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Supply Competition under Quality Scores: Motivations, Information Sharing and Credibility

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Non-price attributes such as product quality, supplier's reliability, and timely delivery can be more important than simply unit price for the buyers. Therefore, the form of supplier competition in which the buyer adjust the prices from the suppliers with the quality scores (QS) becomes more popular than that under price-only format, where the decision is made solely based on prices. That said, QS alters the competition between the suppliers in two ways. First, it changes the nature of price competition among the suppliers as the winner needs to offer the lowest QS-adjusted price (not necessarily the lowest price). Second, the specific value of QS for each supplier is only known to the buyer, which gives rise to the credibility issues from the buyer's perspective. Analyzing supply competition under QS, in this paper, we characterize the equilibrium prices and evaluate whether or not it is beneficial for the buyer to share QS information with the suppliers in a credible fashion. We identify two factors: (i) degree of homogeneity among the suppliers (as measured by relative QS between the suppliers) and (ii) degree of information asymmetry (as measured by the range of uncertainty for the relative QS). The buyer prefers not to share the relative QS with the suppliers if they are relatively similar to each other in terms of QS. This is because the suppliers engage in a more intensified price competition under information asymmetry compared to when they have access to exact value of the relative QS. However, the opposite holds true if the suppliers become more uncertain about their relative QS. Hence, in this case, the buyer finds sharing QS information with the suppliers beneficial for the sake of lowering equilibrium prices notwithstanding the cost of credible sharing.

Key words: Supply Competition; Quality Score; Asymmetric Information; Credibility; Signaling.

1. Introduction

An increasing number of buyers nowadays use (electronic) B2B platforms to manage their sourcing processes (Demery 2016). There are two main benefits of e-sourcing. First, it considerably helps to streamline the end-to-end procurement process. According to a survey conducted among more than 200 companies, the deployment of e-sourcing cuts in half the sourcing cycle, which averages from 3.3 to 4.2 months (Minahan 2005). Popular B2B online services such as AliSourcePro literally enable anyone to receive several quotes within 48 hours after posting a simple buying request to a vast network of suppliers and help to finalize the procurement contract in a few days (BusinessWire 2014). Second benefit of e-sourcing comes in the form of reduction in purchase price due to the increased nature of supplier competition, which presents itself as direct savings to the bottom-line (BuyIT 2004). For instance, the U.S. General Services Administration attributed savings of

12%-48% to the use of competitive procurement processes (Sawhney 2003).

When it comes to allocating orders among competing suppliers, a buyer may use either the price-only or price-plus allocation rules. When price-only policy is applied, the order is awarded to the supplier with the lowest price, whereas in the price-plus policy, other non-price factors, such as quality, reliability, timely delivery, etc., are also factored into the buyer's decision calculus to determine the order allocation (Jap and Haruvy 2008). One of the commonly used procedures for incorporating these non-price factors is to assign a score, so-called *Quality Score* (QS), which represents the *buyer's evaluation of suppliers on the non-price factors*. The buyer then adjusts the prices of the suppliers using these scores, and allocates the order to the supplier whose QS-adjusted price, so-called *generalized price*, is the lowest (Anderson and Frohlich 2001, Jap 2002).

The evaluation of quality scores can take place in different forms. In some cases, buyers compute a single QS that may be based on the evaluation of one or multiple factors. For instance, the British Government has defined QS in its price-plus e-auctions as a numerical score resulting from the buyer's evaluation of quality as expressed in the "Invitation to Tender" (British 2015). For sourcing of legal services, General Electric evaluates one overall legal score for each supplier that is a weighted average of suppliers' expertise, efficiency, capacity, and legal rating (Tunca et al. 2014). In other cases, buyers may utilize multiple non-price (quality) scores to adjust suppliers' prices via a linear or nonlinear scoring formula. For example, health maintenance organizations (HMOs) usually attribute multiple scores to each online proposal submitted for the procurement of health insurance, including plan performance score, satisfaction score, significant plan design variations, and plan quality assurances (Gupta et al. 2012). QS can also be evaluated in terms of dollar values and be interpreted as either the additional cost the buyer should incur due to the supplier's quality shortage relative to the optimal level of quality required and be added to the bid price, or as the cost savings resulting from the supplier's quality excess relative to the minimum quality requirement, which should be subtracted from the bid price. These allocation rules are also known as quality-to-price scoring. Alternatively, if the quality is extremely important, some buyers may transform the price into a score and incorporate it with the QS (aka price-to-quality scoring). Please refer to Lundberg and Bergman (2011) for a detailed comparison of price-to-quality and quality-to-price scoring methods.

Even though price-plus allocation rules provide the buyers with the increased level of flexibility in the sense that the order is not awarded only on the basis of purchase price, it leads to two inter-related problems. One is informational, and the other one is related to its impact on the degree of competition. Informational problem arises among the parties because the suppliers do not know exactly how the buyer calculates QS. This can come from two main sources: (1) uncertainty on which non-price factors are used by the buyer (attribute uncertainty), and (2) uncertainty on how these non-price factors are combined to evaluate suppliers' final quality scores (procedural uncertainty). As noted in the literature, these two uncertainties result in informational asymmetries between buyers and suppliers regarding the rules of competitions (Beall et al. 2003). On the other hand, the buyer may attempt to alleviate this information asymmetry by communicating both attributes and procedure (together known as the scoring formula) to the suppliers. However, this can adversely impact the degree of competition among the suppliers. This is the source of the second problem. Namely, when the suppliers know the exact scoring formula and their quality scores, they can reverse-engineer the winning price and intentionally adjust their prices so as to win the competition (Haruvy and Katok 2013).

Even though the supply competition have been extensively explored in the operations literature, to the best of our knowledge, the informational and strategic issues regarding the quality scores have not received due attention. In this context, the objectives of this paper are to address the following research questions:

(i) *When* does the buyer share the QS information with the suppliers?

(ii) If the buyer decides to share QS with the suppliers, *how* can it be *credibly* shared?

(ii) *What* is the impact of sharing QS information on the decisions, and profits/cost of channel parties?

In order to address these issues, we develop a bi-level supply chain model in which the downstream party, the buyer, procures from one of the two competing sellers (hereinafter refereed to as supplier H and supplier L) at the upstream level. Suppliers are heterogeneous in terms of both marginal costs and quality scores. Namely, both marginal cost and QS of supplier H are higher than those of supplier L. To better focus on information asymmetry with respect to suppliers' relative QS, we assume all parameters are commonly known except the relative QS, which is only known to the buyer. The parties interact with each other in the following order: First, the buyer evaluates the non-price attributes of the suppliers H and L and assigns to each[1] a QS, which is privately known only to the buyer. Second, the buyer decides whether or not to share QS information with the suppliers. Then, suppliers *competitively* offer their prices. Finally, the buyer calculates the generalized prices of suppliers based on the QS-adjusted bids, and awards the order to the one with the lowest generalized price.

We characterize decisions (prices and quantities), and pay-offs (profits and costs) of all the supply chain parties under both pooling and separating equilibria. Their comparative analyses allow us to evaluate when and how the QS information can be credibly shared by the buyer with the suppliers

[1] Throughout the paper, we use masculine and feminine pronouns for the buyer and suppliers, respectively.

and how it affects the degree of price competition among the suppliers and the payoffs of supply chain partners. First of all, the fact that the suppliers do not have access to the quality scores leads to an uncertainty on them regarding what price to charge. We show that this leads to higher prices than those under symmetric information particularly when the degree of information asymmetry on quality scores is high. This in turn generates an incentive for the buyer to share QS information with the suppliers. That said, we also show that the buyer has always incentive to distort the relative QS information between the suppliers, which puts the credibility of QS information at stake. In this context, we show that the buyer can share relative QS between the suppliers credibly with the help of a price and quantity guarantee, a commonly used commitment contract in the supply chain procurement[2]. This increases the degree of competition among the suppliers (which in turn lowers the equilibrium bid prices) when they are heterogeneous. However, it comes at a [signalling] cost for the buyer. Hence, the buyer opts for sharing QS information only when the degree of information asymmetry on the quality scores is sufficiently high.

Finally, the analysis of a general case with more than two suppliers allows us to show that an increase in the number of competing suppliers naturally intensifies the price competition and hence reduces the need for sharing QS information credibly.

2. Related Literature

Our work is primarily related to two streams of research in the context of supply chains: (i) papers analyzing various competitive sourcing mechanisms, and (ii) papers dealing with informational asymmetry issues.

Most of the papers in the first stream of research can be categorized into three groups. The first group includes papers focusing on the game-theoretical competition among suppliers on price and/or quality (e.g., Chakraborty et al. 2015, Chen et al. 2015, Li and Chen 2018, Xie et al. 2011). Our work is distinct from them in the sense that we let the suppliers compete based on their price while their exogenous quality, evaluated by the buyer, can also affect their chance of winning. The papers in the second group compare price-plus with price-only allocation policies experimentally or analytically and show that price-plus allocation policies are more effective in increasing buyer's utility compared to price-only settings (see Chen-Ritzo et al. 2005, Bichler 2000, and Asker and Cantillon 2008).

[2] Price and quantity contracts enable supply chain parties to commit a certain minimum quantity at a fixed price. We observe different versions of such contracts in commodity industries such as electricity/metal/coffee/natural gas (see Stevenson 2006; Creti and Fabra 2007), in the printed circuit board (Heyes 2008) as well as in food supply chains (USDA 2001). Such contracts are also used in spare part supply services of transportation equipments like railcars (see Alstom 2009).

The third group of papers in the first stream compare supplier- vs. buyer-determined price-plus supply auctions and show that the outcome depends on the number of participating bidders (Engelbrecht-Wiggans et al. 2007), and the relative cost differences among the suppliers and the number of non-price attributes (Santamaría 2015). Note that in a buyer-determined auction, it is the buyer who decides on non-price attributes based on some pre-determined scoring rules, whereas in supplier-determined auctions, suppliers bid on not only prices but also non-price attributes, such as delivery time, quality etc. In the former, buyers might evaluate non-price attributes before or after the bidding process. Wan and Beil (2009) analytically compare the performance of pre- and post-evaluations and show how the buyer's choice depends on the evaluation (qualification screening) cost. The latter is also called a menu auction, in which the bidder is allowed to offer a menu of price and non-price attributes. We refer the readers to Bernheim and Whinston (1986) for a detailed analysis of menu auctions.

Recent empirical studies provide strong evidence that information asymmetry can have significant impacts on the competition's results and certainly affects the buyer's surplus (Mithas and Jones 2007). Haruvy and Katok (2013) using experiments show that in on-line procurement auctions with open-bid format where exogenous bidder quality affects determination of the winner, the buyer surplus significantly decreases when the information about bidders' quality is publicly known. Our paper is also related to the stream of research on (forward) ad auctions in which the auction-holder assigns a QS to each bidder in order to capture critical non-price features. The key research question in this stream is to analyze the impact of competition formats on the truth-telling property (see Liu et al. 2010 and references therein). To the best of our knowledge, no paper in this stream analytically explores the impact of information asymmetry about the non-price attributes on bidding behaviour of the suppliers as well as the buyer's surplus.

The second stream of research that is related to our work is on information asymmetry and the resulting credibility issues in procurement competition and supply chains. The papers are divided into two groups depending on whether the asymmetric information is on the supply side such as costs and reliabilities of the suppliers (Chakraborty et al. 2019, Ghosh and Shah 2015, Kim and Netessine 2013, Beil and Wein 2003, Corbett and De Groote 2000, Ha 2001, Yang et al. 2009, Yang et al. 2012, Gümüs et al. 2012) or on the demand from the buyer's side (Guan et al. 2019, Cachon and Lariviere 2001, Li and Scheller-Wolf 2011, Wang et al. 2014, Gümüş 2014, Özer and Wei 2006). Our paper differs from this literature in the sense that the private information is defined on the suppliers' quality score but known only to the buyer. The papers in this stream are also methodologically divided into mechanism design and signalling depending on whether it is the uninformed or informed party who offers the contract. In our analysis, we use the latter framework to model an informed principal who utilizes the price and quantity guarantees with the aim of sharing QS information in a credible fashion (see Riley 2001 for an extensive literature review on signaling games).

Lastly, a stream of research related to our study is about price and quantity guarantees in the supply chains. Similar to our use of guarantee for signaling quality score information, Klotz and Chatterjee (1995) use a quantity guarantee to the incumbent supplier in exchange for participating in the procurement competition. Signalling characteristics of commitment contracts have been analyzed in both operations and marketing literature. Cachon (2004) studies the use of advance purchase discount contracts as a mechanism for sharing the inventory risk in a supply chain. Özer and Wei (2006) and Gümüs et al. (2012) analyze the role of price and quantity guarantee contracts in enabling credible forecast and supply information sharing, respectively, between supply chain parties. Tang et al. (2004) and Yu et al. (2014) study the role of advance selling commitments between retailers and consumers in updating demand forecast and signaling product quality, respectively.

3. Model Framework

In order to investigate the impact of QS information sharing in supply competition, we model a stylized two-level supply chain consisting of one buyer and two competing suppliers. The suppliers differ in terms of both marginal costs and quality scores. Let c_i, and QS_i denote the marginal cost and quality score of supplier $i \in \{L, H\}$. Throughout the paper, we assume $c_L < c_H$. Also, we assume that quality score of supplier H is known to be higher than that of supplier L. However, the suppliers H and L do not know how much their quality scores assessed by the buyer, i.e., QS_H and QS_L, respectively, differ from each other. Note that what helps a supplier to make informed pricing decisions is the knowledge to the relative difference between suppliers' QS, and not just her own QS. In order to capture the relative difference between quality scores of the suppliers, we define α and let it equal to QS_L/QS_H. Note that α essentially captures the degree of *relative similarity* between suppliers H and L in terms of their quality scores. That means, the closer α is to 1 (resp, 0), the more similar (resp., dissimilar) supplier L becomes to supplier H in terms of their quality scores.

In order to model the asymmetric information regarding the quality scores, we assume that the true value of relative QS, α, is known only to the buyer, whereas all other parameters, including suppliers' costs, are commonly known to all the parties. For the sake of tractability, we assume that suppliers hold a-priori belief on α in the sense that it is uniformly distributed between $\underline{\alpha}$ and $\bar{\alpha}$, where without loss of generality, $0 < \underline{\alpha} \leq \bar{\alpha} \leq 1$. Note that the difference between upper and lower bounds denoted by $\Delta = \bar{\alpha} - \underline{\alpha}$ represents the degree of information asymmetry on the quality scores between the buyer and the suppliers L and H.

Upon receiving the prices from the suppliers, the buyer then decides on the order allocation. There are various ways to merge price and quality score data of suppliers. One of the simplest rule employed in practice is the multiplicative generalized price rule.[3] Briefly, in this case, the buyer adjusts the price of each supplier with its quality score by computing price-to-QS ratio, i.e., $p'_i = p_i/QS_i$. The generalized prices of all the suppliers are then sorted in ascending order. The supplier whose generalized price is lowest wins the order. Note that in the case of two suppliers, the above multiplicative form boils down to the following simplified comparison between relative price and QS of suppliers H and L. Namely, supplier L wins if $p_L/p_H < \alpha$, otherwise, supplier H wins.

We also define a cap on the bid prices offered by the suppliers denoted by p_r. Essentially, one can interpret this cap as the cost of outside option for the buyer or price in the spot market to which he has always access. We also assume that p_r is greater than c_H. Finally, in order to focus on the main research questions related to the quality score, we assume that buyer's demand is deterministic and equal to Q units.

Given the above order allocation rule, the cost of the buyer and the profits of the suppliers H and L (denoted by κ_B, π_H, and π_L, respectively) can be expressed as follows. In case buyer receives equal generalized prices from suppliers, we simply assume supplier H will be selected without loss of generality.

$$(\kappa_B, \pi_H, \pi_H) = \begin{cases} (Q \times p_H, Q \times [p_H - c_H], 0) & \text{if } \frac{p_L}{p_H} \geq \alpha, p_H \leq p_r \\ (Q \times p_L, 0, Q \times [p_L - c_L]) & \text{if } \frac{p_L}{p_H} < \alpha, p_L \leq p_r \\ (Q \times p_r, 0, 0) & \text{otherwise} \end{cases} \tag{1}$$

The timing of decisions and events is shown in Figure 1 and provided as follows.

1. Buyer evaluates α, i.e., the ratio between quality scores of the suppliers L and H.

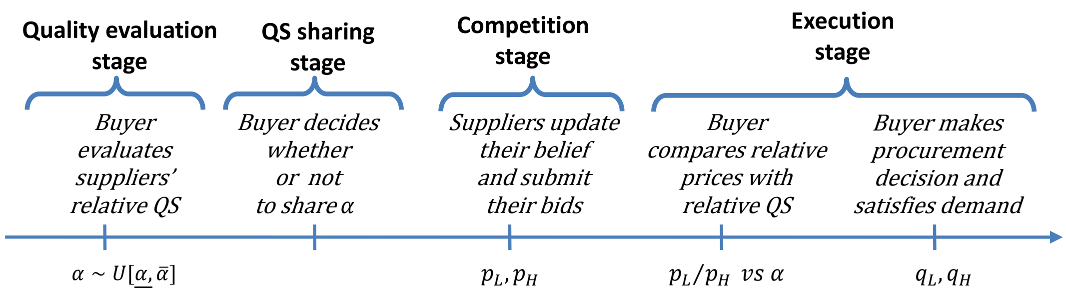
2. Buyer decides whether or not to share α with the suppliers.

3. In response to the buyer's decision, suppliers update their prior beliefs on α via Bayesian updating and submit their prices p_i.

4. Buyer adjusts suppliers' prices with their quality scores, and allocates the order to the supplier with the lowest quality-score adjusted price.

[3] In practice, additive formulas (i.e., $p' = p + QC$ with QC, p and p' representing quality cost, price, and generalized price, respectively) are also commonly employed (for example see Kostamis et al. 2009). Since we can convert the additive form of $p' = p + QC$ to the multiplicative form of $p' = p/QS$ with a one-to-one relationship between QC and QS for a fixed p, the analysis of either of these forms would lead to the same qualitative results. That said, we use multiplicative calculation in this paper for simpler presentation as we can let quality score (QS) to take values between 0 and 1.

Figure 1 Timeline of Decisions and Events.



Before we start the analysis, we summarize in Table 1 the list of notations used for parameters and decision variables throughout the paper.

Table 1 Notation used for model parameters and decision variables.

Model parameters	
$c_L; c_H$	Marginal cost of suppliers L and H, respectively.
α	The true value of relative ratio between quality scores of suppliers L and H, i.e., QS_L/QS_H.
$\underline{\alpha}; \bar{\alpha}$	Lower and upper bounds on suppliers' uniform a priori belief distribution for the true value of α.
$\pi_L; \pi_H$	Expected profit of the suppliers L and H, respectively.
κ_B	Expected cost of the buyer
Q	Total demand
p_r	Reserve price (outside option price)
Decision variables	
η_L, η_H	The level of guarantee offered to suppliers L and H, respectively.
$p_L; p_H$	Unit prices quoted by suppliers L and H, respectively.
$q_L; q_H$	Buyer's order allocation decisions for suppliers L and H, respectively.

4. Symmetric Information: Benchmark

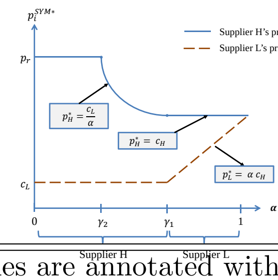
To establish a benchmark, we first consider the case where the true value of α is known to all the parties in the supply chain. The problem, therefore, transforms to a price competition game under symmetric information between suppliers H and L, in which at the equilibrium, the suppliers would reduce their prices down to a point where one of them hits her marginal cost.

Delegating the details of the analysis to the Appendix, we provide full characterization of equilibrium under symmetric information in the following proposition (proofs for all propositions are provided in Appendix).

Proposition 1. *Let $\gamma_1 = c_L/c_H$ and $\gamma_2 = c_L/p_r$ (where $\gamma_2 < \gamma_1$ as $p_r > c_H$). Under symmetric information equilibrium, the buyer orders from supplier L if $\alpha > \gamma_1$, and from supplier H if $\alpha \leq \gamma_1$. For when $\alpha < \gamma_2$, the buyer orders from H at the reserve price (p_r). Complete characterization of equilibrium decisions and profits/costs of the supply chain parties under symmetric information is provided in Table 2.*

Table 2 **Equilibrium decisions, profits, and cost under symmetric information.**

Regions		$0<\alpha<\gamma_2$	$\gamma_2<\alpha<\gamma_1$	$\gamma_1<\alpha<1$
Prices (bids)	p_H^*	p_r	$\frac{c_L}{\alpha}$	c_H
	p_L^*	c_L		$c_H\alpha$
Order Alloc.	q_H^*, q_L^*	$Q, 0$		$0, Q$
Suppliers'	π_H^*	$Q(p_r - c_H)$	$Q(\frac{c_L}{\alpha} - c_H)$	0
Profits	π_L^*	0		$Q(\alpha c_H - c_L)$
Buyer's Cost	κ_B^*	Qp_r	$Q\frac{c_L}{\alpha}$	$Qc_H\alpha$



Throughout the paper, equilibrium profits/costs and decision variables are annotated with asterisks.

Note that when α is relatively high ($\gamma_1 < \alpha$), i.e., suppliers L and H are relatively similar in terms of their quality scores, supplier L becomes the sole supplier for the buyer due to her cost advantage. This enables her to always set a price p_L such that $\frac{p_L}{\alpha}$ is infinitesimally smaller than supplier H's marginal cost c_H. Letting $\frac{p_L}{\alpha} = c_H$ and solving for p_L would yield the equilibrium price p_L^* for supplier L. Likewise, when α is between γ_1 and γ_2, supplier H wins and her equilibrium price can be characterized in a similar fashion. Finally, when α is less than γ_2, then supplier H would always win by charging infinitesimally less than the reserve price. In the following corollary, we characterize the sensitivity of equilibrium prices and profits of the suppliers with respect to α and their marginal costs:

Corollary 1. *Under symmetric information setting,*

1. *The equilibrium price and profit of supplier H (p_H^*, π_H^*) (weakly) decrease in α, while those of supplier L (i.e., p_L^* and π_L^*) (weakly) increase in α.*
2. *With an increase in c_L for a fixed c_H, both suppliers L and H weakly increase their bid prices.*

The first part of this corollary in fact implies that α influences the degree of price competition among suppliers, which in turn affects their prices in equilibrium. The second part shows the impact of suppliers' relative cost efficiency on their pricing decisions in the competition. In the next section, we show that this impact of α will be important in determining the equilibrium under asymmetric information.

5. Asymmetric Information

In this section, we analyze the equilibrium under asymmetric information setting where the true value of α is known only to the buyer. We assume that any information shared by the buyer regarding the true value of α is non-verifiable by the suppliers. In addition, we do not consider separate signalling channels for suppliers, i.e. any signal by the buyer is transparently visible to both suppliers. The following Lemma implies that in the absence of a credible signal, the buyer would always have incentive to distort the true value of α:

LEMMA 1. *There is no separating equilibrium under which the buyer discloses the true value of α to the suppliers.*

The above result is an artefact of Corollary 1 and shows that sharing α cannot trivially be done by cheap talks. Recall that the buyer can indirectly influence the equilibrium outcome of the competition by manipulating the value of relative QS, i.e. α. Hence, in order to credibly share the true value of α with the suppliers, the buyer would need a costly signal. In this paper, we consider a commitment contract ("price and quantity guarantees"), which is commonly used in the context of supply chain procurement - please refer to §1.

Basically, this contract provides supplier i with a guarantee of minimum level of quantity that is expressed as a pre-determined percentage η_i of demand Q at some fixed reserve price p_r. More specifically, under such contract, the supplier i's revenue would be equal to $\eta_i Q p_r$ if she loses the competition. If she wins though, her revenue would be either $p_i Q(1-\eta_{-i})$ or $\eta_i Q p_r$, whichever is the higher[4]. Taking into account the marginal cost, one can write down the profit expressions for suppliers H and L under price and quantity guarantee contract as follows:

$$(\pi_H, \pi_L) = \begin{cases} \eta_H Q(p_r - c_H), \max\left[Q(1-\eta_H)p_L, Q\eta_L p_r\right] - Q(1-\eta_H)c_L & \text{if supplier } L \text{ wins, i.e., } \frac{p_L}{p_H} < \alpha \ \&\ p_L \le p_r, \\ \max\left[Q(1-\eta_L)p_H, Q\eta_H p_r\right] - Q(1-\eta_L)c_H, \eta_L Q(p_r - c_L) & \text{if supplier } H \text{ wins, i.e. } \frac{p_L}{p_H} \ge \alpha \ \&\ p_L \le p_r. \end{cases}$$

Note that suppliers H and L's profits depend on not only their bid prices p_H and p_L but also the guaranteed levels η_H and η_L. Because of this dependency, the procurement competition under a price and quantity guarantee leads to a costly signalling game (See Fudenberg and Tirole 1991 for a detailed description of signaling games), where the buyer can potentially share α with the suppliers in a credible fashion. As in any signalling game, the equilibrium can be of three types: (i) pooling, where the buyer sends the same signal regardless of his type, i.e., $\eta_i(\alpha) = \eta_i$ for all $\alpha \in [\underline{\alpha}, \bar{\alpha}]$, (ii) separating, where the buyer, depending on his type, sends different signals, i.e., $\eta_i(\alpha) \neq \eta_i(\alpha')$ for all $\alpha \neq \alpha'$ and (iii) semi-separating, where the buyer sends the same signal for a group of types and different signals for another group of types, i.e., $\eta_i(\alpha)$ satisfies pooling and separating conditions for different subsets of α. In what follows, we analyze each type separately.

5.1 Pooling Equilibrium: No information sharing

Note that in a pooling equilibrium, $\eta_i(\alpha) = \eta_i$ for all α, where $0 \le \eta_i \le 1$. In other words, the buyer provides the same level of guarantee regardless of the true value of his type α. Therefore, suppliers' a-posterior beliefs will be the same as their a-priori beliefs. In this situation, suppliers' bidding

[4] Throughout the paper, we use the standard game theory notation to represent the index of supplier i's opponent with $-i$.

prices will be solely based on their prior beliefs. As it happens in a typical signalling game, we obtain multiple pooling equilibria by varying the value of guarantee η_i from 0 to 1. However, we can eliminate all but the one with $\eta_i = 0$ by employing the least cost refinement argument and Intuitive Criterion proposed by Cho and Kreps (1987) that are commonly used in signalling literature for equilibrium refinement purposes. More specifically, under a constant but non-zero guarantee of $\eta_i > 0$, we can always show that supplier i will never offer a bid, which is smaller than p_i^{low}, where

$$p_i^{low} = c_i + \frac{\eta_i}{1-\eta_{-i}}(p_r - c_i)\ ,\ i = L\ \&\ H \tag{2}$$

Note that there is no incentive for the supplier i to offer a bid price less than p_i^{low} as otherwise, she can earn more by charging more than her opponent and delivering only the guaranteed portion η_i.[5] This suggests that among all the pooling equilibria, where the buyer sets a constant guarantee for all α, the one with $\eta_i = 0$ for both $i = L$ and H is the *least costly pooling equilibrium* for the buyer. Therefore, throughout the paper, we refine all the pooling equilibria and focus only on the least costly one, which also survives the Intuitive Criterion refinement. Given $\eta_i = 0$ for both suppliers L and H, we can then characterize the price competition between the suppliers under asymmetric quality score information as follows.

Lemma 2. *Under pooling equilibrium (PE), the price competition between suppliers leads to one of the following four different equilibrium prices:*

- *PE-1: Interior solution of* $p_H^{int} = \frac{\bar{\alpha}c_H + \sqrt{\bar{\alpha}^2 c_H^2 + 8\underline{\alpha}c_H c_L}}{4\underline{\alpha}}$ *and* $p_L^{int} = \frac{(\bar{\alpha}^2 c_H + \bar{\alpha}\sqrt{\bar{\alpha}^2 c_H^2 + 8\underline{\alpha}c_H c_L} + 4\underline{\alpha}c_L)}{8\underline{\alpha}}$*;*
- *PE-2: Boundary solution of* $p_H = p_r$ *and* $p_L = max(\frac{\bar{\alpha}p_r + c_L}{2}, c_L)$*;*
- *PE-3: Boundary solution of* $p_H = c_H$ *and* $p_L = c_H\underline{\alpha}$*;*
- *PE-4: Boundary solution of* $p_H = \min(\frac{c_L}{\bar{\alpha}}, p_r)$ *and* $p_L = c_L$*.*

The above lemma shows that except for the case of PE-1, the price competition under pooling equilibrium leads to a boundary solution. Under these boundary cases, similar to the competition under symmetric information, suppliers undercut each other until one of them hits her marginal cost. On the other hand, in the case of PE-1, the price competition under asymmetric information leads to an interior equilibrium pair (p_H^{int} and p_L^{int}), which is sustained by the inherent uncertainty regarding the quality score among the suppliers (as opposed to price-undercutting forces). Therefore, the equilibrium prices in PE-1 depend on both lower and upper ranges of relative QS

[5] Note that by the definition of the price and quantity guarantee, supplier i will be offered a quantity of η_i at the price of p_r, which gives her a guaranteed profit of $\pi_i^G = \eta_i(p_r - c_i)$, only if she fails in competition. On the other hand, she will earn a profit of $\pi_i^W(p_i) = (p_i - c_i)(1 - \eta_{-i})$ if she undercuts her competitor. Consequently, a supplier would rationally prefer not to undercut and instead obtain the minimum guaranteed profit than to win at a small price with a profit lower than the guaranteed profit level. This implies that a supplier would not logically bid lower than $p_i^{low} = \min\{p_i | \pi_i^W(p_i) \geq \pi_i^G\}$.

information uncertainty (i.e., $\underline{\alpha}$, and $\bar{\alpha}$) as well. Given the possible equilibrium bid prices, we can now characterize the regions for $\underline{\alpha}$ and $\bar{\alpha}$ under which each one of the above equilibria is sustained as a unique pooling equilibrium.

PROPOSITION 2. *Complete characterization of equilibrium decisions (prices and quantities), and pay-offs (profits and costs) for the supply chain parties under pooling equilibrium for each case is provided in Table 3.*

There are two take-aways from the above Proposition.

• When the degree of QS uncertainty is relatively small, then either PE_3 or PE_4 appears in the equilibrium. This case leads to an intensive price competition, in which the suppliers sustain the equilibrium only by undercutting each other's offers similar to the price competition under symmetric information. However, under the asymmetric information scenario, the suppliers do not know the exact value of QS. Hence, a supplier cannot decide on the exact price that would undercut her opponent's offer at the marginal cost. The equilibrium analysis shows that when the range of uncertainty on QS (i.e., $\bar{\alpha} - \underline{\alpha}$) is sufficiently small, the winner sets a bidding price that would undercut her opponent even under the worst-case belief on the quality score.

• As the range of uncertainty on QS uncertainty increases, then the worst-case bidding strategy becomes very costly for the suppliers. Therefore, they instead use *expected-case* bidding strategy, under which each maximizes the likelihood of winning the competition multiplied by the bid price assuming that true value of QS is distributed uniformly between $\underline{\alpha}$ and $\bar{\alpha}$. Consequently, either PE_1 or PE_2 appears in the equilibrium.

Given these observations, we conduct sensitivity analyses first in Proposition 3 about how the equilibrium bid prices change with respect to system parameters such as costs, i.e., c_L and c_H, and upper and lower bounds of QS, i.e., $\bar{\alpha}$ and $\underline{\alpha}$, and then in Proposition 4 about how they compare with respect to their symmetric information counterparts.

PROPOSITION 3. *Sensitivity analyses with respect to the effect of parameters on the suppliers' optimal prices in pooling equilibria lead to the following.*

1. ***Effect of the Marginal Costs:*** *As the marginal cost of supplier L converges to that of supplier H, equilibrium bid prices of both suppliers increase and the regions for PE_4 increase while those for PE_3 decrease.*

2. ***Effect of QS Uncertainty:*** *In regions for PE_1 and PE_2, the equilibrium bid prices p_H^* and p_L^* increase in $\bar{\alpha}$ (for a fixed $\underline{\alpha}$) and decrease in $\underline{\alpha}$ (for a fixed $\bar{\alpha}$). However, in regions PE_3 and PE_4, the bid prices decrease in $\bar{\alpha}$ (for a fixed $\underline{\alpha}$) and weakly increase in $\underline{\alpha}$ (for a fixed $\bar{\alpha}$).*

Figure 2 **Equilibrium characterization under asymmetric information: Pooling Equilibrium.**

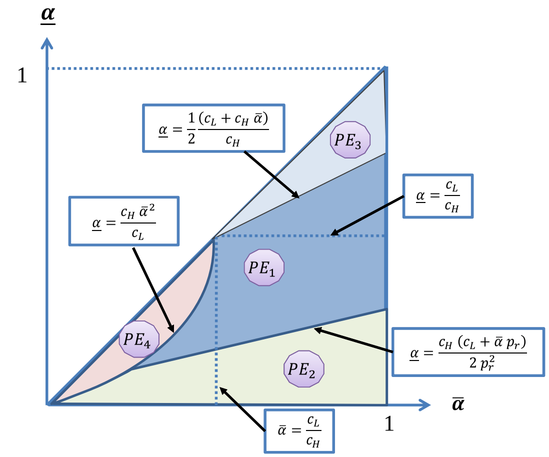
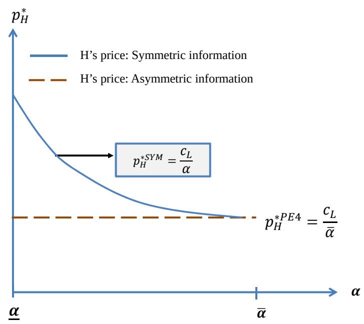


Table 3 **Equilibrium characterization under asymmetric information: Pooling Equilibrium.**

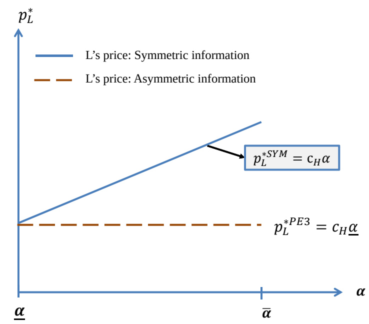
Regions		$(\underline{\alpha},\bar{\alpha}) \in PE_1$		$(\underline{\alpha},\bar{\alpha}) \in PE_2$		$(\underline{\alpha},\bar{\alpha}) \in PE_3$	$(\underline{\alpha},\bar{\alpha}) \in PE_4$
Range of α		$\alpha \le \gamma_1$	$\alpha > \gamma_1$	$\alpha \le \gamma_2$	$\alpha > \gamma_2$	$\underline{\alpha} \le \alpha \le \bar{\alpha}$	$\underline{\alpha} \le \alpha \le \bar{\alpha}$
Prices	p_H^*	$\frac{\bar{\alpha}c_H + \sqrt{\bar{\alpha}^2 c_H^2 + 8\underline{\alpha}c_H c_L}}{4\underline{\alpha}}$		p_r		c_H	$\min(\frac{c_L}{\bar{\alpha}}, p_r)$
	p_L^*	$\frac{(\bar{\alpha}^2 c_H + \bar{\alpha}\sqrt{\bar{\alpha}^2 c_H^2 + 8\underline{\alpha}c_H c_L} + 4\underline{\alpha}c_L)}{8\underline{\alpha}}$		$max(\frac{\bar{\alpha}p_r + c_L}{2}, c_L)$		$c_H\underline{\alpha}$	c_L
Alloc.	$q_H^*,\ q_L^*$	$Q, 0$	$0, Q$	$Q, 0$	$0, Q$	$0, Q$	$Q, 0$
Suppliers'	π_H^*	$Q(\frac{\bar{\alpha}c_H + \sqrt{\bar{\alpha}^2 c_H^2 + 8\underline{\alpha}c_H c_L}}{4\underline{\alpha}} - c_H)$	0	$Q(p_r - c_H)$	0	0	$Q(\min(\frac{c_L}{\bar{\alpha}}, p_r) - c_H)$
Profits	π_L^*	0	$\frac{(\bar{\alpha}^2 c_H + \bar{\alpha}\sqrt{\bar{\alpha}^2 c_H^2 + 8\underline{\alpha}c_H c_L} + 4\underline{\alpha}c_L)}{8\underline{\alpha}} - c_L)$	0	$Q(max(\frac{\bar{\alpha}p_r + c_L}{2}, c_L) - c_L)$	$Q(c_H\underline{\alpha} - c_L)$	0
Cost	κ_B^*	$Q\frac{\bar{\alpha}c_H + \sqrt{\bar{\alpha}^2 c_H^2 + 8\underline{\alpha}c_H c_L}}{4\underline{\alpha}}$	$Q\frac{(\bar{\alpha}^2 c_H + \bar{\alpha}\sqrt{\bar{\alpha}^2 c_H^2 + 8\underline{\alpha}c_H c_L} + 4\underline{\alpha}c_L)}{8\underline{\alpha}}$	Qp_r	$Q(max(\frac{\bar{\alpha}p_r + c_L}{2}, c_L))$	$Qc_H\underline{\alpha}$	$Q\min(\frac{c_L}{\bar{\alpha}}, p_r)$

Let $\gamma_1 = \frac{(\bar{\alpha}^2 c_H + \bar{\alpha}\sqrt{\bar{\alpha}^2 c_H^2 + 8\underline{\alpha}c_H c_L} + 4\underline{\alpha}c_L)}{2(\bar{\alpha}c_H + \sqrt{\bar{\alpha}^2 c_H^2 + 8\underline{\alpha}c_H c_L})}$ and $\gamma_2 = \frac{max(\frac{\bar{\alpha}p_r + c_L}{2}, c_L)}{p_r}$ for PE-1 and PE-2, respectively.

Figure 3 **The impact of low uncertainty on the equilibrium prices under symmetric information vs. pooling equilibrium.**



(a) Supplier H's price; $\frac{c_H\bar{\alpha}^2}{c_L} \leq \underline{\alpha} < \bar{\alpha} < \frac{c_L}{c_H}$



(b) Supplier L's price; $\bar{\alpha} > \frac{c_L}{c_H}$ **and** $\underline{\alpha} \geq \frac{c_L + c_H\bar{\alpha}}{2c_H}$

The first part of Proposition 3 shows that the equilibrium bid prices increase as the suppliers become more similar in terms of their marginal costs. The second part addresses the effect of information asymmetry in relative QS on the suppliers' bid prices. Reducing uncertainty generally leads to lower bid prices from both suppliers as long as the range of uncertainty in QS is sufficiently large. On the other hand, when the range of uncertainty is low, further reducing uncertainty would lead to higher bid prices. In fact, for each α, there are thresholds for $\underline{\alpha}$ and $\bar{\alpha}$ at which the equilibrium bid prices are at their lowest possible levels under asymmetric information scenario. The following proposition explores these thresholds and identify the circumstances where asymmetric information results in lower bid prices than symmetric information.

Proposition 4. *The winning price under pooling equilibrium is lower than that under symmetric information for all values of* $\alpha \in [\underline{\alpha}, \bar{\alpha}]$*, where the difference between* $\bar{\alpha}$ *and* $\underline{\alpha}$ *is sufficiently small, i.e.,* $\bar{\alpha} - \underline{\alpha}$ *is smaller than* $\frac{\bar{\alpha}(c_L - c_H\bar{\alpha})}{c_L}$ *if* $\bar{\alpha} \leq \frac{c_L}{c_H}$*, and* $\frac{c_H\bar{\alpha} - c_L}{2c_H}$ *otherwise.*

Proposition 4 is illustrated in Figure 3. Left panel corresponds to $\bar{\alpha} \leq c_L/c_H$, i.e., the relative QS of supplier L is low, whereas the right panel corresponds to the opposite case, i.e., $\bar{\alpha} > c_L/c_H$. Recall that in both cases, suppliers use worst-case bidding strategy under pooling equilibrium, which results in bid prices that are lower than those under symmetric information. Hence, without further investigation, we can conclude that if the difference between $\bar{\alpha}$ and $\underline{\alpha}$ is sufficiently small, the buyer is always better off by keeping QS information private from the suppliers in order to induce them to apply the worst-case bidding strategy.

5.2 Separating Equilibrium

In a separating equilibrium, $\eta_i(\alpha) \neq \eta_i(\alpha')$ for $\alpha \neq \alpha'$. In other words, the buyer provides different levels of guarantee depending on the true value of his type α. In this situation, suppliers' bidding prices will be based on their posterior beliefs updated after observing the buyer's signal. Under a separating equilibrium, by definition, the buyer must have no incentive to deviate from telling the true value of α, and consequently, suppliers L and H would be able to correctly infer the true value of α, and act accordingly. In order to achieve the consistency between buyer's and the suppliers' decisions, the resulting *Perfect Bayesian Equilibrium* must meet the following two requirements.

First, there must be a one-to-one mapping between the true value of α and the level of buyer's advance guarantee $\eta_i(\alpha)$. Technically speaking, this means that if $\alpha \neq \alpha'$, then $(\eta_H(\alpha), \eta_L(\alpha)) \neq (\eta_H(\alpha'), \eta_L(\alpha'))$. This ensures that the buyer sends different signals for different values of α. Suppliers then correctly infer the true value of α when they observe a pair of $(\eta_H(\alpha), \eta_L(\alpha))$. Second, the choice of guarantees $\eta_H(\alpha)$ and $\eta_L(\alpha)$ should be incentive compatible for the buyer so that the buyer has no incentive to deviate from the equilibrium. To validate if these two requirements are satisfied in the equilibrium, we first characterize the best response of the suppliers given $\eta_H^*(\alpha)$ and $\eta_L^*(\alpha)$. We then verify that the buyer has no incentive to deviate from equilibrium $\eta_i^*(\alpha)$, $i \in \{H, L\}$.

The next lemma characterizes the first part, i.e., the suppliers' optimal bids and the equilibrium cost and profits given that the buyer offers $\eta_H^*(\alpha)$ and $\eta_L^*(\alpha)$.

LEMMA 3. *Assume* $\gamma_1 = \frac{p_L^{low}}{p_H^{low}} < 1$ *,* $\gamma_2 = \frac{p_L^{low}}{p_r}$ *(*$\gamma_2 < \gamma_1$*), where* $p_i^{low} = c_i + \frac{\eta_i}{1-\eta_{-i}}(p_r - c_i)$ *for* $i = L$ *and* H*. In a separating equilibrium, the suppliers would charge the equilibrium bids characterized in Table 4.*

Table 4 Best responses of the suppliers and the buyer after receiving the signal: Separating Equilibrium.

Equilibrium decisions		$(\eta_H, \eta_L) \in [0,1]^2, \quad 0 \le \eta_H + \eta_L \le 1$		
		$0 < \alpha \le \gamma_2$	$\gamma_2 \le \alpha \le \gamma_1$	$\gamma_1 \le \alpha \le 1$
Prices (bids)	p_H^*	p_r	$\frac{p_L^{low}}{\alpha}$	p_H^{low}
	p_L^*	p_L^{low}		αp_H^{low}
Order Alloc	q_H^*, q_L^*	$(1-\eta_L)Q, \eta_L Q$		$\eta_H Q, (1-\eta_H)Q$
Suppliers'	π_H^*	$Q(1-\eta_L)(p_r - c_H)$	$Q(1-\eta_L)(\frac{p_L^{low}}{\alpha} - c_H)$	$\eta_H Q(p_r - c_H)$
Profits	π_L^*	$\eta_L Q(p_r - c_L)$		$(1-\eta_H)Q(\alpha p_H^{low} - c_L)$
Buyer's Cost	κ_B^*	Qp_r	$Q\left(\eta_L p_r + (1-\eta_L)\frac{p_L^{low}}{\alpha}\right)$	$Q\left(\eta_H p_r + (1-\eta_H)\alpha p_H^{low}\right)$

† Note that $p_i^{low} = c_i + \frac{\eta_i}{1-\eta_{-i}}(p_r - c_i)$ for $i = L$ and H if suppliers L and H are offered a minimum revenue of $\eta_L Q p_r$ and $\eta_H Q p_r$, respectively.

This lemma follows directly from the fact that after receiving the signal and correctly inferring α, the suppliers' bidding strategy would be very similar to the symmetric information case except that the minimum price would be the price implied by the guarantees p_i^{low} instead of their marginal costs c_i for $i = H, L$. Consider for example the case where the buyer offers the guarantee only to supplier H, i.e. $\eta_H > 0$ and $\eta_L = 0$. If the supplier L's QS is very low, i.e., $\alpha \le \gamma_1$, then there is no need for supplier H to lower her price in order to outbid supplier L and win the entire order from the buyer. Hence, in this case, the equilibrium will be exactly the same as the one under symmetric information ($\frac{c_L}{\alpha}$). When the QS of supplier L becomes closer to that of supplier H, i.e., $\gamma_1 \le \alpha \le 1$, supplier H needs to engage in an intensive price competition with supplier L in order to win the entire order allocation from the buyer. There is however another option for supplier H if she is content with winning only the partial order. In this case, she could simply offer $p_H^{low} = c_H + \frac{\eta_H}{1-\eta_L}(p_r - c_H)$, receive $\eta_H(\alpha)Q$ from the buyer and share the remaining $(1-\eta_H(\alpha))Q$ with supplier L. The main difference in this case is that the buyer's order is shared among the suppliers when the QS of supplier L is sufficiently lower than that of supplier H because this is the case when supplier L has to lower her price in order to outbid supplier H if she wants to win the total order.

Given the suppliers' best response strategies, there still remains to show that the buyer must have no incentive to misreport the true value of α. In other words, given α, the buyer must prefer or at least be indifferent to offer the guarantees characterized by $\eta_H(\alpha)$, and $\eta_L(\alpha)$ to any other guarantee level $\eta_H(\alpha')$ and $\eta_L(\alpha')$, where $\alpha' \neq \alpha$. The necessary condition for this requirement is expressed in terms of the buyer's total cost function, denoted by κ_B, as follows:

$$\kappa_B(\eta_H(\alpha), \eta_L(\alpha), p_H(\alpha), p_L(\alpha), \alpha) \le \kappa_B(\eta_H(\alpha'), \eta_L(\alpha'), p_H(\alpha'), p_L(\alpha'), \alpha) \quad \forall \alpha, \alpha' : \alpha \neq \alpha', \tag{3}$$

For the regions of α in which the total cost function is smooth (i.e., differentiable in the first-order sense) the above condition can be rewritten *locally* as follows:

$$\frac{\partial \kappa_B(\eta_H(\alpha'), \eta_L(\alpha'), p_H(\alpha'), p_L(\alpha'), \alpha)}{\partial \alpha'} \Big|_{(\alpha'=\alpha)} = 0$$

We can use the above condition to derive non-linear ordinary differential equations (ODE) to characterize incentive-compatible guarantee levels $\eta_i(\alpha)$ for supplier $i \in \{L, H\}$ – refer to the Appendix for the ODEs.

Also, in order for the above equations to possess the feasible solutions, we need to impose appropriate boundary conditions at $\underline{\alpha}$ and $\bar{\alpha}$. Delegating the details of the analysis to the Appendix, in the following proposition, we provide the conditions under which the above ODEs yield equilibrium solutions as well as characterize the equilibrium in the closed-form.

Proposition 5. *1. Existence of Separating Equilibrium: There exists incentive-compatible solutions only when $\frac{c_L}{c_H} \le \bar{\alpha} \le 1$ for all $\alpha \in [\underline{\alpha}, \bar{\alpha}]$.*

2. Characterization of Separating Equilibrium: Among all separating equilibria, the least-costly one to the buyer is characterized as follows:

$$\eta_L(\alpha) = 0 \text{ for all } \alpha \in [\underline{\alpha}, \bar{\alpha}] \text{ and } \eta_H(\alpha) = \begin{cases} f(\tilde{\alpha}) & \underline{\alpha} \le \alpha < \tilde{\alpha} \\ f(\alpha) & \max(\underline{\alpha}, \tilde{\alpha}) \le \alpha \le \bar{\alpha} \end{cases}$$

where $f(\alpha) = \frac{\alpha p_r + p_r - 2\alpha c_H - \sqrt{\alpha^2 p_r^2 + 2\alpha p_r^2 + p_r^2 - 4\alpha c_H p_r - 4\alpha c_H \bar{\alpha}(p_r - c_H)}}{2\alpha(p_r - c_H)}$ *and* $\tilde{\alpha} = \frac{(p_r - c_L)c_L}{c_H \bar{\alpha} p_r - \bar{\alpha} c_H^2 + c_H p_r - p_r c_L}$. *Observing upon* $\eta_H(\alpha)$*, the suppliers update their belief on* α *according to the following function:*

$$\alpha(\eta_H) = \begin{cases} \alpha, & \eta_H \in [\eta_H(\bar{\alpha}), \min(f(\underline{\alpha}), f(\tilde{\alpha}))] \\ \sim \mathit{Uniform}(\underline{\alpha}, \tilde{\alpha}), & \eta_H > \min(f(\underline{\alpha}), f(\tilde{\alpha})) \end{cases}$$

and set their bidding prices as follows:

$$(p_H^*, p_L^*) = \begin{cases} (c_H + \eta_H(p_r - c_H), \alpha(c_H + \eta_H(p_r - c_H))) & \eta_H \in [\eta_H(\bar{\alpha}), \min(f(\underline{\alpha}), f(\tilde{\alpha}))] \\ (c_H + \eta_H(\tilde{\alpha})(p_r - c_H), c_L) & \eta_H > \min(f(\underline{\alpha}), f(\tilde{\alpha})) \end{cases}$$

Note that separating equilibrium is sustainable only when upper bound of true value of α is sufficiently large, i.e., $\frac{c_L}{c_H} \leq \bar{\alpha}$. Depending on whether the lower bound $\underline{\alpha}$ is greater than $\tilde{\alpha}$ or not, the equilibrium is either fully separating or semi-separating. In the first case, the buyer can share the true value of α with the suppliers in credible fashion for all values of $\alpha \in [\underline{\alpha}, \bar{\alpha}]$, whereas in the second case, he signals true value only when α is on the upper region. Both fully and semi-separating equilibria are illustrated in Figure 4.

The above result also implies that the signalling takes place only when the degree of homogeneity between suppliers (in terms of their quality scores) is not too low. The rationale behind this comes from the analysis of signalling cost incurred by the buyer when he shares the true value of α via guarantee levels. In the next section, we will see that the signalling cost is derived by two factors: (i) degree of homogeneity among the suppliers in terms of their quality scores and (ii) the degree of information asymmetry between the buyer and the suppliers.

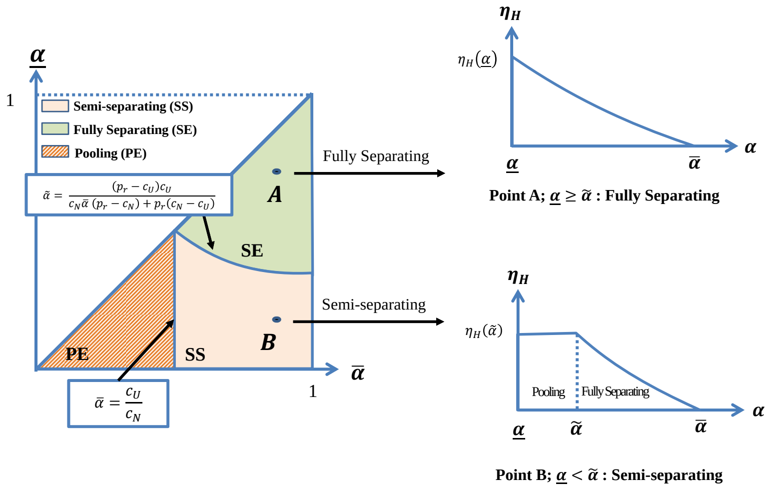
Note that signalling as described in Proposition 5 is possible only if supplier H (high-QS supplier) is less cost-efficient, i.e. $c_H > c_L$ because otherwise, buyer has no incentive to share α as it just provides supplier H with more information to take the most advantage of her cost and QS superiority. Indeed, in that situation lack of QS information makes supplier H to precautiously reduce her price simply to avoid any possibility to lose the competition.

Before we analyze the impact of credible information sharing, we provide the sensitivity of equilibrium contracts and decisions with respect to α:

Corollary 2. *The equilibrium guarantee for supplier H* (η_H^*) *as well as supplier H's price* (p_H^{*SE}) *decrease in* α*, whereas Supplier L's price* (p_L^{*SE}) *increases in* α*.*

The sensitivity of bid prices with respect to α under separating equilibrium follows quite closely to its counterpart under symmetric information. Also, as shown in Figure 4, $\eta_H(\alpha)$ decreases in α. This reinforces our observation that as the suppliers become quite similar to each other in terms of their quality scores, the price competition between them gets more intensified. This reduces the need for (hence cost of) signalling from the perspective of the buyer.

Figure 4 Characterization of separating equilibria.



6. The Impact of Credible Information Sharing

As we raised in the research questions, one of the objectives of this paper is to analyze the impact of sharing QS information with the suppliers on the buyer's cost and suppliers' profits. In order to understand this impact, we first evaluate how it affects the equilibrium decisions of the supply chain parties (i.e., suppliers' prices and buyer's order allocation), and then compare the cost and profits of the buyer and the suppliers, respectively, under pooling or separating equilibria.

6.1 On Equilibrium Decisions: Prices and Quantities

In order to evaluate the impact of sharing QS information on equilibrium decisions, we compare the pooling and separating equilibria characterized in Propositions 2 and 5. From this comparison, we identify two dimensions of quality score information that affect the pooling and separating equilibria: (i) the degree of QS information asymmetry between the buyer and the suppliers (measured by the difference between $\bar{\alpha}$ and $\underline{\alpha}$), and (ii) the degree of homogeneity of the suppliers' QS.

First of all, as shown in Proposition 5, the separating equilibrium is not sustainable when $\bar{\alpha}$ is less than c_L/c_H. Excluding this case (denoted as region C_0 in Figure 5), in what follows, we compare the equilibrium decisions (prices and quantities) between pooling and separating equilibria:

PROPOSITION 6. *Assuming that* $\bar{\alpha} \geq c_L/c_H$*, when the degree of information asymmetry is low, i.e.,* $(\underline{\alpha}, \bar{\alpha}) \in C_1$*:*

- *The expected equilibrium bid prices are lower under pooling equilibrium than under separating equilibrium:* $\bar{p}_L^{*PE} < \bar{p}_L^{*SE}$ *and* $\bar{p}_H^{*PE} < \bar{p}_H^{*SE}$.
- *The expected equilibrium order quantity to supplier H (resp. L) is lower (resp. higher) under pooling equilibrium than under separating equilibrium:* $\bar{q}_L^{*PE} > \bar{q}_L^{*SE}$ *and* $\bar{q}_H^{*PE} < \bar{q}_H^{*SE}$.

The above Proposition implies that when the degree of QS information asymmetry is low, and $\underline{\alpha}$ is bounded below (region C_1), i.e., the QS of supplier L is similar to that of supplier H, the bid prices under separating equilibrium indeed become larger than those under pooling equilibrium. Furthermore, supplier L becomes the sole winner under pooling equilibrium, whereas she has to share the order with supplier H under separating equilibrium.

The rationale behind these results relate to the differences between bidding strategies under pooling and separating equilibria. Namely, under pooling equilibrium, supplier L employs worst-case bidding strategy, i.e., undercuts her opponent assuming that her QS is equal to its lower bound $\underline{\alpha}$. However, when the true value of α is signalled by the buyer (via specific guarantee level), then supplier L does not have to lower her bid price too much. Hence, the buyer is always better off with the pooling equilibrium in region C_1. There is a caveat for supplier L. Due to the presence of guarantee η_H, supplier L has to share the order with supplier H. Therefore, it is not clear whether supplier L is better off with pooling or separating equilibria. In the next subsection, we take into account both equilibrium quantities and prices and evaluate the impact of signalling QS information on supplier L.

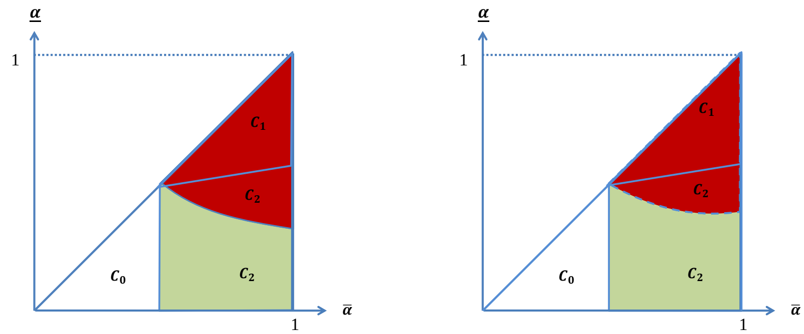
As opposed to region C_1, in region C_2, the equilibrium prices under pooling are not guaranteed to be lower than those under separating equilibrium. Even though we have closed-form expressions for equilibrium prices under both pooling and separating equilibria, it is too complicated to compare these expressions. Through extensive numerical studies, we can derive some general insights. Keeping $\bar{\alpha}$ constant, if we increase the information asymmetry by reducing $\underline{\alpha}$, we observe two things: First, the equilibrium pooling prices become greater than equilibrium separating prices for both suppliers L and H. Secondly, supplier L's expected order allocation under separating equilibrium becomes more than that under pooling equilibrium. The rationale behind these observations again comes from the change in the bidding strategy. Namely, when the information asymmetry is high, both suppliers L and H use a bidding strategy under pooling equilibrium, where each supplier charges a price that maximizes her own expected profit (as opposed to worst-case profit). This makes bid prices under pooling equilibrium higher than those under separating equilibrium.

6.2 On Equilibrium Profits/Costs

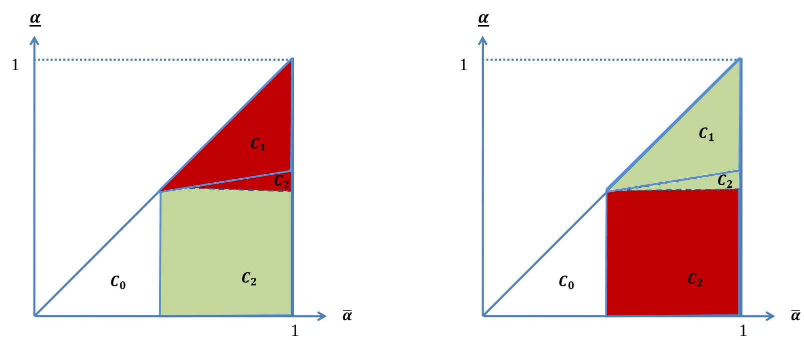
In order to evaluate the full impact of QS information sharing on supply chain parties' payoffs, we need to consider equilibrium prices and quantities together. We establish this by taking into account different regions one at a time. As before, region C_0 is excluded from the analysis because separating equilibrium is not sustainable in this region. Therefore, we first consider region C_1:

Proposition 7. *When the degree of information asymmetry is low, and the degree of homogeneity is high, i.e.,* $(\underline{\alpha}, \bar{\alpha}) \in C_1$*, then:*

Figure 5 Effects of Pooling vs. Separating on price/quantities in asymmetric information setting.



Regions	Supplier H's price	Supplier L's price
$(\underline{\alpha},\bar{\alpha}) \in C_1$	$\bar{p}_H^{PE} < \bar{p}_H^{SE}$	$\bar{p}_L^{PE} < \bar{p}_L^{SE}$
$(\underline{\alpha},\bar{\alpha}) \in C_2$	$\bar{p}_H^{PE} < \bar{p}_H^{SE}$ if $\Delta_{p_H}^{SE1} > 0$; $\bar{p}_H^{PE} \geq \bar{p}_H^{SE}$ o.w.	$\bar{p}_L^{PE} < \bar{p}_L^{SE}$ if $\Delta_{p_L}^{SE1} > 0$; $\bar{p}_L^{PE} \geq \bar{p}_L^{SE}$ o.w.



Regions	Supplier H's quantity	Supplier L's quantity
$(\underline{\alpha},\bar{\alpha}) \in C_1$	$\bar{q}_H^{PE} < \bar{q}_H^{SE}$	$\bar{q}_L^{PE} > \bar{q}_L^{SE}$
$(\underline{\alpha},\bar{\alpha}) \in C_2$	$\bar{q}_H^{PE} < \bar{q}_H^{SE}$ if $\Delta_{q_H}^{SE1} > 0$; $\bar{q}_H^{PE} \geq \bar{q}_H^{SE}$ o.w.	$\bar{q}_L^{PE} > \bar{q}_L^{SE}$ if $\Delta_{q_L}^{SE1} < 0$; $\bar{q}_L^{PE} \leq \bar{q}_L^{SE}$ o.w.

Note. The different colored regions in the above figure denote the following impacts of pooling vs. separating equilibria on decision variables: green (light shaded) regions - decision variable lower under pooling; red (dark shaded) regions - decision variable lower under separating; and, white regions - separating equilibrium not sustainable. $\Delta_{p_H}^{SE1}$, $\Delta_{p_L}^{SE1}$, $\Delta_{q_H}^{SE1}$, and $\Delta_{q_L}^{SE1}$ are characterized in Appendix.

- *The equilibrium profit of supplier H is lower under pooling equilibrium than under separating equilibrium, i.e.,* $\overline{\pi}_H^{*PE} \leq \overline{\pi}_H^{*SE}$.
- *The equilibrium profit of supplier L is lower under pooling equilibrium than under separating equilibrium if and only if* $c_L \geq \bar{c}_L = \frac{(2c_H - p_r)(\sigma_{\alpha,\eta_H} + \mu_\alpha \mu_{\eta_H}) - c_H \frac{\bar{\alpha}-\underline{\alpha}}{2} - (p_r - c_H)E(\eta_H^2 \alpha)}{\mu_{\eta_H}}$.
- *The unit cost of the buyer and the total supply chain' cost are lower under pooling equilibrium than under separating equilibrium, i.e.,* $\overline{\kappa}_B^{*PE} \leq \overline{\kappa}_B^{*SE}$ *and* $\overline{\kappa}_{SC}^{*PE} \leq \overline{\kappa}_{SC}^{*SE}$.

The above results have the following implications for each party:

- First of all, supplier H is always better off with separating equilibrium. This is because irrespective of the true value of α, she always loses out the order allocation against supplier L under pooling equilibrium, whereas under separating equilibrium, there exists at least some cases under which she shares the order allocation with supplier L. Hence, she would always prefer to receive QS information in this case.

- Second, the buyer and total supply chain are always better off with pooling equilibrium. The buyer is better off because of the lower price levels under pooling equilibrium due to a more intensive price competition among the suppliers. Interestingly, no information sharing would also benefit the total supply chain because sharing QS information leads to inefficiency as it shifts some of the order to less efficient supplier (i.e., supplier H).

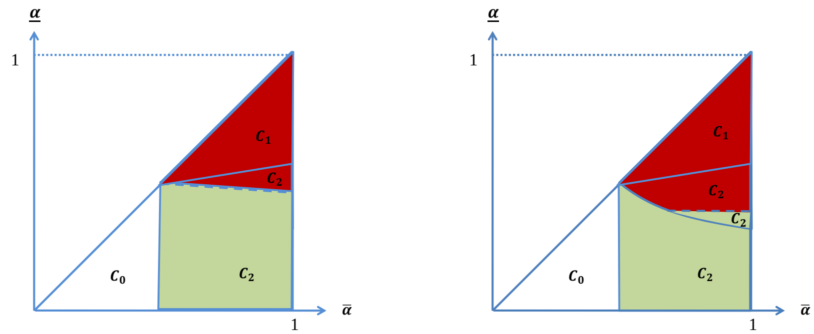
- Finally, supplier L is generally better off with pooling equilibrium (unless her marginal cost is sufficiently high). This is because even though she can increase her bid price under separating equilibrium, she would need to share the buyer's order with supplier H. The decrease in quantity under separating equilibrium leads to a lower total cost for supplier L as well. When she is highly cost efficient this cost saving under separating equilibrium is not very significant and since the reduction in order quantity offsets the increase in the bid prices, she would be eventually worse off with separating equilibrium.

Next, we consider the region C_2 where the degree of information asymmetry is high. Using closed-form characterizations of supply chain parties' payoffs under pooling and separating equilibria, we illustrate in Figure 6 when each stake-holder is better off with separating equilibria, i.e., sharing QS information. In consistent with the previous subsection, the increase in the degree of information asymmetry flips the impact of sharing QS on the payoffs for all the supply chain parties. For example, when $(\underline{\alpha}, \bar{\alpha}) \in C_1$, suppliers are generally better off with separating equilibrium (except for supplier L under certain conditions as illustrated in Proposition 7). However, as $\underline{\alpha}$ decreases (while $\bar{\alpha}$ is kept constant), i.e., as the degree of information asymmetry increases, the suppliers prefer pooling over separating equilibrium, whereas both buyer and total supply chain prefer separating over pooling equilibrium.

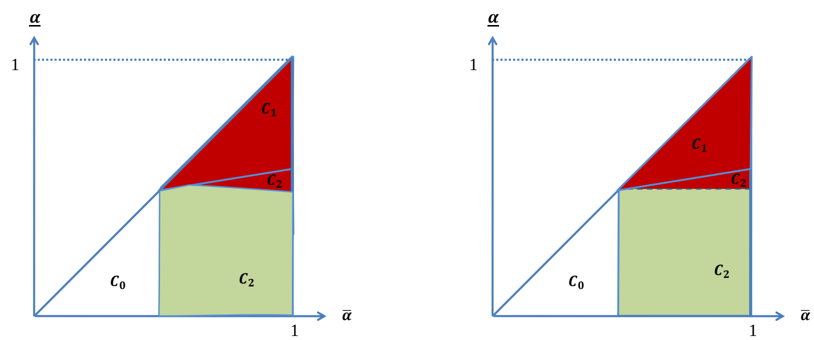
7. Managerial Insights

Our results provide some managerial insights on the use and sharing of quality scores in supply competitions. First, from an information-sharing perspective, if the buyer decides to offer a guarantee, he would conveniently consider the known, incumbent supplier with superior quality scores as providing guarantees to unknown, entrant suppliers would not be effective. Second, the buyer would prefer to share the true value of the relative quality score only when the degree of information asymmetry is sufficiently high. On the other hand, when the suppliers are well informed of

Figure 6 Effects of Pooling vs. Separating on supply chain partners' profit/costs in asymmetric information setting.



Regions	Supplier H's profit	Supplier L's profit
$(\underline{\alpha}, \bar{\alpha}) \in C_1$	$\bar{\pi}_H^{PE} < \bar{\pi}_H^{SE}$	$\bar{\pi}_L^{PE} < \bar{\pi}_L^{SE}$ if $c_L > \bar{c}_L$; $\bar{\pi}_L^{PE} \geq \bar{\pi}_L^{PE}$ o.w.
$(\underline{\alpha}, \bar{\alpha}) \in C_2$	$\bar{\pi}_H^{PE} < \bar{\pi}_H^{SE}$ if $\Delta_{\pi_H}^{SE1} > 0$; $\bar{\pi}_H^{PE} \geq \bar{\pi}_H^{SE}$ o.w.	$\bar{\pi}_L^{PE} < \bar{\pi}_L^{SE}$ if $\Delta_{\pi_L}^{SE1} > 0$; $\bar{\pi}_L^{PE} \geq \bar{\pi}_L^{SE}$ o.w.



Regions	Buyer's cost	Total supply chain cost
$(\underline{\alpha}, \bar{\alpha}) \in C_1$	$\bar{\kappa}_B^{PE} < \bar{\kappa}_B^{SE}$	$\bar{\kappa}_{SC}^{PE} < \bar{\kappa}_{SC}^{SE}$
$(\underline{\alpha}, \bar{\alpha}) \in C_2$	$\bar{\kappa}_B^{PE} < \bar{\kappa}_B^{SE}$ if $\Delta_{\kappa_B}^{SE1} > 0$; $\bar{\kappa}_B^{PE} \geq \bar{\kappa}_B^{SE}$ o.w.	$\bar{\kappa}_{SC}^{PE} < \bar{\kappa}_{SC}^{SE}$ if $\Delta_{\kappa_{SC}}^{SE1} > 0$; $\bar{\kappa}_{SC}^{PE} \geq \bar{\kappa}_{SC}^{SE}$ o.w.

Note. The different colored regions in the above figure denote the following impacts of pooling vs. separating equilibria on decision variables: green (light shaded) regions - costs/profits lower under pooling; red (dark shaded) regions - costs/profits lower under separating; and, white regions - separating equilibria not sustainable. $\Delta_{\pi_H}^{SE1}$, $\Delta_{\pi_L}^{SE1}$, $\Delta_{\kappa_B}^{SE1}$, $\Delta_{\kappa_{SC}}^{SE1}$, and $\bar{c}_L$ are characterized in Appendix.

each other's quality scores and the uncertainty is low, the buyer would be better off to keep the details of the scoring formula private.

Buyers may influence suppliers' beliefs about their relative quality scores before holding the competition in different ways. For example, some procurement competitions start with the buyer's issuing to the set of potential suppliers a formal request for proposal (RFP), in which he may provide some detailed information about the project and scoring criteria. If the buyer wants to make the entire process more ambiguous, he can skip the RFP stage and directly request prices from the suppliers. RFP stage can be also customized specifically to adjust the amount of information-sharing regarding the supplier selection process. For example, in certain RFPs, the buyer provides not only how the scoring is done under each category but also what weights are assigned to each category and how they are combined (e.g., see BC-Procurement 2010). Yet, in other RFPs, the buyer provides only limited information regarding either scoring or weighting and leaves the other one undetermined (e.g., see Trent 2010). The latter makes the ultimate assessment formula more uncertain from the suppliers' perspective. As suggested by our results, this would prevent the suppliers from adjusting strategically their bid prices at the expense of the buyer.

Along these lines, many B2B e-commerce platforms such as AliSourcePro, AribaWeb, etc. streamline the procurement process for the supply chain companies by enabling them to create a simple buying request without going through the hurdles of RFP processes. These are particularly effective in lowering the procurement cost of commodity-type products for small and medium-sized companies. From the lenses of our results, this streamlining has also an increasing effect on the degree of uncertainty regarding the procurer's deliberation process of the winner among the bidders.

8. Conclusion

In this paper, we analyze (i) how a buyer can credibly share the private QS information with the upstream suppliers, (ii) how it impacts the equilibrium decisions and the profits/cost of channel parities, and (iii) what factors induces the buyer to share (and not to share). To address these questions, we develop a decentralized supply chain model with a buyer and two heterogeneous suppliers that are competing for the buyer's order quantity. Buyer decides on the order allocation based on not only the bid prices offered competitively by the suppliers but also their quality scores, which are private information for the buyer.

We first characterize the equilibrium under symmetric information (i.e., when the true value of the relative quality score is known to the suppliers). In this case, suppliers L and H strategically adjust their bid prices in upward and downward directions, respectively, as the true score of supplier L gets closer to that of supplier H. We then characterize the equilibrium under asymmetric information. The comparative analyses of the equilibrium bid prices under pooling and separating equilibria show that the bidding strategy is affected by whether or not the true value of quality score is shared with the suppliers. We identify two cases. First, when the range of true value of quality score α is sufficiently small, both suppliers would aggressively undercut each other's offer irrespective of α. This increases the intensity of price competition among the suppliers, which lowers the equilibrium pooling prices. Second, when the degree of information asymmetry is high, i.e. the range of uncertainty on α is high, this bidding strategy becomes very costly for the suppliers. In this case, rather than attempting to win the order for all values of quality score, each supplier charges a price that would maximize her expected profit based on a-priori beliefs. This however reduces the degree of competition among the suppliers, which in turn increases the equilibrium prices. In the second case, the buyer can signal the true value of relative quality score at a (signalling) cost. That is, the buyer has to offer price and quantity guarantee contract to the incumbent supplier, which indirectly sets a lower bound on the equilibrium prices.

The model presented in this paper can be extended in different directions. First possible extension is to add supply- and demand-side risks to the model. For example, in a situation where the suppliers face uncertain capacities, the buyer may want to diversify his supply base. This leads to multi-unit procurement competition models, where the buyer procures from multiple suppliers all at once. Also, the demand risks may change the buyer's incentive for sharing quality score information with the suppliers. Another important aspect is that both buyers and suppliers may have budget limitations, which affects the equilibrium ordering and pricing decisions. Lastly, we believe that the analysis of the quality scores presents fruitful research opportunities and hope that this model will fuel potential research in the future.

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