similarly, in regions 1, and 3, buyer's cost is same under both full and asymmetric information settings. In region 2, buyer pays $\max(R,\beta_hU^h+(1-\beta_h)K)$, whereas he pays at least $p(\beta_hU^l+(1-\beta_h)K)+(1-p)R$. We show that

$$p(\beta_hU^l+(1-\beta_h)K)+(1-p)R>R$$

and

$$p(\beta_hU^l+(1-\beta_h)K)+(1-p)R>\beta_hU^h+(1-\beta_h)K.$$

First and second inequalities come from the fact that in region 2, $\beta_l>\frac{U\beta_h}{R-(1-\beta_h)K}$ and $p>\frac{\beta_hU^h+(1-\beta_h)K-R}{\beta_hU^l+(1-\beta_h)K-R}$, respectively. Hence, buyer pays more in asymmetric information setting than in full information setting. Finally, in region 4, buyer pays $\frac{R-(1-\beta_h)K}{\beta_h}$ and $\frac{R-(1-\overline{\beta})K}{\overline{\beta}}$ under full and asymmetric information settings, respectively. Since by definition $K>R$ and $\beta_h>\overline{\beta}$, we can show that

$$\frac{R-(1-\beta_h)K}{\beta_h}>\frac{R-(1-\overline{\beta})K}{\overline{\beta}}.$$

Hence, in region 4, buyer pays more in full information case than in asymmetric information case.

- True reliability of supplier U is β_l: We compare U and R's profits and B's cost under asymmetric information setting to full information setting.

— Supplier R: Recall that we show in Proposition 2 that under full information setting, supplier R's profit is zero if $\beta_l \geq 1 - \frac{(R-U)}{K}$, otherwise, it is $\beta_l U^l + (1-\beta_l)K - R$. In other words, supplier R charges $\beta_l U^l + (1-\beta_l)K$ if $\beta_l < 1 - \frac{(R-U)}{K}$, otherwise, she charges R. However, under asymmetric information setting, we show in Proposition 3 that R charges exactly $\beta_h U^h + (1-\beta_h)K$ in region 1, at most $\beta_l U^l + (1-\beta_l)K$ and R in regions 3 and 4. From the comparison of asymmetric information regions 1, 2, 3, and 4 with the full information regions characterized by the condition $\beta_l < 1 - \frac{(R-U)}{K}$, we can show that supplier R weakly earns more in full information setting than she does in asymmetric information setting.

— Supplier U: In regions 1, 2, and 3, supplier U of l type earns exactly same profit under both full and asymmetric information settings. We restrict our attention only to region 4. In this region, l-type supplier U charges $\frac{R-(1-\beta_l)K}{\beta_l}$ and $\frac{R-(1-\overline{\beta})K}{\overline{\beta}}$ under full and asymmetric information settings, respectively. Since by definition $K > R$ and $\beta_l < \overline{\beta}$, we can show that

$$\frac{R-(1-\beta_l)K}{\beta_h} < \frac{R-(1-\overline{\beta})K}{\overline{\beta}}.$$

Hence, in region 4, l-type supplier U earns more in asymmetric information case than she does in full information case.

— Buyer: In region 1, buyer pays $\beta_l U^l + (1-\beta_l)K$ and $\beta_h U^h + (1-\beta_h)K$ under full and asymmetric information settings, respectively. Since $\beta_l < \beta_h$, it is trivial to show that

$$\beta_l U^l + (1-\beta_l)K > \beta_h U^h + (1-\beta_h)K.$$

In region 2, buyer pays $\beta_l U^l + (1-\beta_l)K$, whereas he pays at least $p(\beta_h U^l + (1-\beta_h)K) + (1-p)R$. We show that

$$p(\beta_h U^l + (1-\beta_h)K) + (1-p)R < \beta_l U^l + (1-\beta_l)K,$$

where inequality comes from the fact that, in region 2, $R < \beta_l U^l + (1-\beta_l)K$ and $\beta_h > \beta_l$. In region 3, buyer's cost is $\beta_l U^l + (1-\beta_l)K$ and R under full and asymmetric information setting, respectively. Since $\beta_l < 1 - \frac{(R-U)}{K}$ in region 3, it is trivial to show that

$$\beta_l U^l + (1-\beta_l)K > R.$$

In region 4, buyer pays $\frac{R-(1-\beta_l)K}{\beta_l}$ and $\frac{R-(1-\overline{\beta})K}{\overline{\beta}}$ under full and asymmetric information settings, respectively. Since by definition $K > R$ and $\beta_l < \overline{\beta}$, we can show that

$$\frac{R-(1-\beta_l)K}{\beta_l} < \frac{R-(1-\overline{\beta})K}{\overline{\beta}}. \qquad \square$$

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