Accepted in *Production and Operations Management*

With or Without Forecast Sharing: Competition and Credibility under Information Asymmetry

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Forecast sharing among trading partners lies at the heart of many collaborative and contractual SCM efforts. Even though it has been praised in both academic and practitioner circles for its critical role in increasing demand visibility, some concerns remain: The first one is related to the credibility of forecast sharing, and the second is the fear that it may turn into a competitive disadvantage and induce suppliers to increase their price offerings. In this paper, we explore the validity of these concerns under a supply chain with a competitive upstream structure, focusing specifically on (i) when and how a credible forecast sharing can be sustainable, and (ii) how it impacts on the intensity of price competition. To address these issues, we develop a supply chain model with a buyer facing a demand risk and two heterogeneous suppliers *competing* for order allocation from the buyer. The extent of demand is known only to the buyer. The buyer submits a buying request to the suppliers via a commonly used procurement mechanism called request for quotation (RFQ). We consider two variants of RFQ. In the first type, the buyer simply shares the estimated order quantity with no further specifications. In the second one, in addition to this, the buyer also specifies minimum and/or maximum order quantities. We fully characterize equilibrium decisions and profits associated with them under symmetric and asymmetric information scenarios. Our main findings are that the buyer can use a RFQ with quantity restrictions as a credible signal for forecast sharing as long as the degree of demand information asymmetry is not too high, and that, *contrary* to above concerns, the equilibrium prices that emerge between competing suppliers under asymmetric information may indeed *increase* if the buyer can*not* share forecast information credibly with its upstream partners.

Key words: Forecast Sharing; Competition; Credibility; Asymmetric Information; Signalling.
History: Received: April 2012; Accepted: September 2013 by Anil Arya after three revisions.

1. Introduction

Suppliers and buyers often have to make pricing and sourcing decisions, respectively, without knowing how much supply and demand will actually materialize. This inevitably leads to an excess in supply or demand. In its quest to reduce the detrimental effects of supply-demand mismatches on overall chain performance, supply chain management (SCM) is continually pushing boundaries by considering numerous procurement mechanisms with varying degrees of integration and sophistication. Among the collaborative tools considered are Electronic Data Interchange, Efficient Consumer Response, and Quick Response, all of which serve a common objective: to enhance *demand visibility* across the chain. In most B2B transactions, the buyer initiates the procurement process by issuing a buying request to a set of pre-screened suppliers. We observe various forms of such requests used in practice such as request for proposal, request for bid and request for quotation. In this paper, we focus on the latter and shortly refer to it as "RFQ".

A standard RFQ typically specifies the information about the items/services to be procured, estimated order quantity, and expiration time[1]. In addition to this, the buyers may include additional specifications such as minimum and maximum order quantities to provide more information to the suppliers about his demand. For example, a sample RFQ generated based on UN/EDIFACT standards[2] may stipulate lower and upper bound constraints on the amount of products to be procured from the supplier who wins the bid. Upon receiving the RFQ from the buyer, the suppliers have to respond before the expiration date by submitting their quotations which typically include the price per item/service. After assessing the suppliers' quotations based on their costs and risks, the buyer selects the winner(s), with whom he engages in a procurement contract. At this stage, there are various forms of contractual mechanisms that the buyer can use to implement minimum and/or maximum order specifications such as quantity flexibility and take-or-pay. Agreed between buyers and suppliers, these contracts help the buyer to specify the minimum ("take") and maximum ("pay") quantities that a buyer can order from the supplier (see Farlow et al. 1996b, Bassok et al. 1997 and Masten and Crocker 1985 for the practical uses of these contracts in industries such as the automobile industry, semiconductors, electronic equipments, energy and natural resources).

[1] In practice, the basic logic of a standard RFQ process has been implemented in various ways such as posting a "buying request" in online B2B market places, e.g., Alibaba.com (for sample buying requests, see AliSourcePro 2013), or initiating a "reverse auction" by using one of the sourcing softwares and services, e.g., Ariba, Iasta, etc (Williams 2010). We also refer the readers to Johnson and Whang (2002) for an extensive review of e-procurement in supply chain management.

[2] The specific standard developed for RFQs by the United Nations is called REQOTE (see REQOTE (2002) for the detailed definition of minimum and maximum order quantities). This standard has been implemented by many enterprise resource planning softwares including SAP and Oracle. Particularly, Enterprise Applications Suite developed by Oracle enables the users to specify both *minimum* and *maximum* order quantities in RFQs – see User's Guide for Oracle® Purchasing Release 12 (Oracle 2006).

In SCM, the potential benefits of sharing forecast information to the chain are rarely questioned. Those benefits are mainly attributable to by-products of increased demand visibility (Seifert 2003, Helms et al. 2000). Among the most frequently cited benefits are a reduction in inventory-related costs, an increased response time and improved service levels (Schachtman 2000, Småros 2007). While the benefits of forecast sharing are impressive, its actual implementation offers challenges that hinder its adoption (Barratt 2004). In a recent survey of 120 companies, conducted by Fraser (2003), 42% of all respondents listed a lack of trust in sharing sensitive demand information as one of the top three challenges they faced with this matter[3]. Concerns about the lack of trust can arise for many reasons, including, high demand uncertainty, risk due to potential loss from trusting (Özer et al. 2011), a potential loss of control or security breaches (Fliedner 2003). In this paper, we will focus on two reasons.

The first reason we will study is the credibility of forecast sharing in a competitive supply chain environment. As demonstrated in various studies, a forecast information asymmetry among supply chain parties naturally creates an incentive for information distortion in order to influence the decision of uninformed parties. This in turn raises question marks in the uninformed parties' minds regarding the credibility of the forecast information provided to them. Indeed, prior to adopting specific mechanisms that involve further restrictions on the order quantities, Sun MicroSystems was simply sharing its estimated demand information with its suppliers with no commitment on either party. This in turn made a "dissatisfaction with Sun's component forecasts" the number one issue in the voice-of-the-supplier feedback collected from the suppliers (Farlow et al. 1996a). Planning decisions made with a distorted picture of the actual demand information may create significant inefficiencies at every point along the supply chain, which can potentially hurt the end consumers, causing poorer customer service and higher unit costs (Lee et al. 1997).

Our second concern is just the opposite of the above one. Indeed, it is the fear that *truthful* forecast sharing may adversely affect the degree of competition in a supply chain at the expense of the party who shares the forecasts with the supply chain partners. Stein (1998) describes this fear as follows:

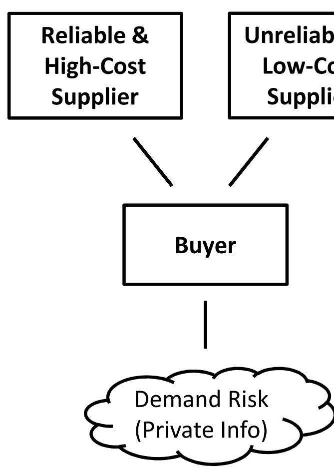
> Few organizations are accustomed to trusting their business partners, and they have a real and justified fear that information-sharing can turn into a competitive disadvantage. "If one of your customers knows you're behind on your production schedule, they may turn around and try to negotiate a more favourable price," says Harry Tse, an analyst with the Yankee Group Inc.

[3] The other top two reasons for not sharing forecast information cited by respondents were internal process change (60% of respondents) and cost of implementation (50% of respondents).

These concerns are also echoed by Verity (1996) and Fliedner (2003). They note that *by coordinating forecasts, two or more suppliers can influence the supply and drive up its price.* Fliedner (2003) adds that such an event is more likely to happen when the item being purchased is custom-made or of a proprietary nature,making it less readily available.

Even though forecast sharing has been extensively explored in the literature, to the best of our knowledge, the credibility of forecast sharing and its impact on the degree of upstream competition have not received due attention for competitive supply chains. Along these lines, the objectives of this paper are threefold: (i) to explore *when* and *how* forecast information can be credibly shared across a supply chain with a *competitive upstream* structure; (ii) to identify how this impacts the degree of upstream competition; and finally (iii) to evaluate the impact of forecast sharing on the decisions/profits/costs of channel partners.

Figure 1 Supply chain model considered in the paper



In order to address these issues, we develop a *bi-level* supply chain model that captures the salient features of industries that would potentially benefit from forecast sharing (i.e., high supply and demand mismatch risk, and asymmetric demand information). See Figure 1 for the high-level representation of the supply chain model considered in this paper. At the upstream level, there are *two competing* heterogeneous sellers (hereinafter referred to as "supplier U" and "supplier R") with different costs and risk structures. At the downstream level, there is one buyer that faces a risky demand, the extent of which is known only to the buyer himself[4]. First, the buyer issues a buying request in the form of a RFQ. We analyze two variants: non-restrictive and restrictive, that will be referred to as RFQ^n and RFQ^r, respectively. In the former, the buyer only specifies

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

the estimated demand information, whereas in the latter, in addition to the estimated demand information, the buyer also specifies a lower and/or upper bound constraint on the amount of products to be ordered. In response to the RFQ, the suppliers compete on prices, and submit their quotations (i.e., "bids"). After assessing the suppliers' bids, the buyer makes his final order allocation decision. Finally, in the last stage, the supply and demand uncertainties are realized and the buyer clears the realized supply-demand mismatch, if needed.

We characterize equilibrium RFQ terms under each RFQ type as well as prices associated with them under both the symmetric and asymmetric information scenarios. Then, the comparative analysis of RFQ^n and RFQ^r under symmetric and asymmetric information settings allows us to evaluate when and how the forecast information can be credibly shared between channel partners and how it affects the degree of upstream competition and the profits and costs.

First of all, the suppliers' incomplete information about the demand leads to an uncertainty on their side regarding what price to charge, which, in turn, generates an incentive for the buyer to distort his forecast information, and invalidates the credibility of the estimated demand information in RFQ^n. We show that this distortion can be fixed via an RFQ^r as long as the degree of information asymmetry is not too high. Secondly, in the symmetric information setting, when one of the suppliers undercuts her opponent's price, she does so by taking into account the true demand scenario of the buyer. However, in the presence of incomplete demand information, the suppliers cannot credibly infer the true demand scenario, which enforces them to decide on their prices solely based on their a priori beliefs. In this case, each supplier makes two choices: (i) whether to undercut her opponent for all possible demand scenarios (*mass-market strategy*) or for a particular one (*niche-market strategy*), and (ii) whether to compete for the same demand scenario(s) (*head-to-head price competition*) or split the demand scenarios between themselves. Depending on the choices made by each supplier, the strength of price competition (resp. equilibrium price) decreases (resp. increases) from one extreme to another as the suppliers move from mass- to niche-market, and from head-to-head price competition for the same market to splitting the market among themselves. Our results show that RFQ^n pushes the degree of price competition to the extremes at either end, whereas RFQ^r keeps it in the middle. This result contradicts the concerns echoed by supply chain practitioners regarding the potential role of forecast sharing in driving prices up. In other words, credible forecast sharing can indeed help the buyer to pull the strings of suppliers and align them to compete for the same forecast, which results in lower prices. Finally, a comparison of costs and profit under both types of RFQs enables us to evaluate when a restrictive RFQ type is a better option [and when it is not] for each supply chain partner.

The paper is organized as follows: in the next section, we review the relevant literature. In §3, we develop the model framework. In §4 and §5, we analyze the symmetric and asymmetric information scenarios. In §6, we compare the impact of each RFQ type on the equilibrium decisions, profits, and cost of channel partners. §7 concludes.

2. Relevant Literature

There are two streams of research in the OM literature that consider the impact of sharing forecast information on supply chains.

Papers in the first stream assume that supply chain partners make their decisions in a cooperative manner (i.e., that they all minimize the same system-wide costs), but that they differ in terms of the amount of demand information that they have before they make operational decisions. In general, asymmetric demand information between supply chain partners leads to a variance increase in the demand in the upstream direction, a phenomenon known as the *bull-whip effect* (Lee et al. 1997). Several models have been developed to quantify the magnitude of the bull-whip effect under various demand models: Integrated Moving Average (IMA) demand model in Graves (1999), Auto-Regressive (AR) demand model in Lee et al. (2000), and Auto-Regressive Moving Average (ARMA) in Gaur et al. (2005). Chen et al. (2000) explore the relation between two commonly used forecasting techniques (moving average and exponential smoothing) and the bull-whip effect. Gavirneni et al. (1999) consider a capacitated supply chain setting and explore the impact of sharing forecast information on inventory policies. Another reason for the bull-whip effect is the lack of coordination between supply chain firms regarding forecast generation. Aviv (2001) considers a supply chain where local and collaborative forecasting techniques are used to decide inventory orders, then compares these types of techniques in a setting with stationary and auto-correlated demand distributions.

The second stream of research explores the value of forecast sharing in decentralized supply chains. We refer the readers to Chen (2003) for a comprehensive review of the impact of information-sharing on decentralized supply chains. Among the papers in this stream, Cachon and Lariviere (2001) are the first to analyze the buyer's incentives to share demand forecast information and the role of compliance regimes in a dyadic supply chain setting. Li (2002) and Zhang (2002) consider a supply chain structure that consists of one manufacturer selling to two retailers. They analyze the impact of forecast sharing on the retail (downstream) competition, which contrasts with our paper. Li and Zhang (2008) extend this to a supply chain setting where a single manufacturer sells to multiple retailers. Ha and Tong (2008) and Ha et al. (2011) consider a similar setting with two competing supply chains, each of which has one retailer and one manufacturer. In all these papers (with the exceptions of Cachon and Lariviere (2001), Özer and Wei (2006), and Oh and Özer (2013)), it is assumed that if the parties decide to share their private forecast information, they do so *truthfully*. Credibility, however, can be a legitimate concern if the parties have an incentive to distort their information. Cachon and Lariviere (2001) and Özer and Wei (2006) are the first to analyze the credibility of the forecast sharing in a dyadic supply chain setting with one manufacturer selling to one retailer. Using one manufacturer-one supplier setting, Oh and Özer (2013) analyze the role of time in forecast information sharing in a dynamic setting where firms' forecast information and hence, the asymmetry among such information evolves overtime. In addition to the analytical models, there are also two other growing streams in operations management that are related our work: (i) empirical analysis of forecast sharing in supply chains (e.g., Terwiesch et al. 2005, and Bray and Mendelson 2012) and (ii) behavioural research related to the role of trust in forecast sharing (e.g., Özer et al. 2011, and Ebrahim-Khanjari et al. 2012). However, these streams differ from our paper in terms of both methodology and setting.

Our paper is also related to another stream of literature, which evaluates the impact of supply contracts with minimum and/or maximum order specifications on operational issues, such as information sharing (Lee et al. 1997, Cachon and Lariviere 2001, Özer and Wei 2006), variance of order-up-to-levels (Bassok and Anupindi 1997), exchange risk (Scheller-Wolf and Tayur 1997), coordination of supply chains (Tsay 1999), and inventory characteristics and fill rate (Bassok and Anupindi 2008). There is an abundant literature in terms of models that consider variants of contracts with constraints on the order quantity such as rolling horizon flexibility (RHZ) contracts (Bassok and Anupindi 2008), contracts that impose constraints on the total order quantity for single and multiple products (Bassok and Anupindi 1997, Anupindi and Bassok 1998, Chen and Krass 2001, and Özer and Wei 2006), and take-or-pay agreements commonly used in the natural gas industry (Masten and Crocker 1985). The common feature among all these contracts is that the buyer guarantees ahead of time that his total order quantity will satisfy certain pre-determined thresholds. We refer the readers to Anupindi and Bassok (1999) and Tsay et al. (1999) for a review of supply contracts with quantity commitments.

The main objective of this paper is to analyze both the credibility of forecast information in a competitive supply chain setting and the impact of forecast-sharing on the degree of upstream competition. These features distinguish our model from the ones above. To address these issues, we explicitly consider a decentralized supply chain setting where (i) the buyer sources from two competing suppliers, (ii) the buyer faces private demand uncertainty, and (iii) the credibility of the demand information shared by the buyer is not assumed exogenously. This contrasts with the above papers, which consider a supply chain configuration where each buyer is served only by one supplier, and therefore analyze the credibility and/or the impact of forecast sharing on either downstream or vertical (i.e., supplier-buyer) competition.

Finally, we use a mixed modelling approach in order to model the impact of credible information sharing on the strength of upstream competition. Namely, we use a signalling-game framework to model the RFQ-stage game between the buyer and the two suppliers, and a common agency framework to model the pricing-stage game between two suppliers (competing principals) and the buyer (common agent) (see Riley (2001) and Martimort (2006) for extensive literature review on signalling games, and common agency problems, respectively). This distinguishes our modelling framework from the informed principal literature (e.g., Maskin and Tirole 1990, Tan 1996, Severinov 2008, and Mylovanov and Tröger 2012) in three ways. First, in the models analyzed in this literature ("informed principal models with private values"), the informed party would never be hurt by its private information, whereas in our framework, as typical in a standard signalling game à la Spence (1973), it is not the case. In other words, the informed party (i.e., the buyer in our framework) needs to undertake costly signalling action in order to credibly convey his private information to the uninformed parties (i.e., the suppliers). Second, the revelation principle (Myerson 1979) can be employed to simplify the characterization of the optimal complete contract in informed principal models. However, it has long been known to be extremely challenging to characterize similar complete contracts for signalling games[5]. Finally, while the multiplicity of equilibria can generally be avoided in the informed principal literature, it is well known that both signalling and common agency games suffer from multiple equilibria due to the extra degrees of freedom caused by unrestricted off-equilibrium beliefs. For this reason, the main theme of these literatures has been on the equilibrium selection (refinement) problem (please refer to Fudenberg and Tirole 1991 and Martimort 2006).

3. Model Framework

In order to model the impact of credible forecast sharing on the degree of upstream competition, we consider a *bi-level decentralized* supply chain model with *asymmetric forecast information*. The supply chain consists of two competing suppliers at the upstream level and a buyer at the downstream level. The buyer is exposed to demand uncertainty, whose distribution is known only

[5] A notable exception is Maskin and Tirole (1992), where the authors characterize the set of equilibria by using a strategy space that consists of all contracts. However, they consider a restrictive case in which there is only one agent.

to him. On the other hand, the suppliers have prior beliefs on the true demand distribution. For the sake of analytical tractability, we assume that the demand distribution can be of two types; either high ($\phi = h$), or low ($\phi = l$). Let r^ϕ be the suppliers' prior beliefs for a ϕ-type demand distribution, where r^h and r^l are common knowledge and sum up to 1, i.e., $r^h + r^l = 1$. Let a ϕ-type buyer denote the buyer whose demand uncertainty is of type ϕ and ϵ^ϕ represent the demand uncertainty he faces. In order to develop analytical managerial insights, we assume that the ϕ-type buyer's demand uncertainty (shortly, the ϕ-type demand) has a two-point distribution, where low and high demand states are represented by 0 and Q, respectively[6]. Therefore, the demand uncertainty faced by ϕ-type buyer, i.e., ϵ^ϕ, can be expressed as follows:

$$\epsilon^\phi = \begin{cases} 0 & \text{with prob. } 1 - \beta^\phi \\ Q & \text{with prob. } \beta^\phi. \end{cases} \tag{1}$$

where $\beta^\phi \in [0,1]$, $\phi \in \{l, h\}$, is the likelihood of the high demand state for ϕ-type demand. In order to make sure that an h-type demand is *larger* than an l-type demand in the sense of first-order stochastic dominance[7], we also assume that $\beta^l \leq \beta^h$.

Suppliers at the upstream layer engage in price competition and seek an order allocation from the buyer. However, they differ in terms of their exposure to yield risk and their cost structure[8]. The *unreliable* supplier (hereafter referred to as "U") has access to a production technology with random yield at a lower marginal cost of c_U per unit. So, if the buyer orders q_U units from supplier U, she delivers only $\tilde{q}_U$ units to the buyer, where, similar to the demand uncertainty, we assume "all-or-nothing"-type distribution for $\tilde{q}_U$, i.e.,

$$\tilde{q}_U = \begin{cases} 0 & \text{with prob. } 1 - \alpha \\ q_U & \text{with prob. } \alpha \end{cases} \tag{2}$$

where α denotes the expected yield for supplier U. In contrast, the *reliable* supplier (hereinafter referred to as "R") has access to a fully reliable production technology (i.e., $\tilde{q}_R = q_R$ with prob. 1) albeit at a higher marginal cost of c_R per unit, where $c_U \leq c_R$. That is, if the buyer orders q_R units from supplier R, she incurs $c_R q_R$ in total and delivers all the units to the buyer. Once demand and yield uncertainties are realized, the buyer pays to the suppliers only for the units delivered, (in total, $p_R q_R$ and $p_U \tilde{q}_U$ for suppliers R and U, respectively), and clears the mismatch between

[6] "Two-point" (all-or-nothing) distributions are commonly used in asymmetric information literature for analytical tractability. Refer to Yang et al. (2009) and references therein for examples.

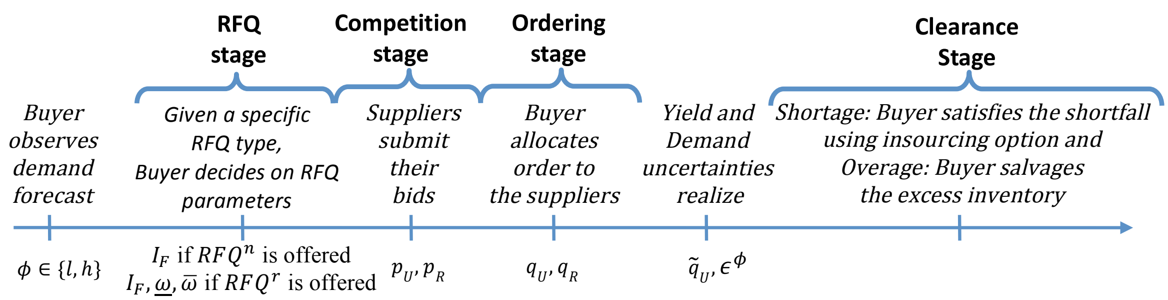
[7] The first-order stochastic dominance implies that h-type is more likely to have a high demand state than l-type. For the rigorous definition and treatment of stochastic orders, see Shaked and Shanthikumar (1994).

[8] We have performed additional analyses on similar models where the uncertainty is defined on the suppliers' capacities (as opposed to their yields) and shown that our results are not qualitatively affected by this modeling extension.

realized demand and supply as follows. If the realized demand exceeds the total number of units delivered by the two suppliers, i.e., $\epsilon^\phi \geq \tilde{q}_U + q_R$, the buyer satisfies the shortfall from an insourcing option at a marginal cost c_I. The insourcing option[9] is assumed to have a zero lead time, be fully reliable, and be more costly than both suppliers. On the other hand, if the total realized supply exceeds total demand, the buyer salvages excess inventory $(\tilde{q}_U + q_R - \epsilon^\phi)^+$ at c_S per unit, where we assume $c_S \leq c_U$ to eliminate trivial cases. To simplify the analysis and presentation of our results, throughout this paper, we further normalize marginal insourcing cost c_I to 1, marginal salvage value c_S to 0, and assume that $0 \leq c_U \leq c_R \leq \beta^\phi$ for both $\phi \in \{l, h\}$[10].

Based on the above framework, we then consider two RFQ types that differ only in terms of whether or not the buyer imposes lower and/or upper bound constraints on his initial estimated order quantity. Under each RFQ type, the three entities introduced above (i.e., the buyer, and two suppliers) interact with each other in the following *four stages*. The timing of decisions and events is illustrated in Figure 2.

Figure 2 **Timeline of Decisions and Events.**



- The buyer observes his true demand type ϕ, where $\phi \in \{l, h\}$.
- *RFQ stage:* Depending on the type of RFQ, the buyer decides on the RFQ parameters. That is, if he offers an RFQ^n, he decides on I_F, whereas if he offers an RFQ^r, then he decides on $(I_F, \underline{\omega}, \bar{\omega})$, where I_F represents initial forecast and $\bar{\omega}$ and $\underline{\omega}$ correspond to, respectively, the upper and lower bounds on the total order quantity in terms of I_F.

[9] Technically speaking, the insourcing option is equivalent to a lost sales demand model, where the buyer collects revenue p from each unit sold, and unmet demand is assumed to be lost. We can transform the insourcing option to a lost sales demand model by letting the buyer's marginal revenue be equal to the marginal insourcing cost, i.e., $p = c_I$.

[10] Essentially, the last assumption implies that the buyer never finds it optimal to set $q_U + q_R = 0$ in the equilibrium. For details, please refer to the Appendix. We would like to note that this assumption can be relaxed without affecting the qualitative nature of our results. The extended analysis is available from the authors upon request.

- *Competition stage:* In response to the buyer's RFQ parameters, suppliers U and R update their prior beliefs and *simultaneously* submit their unit prices (i.e., "bids"), p_U and p_R, respectively.
- *Ordering Stage:* Based on the unit prices from the suppliers, the buyer then decides on his final order allocation decision. If an RFQ^r is offered, then the buyer's total order quantity should be between $I_F(1-\underline{\omega})$ and $I_F(1+\bar{\omega})$, i.e., $I_F(1-\underline{\omega}) \leq q_U + q_R \leq I_F(1+\bar{\omega})$.
- Demand and yield uncertainties are realized, suppliers R and U deliver q_R and $\tilde{q}_U$ and receive in total $p_R q_R$ and $p_U \tilde{q}_U$ from the buyer, respectively.
- *Clearance Stage:* If the total amount delivered by the suppliers turns out to be less than the realized demand, i.e., $q_R + \tilde{q}_U \leq \epsilon^\phi$, then the buyer satisfies the shortfall, $[\epsilon^\phi - (q_R + \tilde{q}_U)]^+$, from the insourcing option.

Before analyzing the game, we summarize the list of notations used for the problem parameters and decision variables in Table 1.

Table 1 Notation used for model parameters and decision variables.

Model parameters	
$\phi \in \{l, h\}$	Type of true demand distribution
r^ϕ; $\hat{r}^\phi$	Suppliers' prior and updated (posterior) beliefs about true demand type.
ϵ^ϕ; β^ϕ	Random variable denoting ϕ-type demand; the likelihood of high-demand state for ϕ-type demand
$\tilde{q}_U$	Random variable denoting supplier U's output
α; $\bar{\alpha}$	Probability of no-disruption and disruption for supplier U, respectively, i.e., $\bar{\alpha} = 1 - \alpha$
c_U; c_R	Marginal costs of suppliers U and R, respectively
Profit and cost functions	
π_U; π_R	Expected profits for suppliers U and R, respectively.
TC_B^ϕ	Expected cost for the buyer facing ϕ-type demand
Decision variables	
I_F^ϕ	RFQ^n parameter offered by ϕ-type buyer
I_F^ϕ; $\underline{\omega}^\phi$; $\bar{\omega}^\phi$	RFQ^r parameters offered by ϕ-type buyer.
p_U; p_R	Unit prices ("bids") quoted by suppliers U and R, respectively.
q_U^ϕ; q_R^ϕ	ϕ-type buyer's order allocations for suppliers U and R, respectively.

Note: Throughout the paper, equilibrium profits/cost and decision variables are annotated with asterisks ("*").

4. Equilibrium Analysis under a Symmetric Information Scenario

To establish a benchmark, in this section, we restrict our attention to the case where the true demand type is known by all the parties in the supply chain. This assumption transforms the problem to a symmetric information *Stackelberg* game between two competing suppliers at the upstream level and the buyer at the downstream level. Note that since the true demand type is common knowledge, there is no need on the side of suppliers to update their beliefs about whether $\phi = l$ or $\phi = h$. For this information scenario, we first characterize the equilibria under RFQ^n and RFQ^r and analyze the equilibrium decisions and profits/costs of supply chain firms.

4.1 The Equilibrium Characterization

Recall that there are three decision stages in the game, namely RFQ, pricing and ordering stages. Since the last two stages are common to both types of RFQs, we can combine the analyses of the pricing and ordering stages and characterize the Stackelberg equilibria using backward induction, starting from the buyer's optimal (cost-minimizing) order allocation stage. Let $TC_B^{\phi}(p_U, p_R)$ be the expected minimum total cost function for a ϕ-type buyer given that suppliers U and R offer p_U and p_R, respectively. Then, this cost function can be defined as follows:

$$TC_B^{\phi}(p_U,p_R) = \min_{q_U \geq 0, q_R \geq 0} \beta^{\phi} \cdot (Q - q_U - q_R)^+ + (\alpha p_U + (1-\alpha)\beta^{\phi}) \cdot q_U + p_R \cdot q_R \tag{3}$$

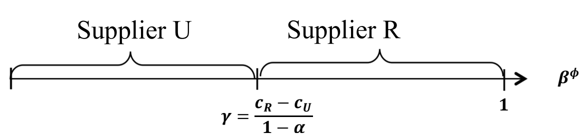
$$\text{s. t.}$$

$$0 \leq q_U + q_R \leq Q, \qquad \text{if } RFQ^n \text{ is offered;}$$

$$I_F(1-\underline{\omega}) \leq q_U + q_R \leq I_F(1+\bar{\omega}), \qquad \text{if } RFQ^r \text{ is offered;}$$

where the first term in the objective function represents the buyer's expected cost of using his insourcing option, and the second and third terms represent the buyer's expected cost of buying from suppliers U and R, respectively (refer to Appendix for the derivation of these expressions). Note that since the buyer's order allocation is a linear problem, depending on the coefficients of q_U and q_R, one of the constraints will always be binding at the optimal solution. Once the optimal order allocation decision is characterized, we substitute it into the suppliers profit functions and then solve the simultaneous price game between suppliers U and R. Note that the price competition between supplier U and R always results in one of the suppliers charging her marginal cost (c_R for supplier R and $\frac{c_U}{\alpha}$ for supplier U) and the other supplier charging a price such that the expected cost for the buyer in buying from her is infinitesimally less than his expected cost of buying from her opponent. We delegate the detailed analysis to the Appendix and provide the overall equilibrium characterization in Proposition 1:

Figure 3 Equilibrium order allocation under symmetric information setting



PROPOSITION 1. *Let $\gamma = \frac{c_R - c_U}{1-\alpha}$. Then, under symmetric information equilibrium, the buyer orders from supplier U if $\beta^{\phi} \leq \gamma$, otherwise, he orders from supplier R. The complete characterization of equilibrium decisions, profits and costs for the supply chain parties under symmetric information is provided in Table 2 for both RFQ^n and RFQ^r.*

Table 2 **Equilibrium characterization under symmetric information setting.**

		Low Demand	High Demand
		$\beta^{\phi} \leq \gamma$	$\beta^{\phi} > \gamma$
RFQs	RFQ^n	any $I_F \in [0, Q]$	any $I_F \in [0, Q]$
	RFQ^r	$I_F(1-\underline{\omega}) = 0,\ I_F(1+\bar{\omega}) = Q$	$I_F(1-\underline{\omega}) = 0,\ I_F(1+\bar{\omega}) = Q$
Prices	$p_R^{\phi*}$, $p_U^{\phi*}$	$c_R,\ \left[\frac{c_U}{\alpha} + \frac{(1-\alpha)(\gamma-\beta^{\phi})}{\alpha}\right]^{(-)}$	$\left[c_R + (1-\alpha)(\beta^{\phi}-\gamma)\right]^{(-)},\ \frac{c_U}{\alpha}$
Order Allocation	$q_R^{\phi*}$, $q_U^{\phi*}$	$0, Q$	$Q, 0$
Suppliers' Profits	$\pi_R^{\phi*}$, $\pi_U^{\phi*}$	$0,\ (c_R - (1-\alpha)\beta^{\phi} - c_U)Q$	$(c_U + (1-\alpha)\beta^{\phi} - c_R)Q\ ,\ c_U$
Buyer's Cost	$TC_B^{\phi*}$	$c_R Q$	$(c_U + (1-\alpha)\beta^{\phi})Q$

Note that when the demand is expected to be low, supplier U becomes the sole supplier for the buyer and sets a price $p_U^{\phi*}$ such that the buyer's expected cost of buying from her $(= \alpha p_U^{\phi*} + (1-\alpha)\beta^{\phi})$ is infinitesimally less than supplier R's marginal c_R. Letting $\alpha p_U^{\phi*} + (1-\alpha)\beta^{\phi} = c_R$ and solving for $p_U^{\phi*}$ would then yield the equilibrium price for supplier U. As shown in Table 2, the equilibrium price for supplier U can be expressed in terms of his marginal cost (c_U/α) plus a markup term that depends on the demand uncertainty, and the suppliers' cost and risk parameters. In § 4.2, we explain these terms in more detail. Similarly, when the demand is expected to be high, supplier R can then set the price $p_R^{\phi*}$ in a similar fashion and become the sole supplier for the buyer.

4.2 The impact on the equilibrium decisions under symmetric information

First of all, as shown in Figure 3, the buyer prefers suppliers U and R for low and high values of β^{ϕ}, respectively; the intuition behind this comes from the comparison between relative overage and underage costs[11] associated with suppliers U and R.

- By ordering one more unit from supplier U as opposed to supplier R, the buyer's expected cost changes by $(1-\alpha+\alpha p_U - p_R)$ if demand is realized and by $(\alpha p_U - p_R)$ if it is not. The relative comparison between these expressions suggests that ordering from supplier U instead of from R would increase[12] the buyer's expected cost more when the demand is realized than when it is not. In other words, if the demand is more likely to be realized, the buyer would reduce his underage cost by ordering more from supplier R since she is more secure than supplier U. On the other hand, if demand is less likely to be realized, the buyer would prefer to order more from supplier U in order to lower his overage cost. As characterized in proposition 1, this implies a threshold $(= \gamma)$ for β^{ϕ}, above which the buyer opts for ordering from supplier R (see region "supplier R" in Figure 3), and below which he opts for sourcing from supplier U (see regions "supplier U" in Figure 3).

[11] Relative underage (resp., overage) cost represents the differential cost incurred by the buyer when he ordered from supplier U as opposed to from supplier R if demand turns out to be more (resp., less) than supply.

[12] Throughout the paper, we use greater/smaller, higher/lower and increasing/decreasing in the weak sense.

- Further analysis of this threshold ($\gamma = \frac{c_R - c_U}{1-\alpha}$) yields a comparative metric for supplier U that shows how she compares with supplier R in terms of cost ($c_R - c_U$) and yield risk ($1-\alpha$). This metric implies that the higher the cost differential and/or the lesser the yield risk differential is between the suppliers, the higher the chances are for supplier U to receive the order allocation from the buyer.

The above findings also imply that the equilibrium prices charged by the suppliers depend on the extent of demand faced by the ϕ-type buyer (as measured by β^{ϕ}) and the cost-to-risk ratio of supplier U with respect to supplier R (as measured by γ). In general, lower values of β^{ϕ} and/or higher values of γ make supplier U more preferable for the buyer, which in turn enables her to gain more pricing power against R and consequently increase her price $p_U^{\phi*}$.

Finally, the equilibrium profits and costs for the channel partners are exactly the same under both RFQ^n and RFQ^r. So, when all the supply chain partners have access to the same demand forecast information, a specific RFQ type does not play a significant role. However, as we will see in the next section, when there is information asymmetry among the supply chain parties about the demand risks facing the buyer, both the sourcing and pricing strategies change significantly with the type of RFQ offered by the buyer.

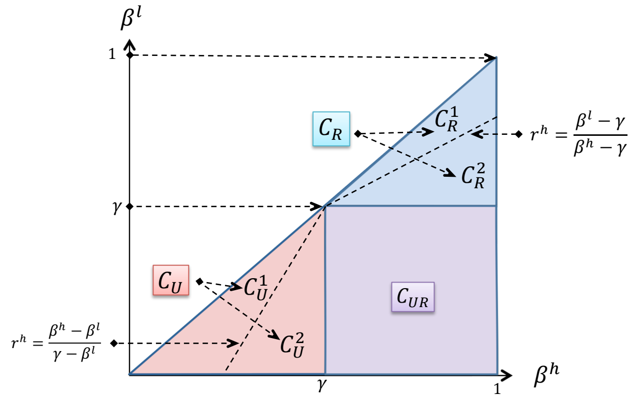
5. Equilibrium Analysis under an Asymmetric Information Scenario

In this section, we analyze the equilibrium for the case where the true demand type is known only to the buyer and the other two suppliers face information asymmetry about the true demand type. Recall that in the presence of incomplete information, the suppliers need to rely on their updated beliefs about the probability of demand being of h- or l-type (denoted by $\hat{r}^h$ and $\hat{r}^l$, respectively, where $\hat{r}^h + \hat{r}^l = 1$) in order to make pricing decisions. We analyze RFQ^n and RFQ^r in §§5.1, and 5.2, respectively.

5.1 The Equilibrium characterization of RFQ^n under Asymmetric Information

Following a similar approach as the one in §4, we can characterize the equilibrium using backward induction, starting from the buyer's optimal (cost-minimizing) order allocation stage, given that suppliers U and R offer p_U and p_R, respectively. Note that since the buyer solves the same order allocation problem as the one under symmetric information setting (3), the equilibrium order allocation will be exactly same. However, there is a significant difference between symmetric and asymmetric information settings. Indeed, under the asymmetric information setting, there are two different allocation policies associated with two demand types, and suppliers do not know which allocation policy will eventually be used by the buyer unless he signals his true demand information

Figure 4 **Equilibrium characterization cases for RFQ^n and RFQ^r under asymmetric information**



Note: Refer to Table 3 for equilibrium characterization of RFQ^n for the cases C_U, C_R, and C_{UR}, and RFQ^r for C_{UR}, and refer to Table 4 for equilibrium characterization of RFQ^r for the cases C_U and C_R.

($\phi = h$ or $\phi = l$) vian RFQ^n. In the next proposition, we show that the buyer cannot credibly signal his true demand type under RFQ^n:

Proposition 2. *Under RFQ^n, the only equilibrium in an asymmetric information scenario is of pooling type, where both the h-type and the l-type buyer submit the same initial forecast, i.e., $I_F^h = I_F^l$.*

The above proposition implies that credible forecast sharing is not sustainable in equilibrium under RFQ^n because either l- or h-type buyer can always decrease his expected cost by imitating the other type if they offer different I_F. Therefore, in equilibrium, the suppliers' updated beliefs will be the same as their prior beliefs, i.e., $\hat{r}^\phi = r^\phi$ for both $\phi \in \{l, h\}$. In the following proposition, we characterize the equilibrium of the pricing game between suppliers U and R in the presence of incomplete information about the true demand type:

Proposition 3. *Under RFQ^n, the suppliers' equilibrium pricing strategies and expected profits and the buyer's expected cost are characterized in Table 3 for all the cases shown in Figure 4.*

A closer examination of Table 3 and Proposition 3 reveals that the equilibrium characterization crucially depends on the suppliers' a priori beliefs about the probability distribution of the true demand type, i.e., r^h and r^l. To see why this is so, recall that in the symmetric information setting, when one of the suppliers undercuts her opponent's price, she does so by taking into account the true demand type of the buyer. However, as shown in proposition 2, the suppliers cannot credibly infer the demand type, which forces each supplier to decide between the following two alternatives:

Table 3 Equilibrium characterization of RFQ^n under asymmetric information (for the cases C_U, C_R and C_{UR}).

Regions and		$(\beta^l,\beta^h)\in C_U$: $\beta^l\le\beta^h\le\gamma=\frac{c_R-c_U}{1-\alpha}$		$(\beta^l,\beta^h)\in C_{UR}$:$\beta^l\le\gamma\le\beta^h$	$(\beta^l,\beta^h)\in C_R$: $\gamma\le\beta^l\le\beta^h$	
Conditions		C_U^1: $r^h\ge\frac{\beta^h-\beta^l}{\gamma-\beta^l}$	C_U^2: $r^h<\frac{\beta^h-\beta^l}{\gamma-\beta^l}$	for all $r^h\in[0,1]$	C_R^2: $r^h>\frac{\beta^l-\gamma}{\beta^h-\gamma}$	C_R^1: $r^h\le\frac{\beta^l-\gamma}{\beta^h-\gamma}$
Prices	p_R^*	c_R	$\sim F_R(p_R)=\frac{1}{r^h}\left(1-\frac{r^l(\overline{p}_R-\bar{\alpha}\beta^h-c_U)}{p_R-\bar{\alpha}\beta^h-c_U}\right)$ for $p_R\in\left[\underline{p}_R,\overline{p}_R\right]$			$\left[c_U+\bar{\alpha}\beta^l\right]^{(-)}$
	p_U^*	$\left[\frac{c_R-\bar{\alpha}\beta^h}{\alpha}\right]^{(-)}$	$\sim F_U(p_U)=1-\frac{\alpha\underline{p}_U+\bar{\alpha}\beta^h-c_R}{\alpha p_U+\bar{\alpha}\beta^h-c_R}$ for $p_U\in\left[\underline{p}_U,\overline{p}_U\right]$			$\frac{c_U}{\alpha}$
Alloc	$(q_U^l,\, q_R^l)$; $(q_U^h,\, q_R^h)$	$(Q,0)$; $(Q,0)$	$\begin{cases}(Q,0);(Q,0) & \text{if } \alpha p_U^*+\bar{\alpha}\beta^h\le p_R^*\\(Q,0);(0,Q) & \text{if } \alpha p_U^*+\bar{\alpha}\beta^h> p_R^*\end{cases}$			$(0,Q)$; $(0,Q)$
Profits	π_R^*	0	$r^h(\underline{p}_R-c_R)Q$			$(c_U+\bar{\alpha}\beta^l-c_R)Q$
	π_U^*	$(c_R-\bar{\alpha}\beta^h-c_U)Q$	$r^l(\alpha\overline{p}_U-c_U)Q$			0
Cost	TC_B^{l*}	$(c_R-\bar{\alpha}(\beta^h-\beta^l))Q$	$\underline{p}^l+(\underline{p}^l+\bar{\alpha}\beta^h-\bar{\alpha}\beta^l-c_R)\ln\left(\frac{\overline{p}^l+\bar{\alpha}\beta^h-\bar{\alpha}\beta^l-c_R}{\underline{p}^l+\bar{\alpha}\beta^h-\bar{\alpha}\beta^l-c_R}\right)$			$(c_U+\bar{\alpha}\beta^l)Q$
	TC_B^{h*}	c_RQ	$\underline{p}^h+\frac{r^l}{r^h}(\underline{p}^h-c_R)\left[\frac{\overline{p}^h-c_R}{c_R-\bar{\alpha}\beta^h-c_U}\ln\left(\frac{\overline{p}^h-c_R}{\underline{p}^h-c_R}\right)+\frac{\overline{p}^h-\bar{\alpha}\beta^h-c_U}{c_U+\bar{\alpha}\beta^h-c_R}\ln\left(\frac{\overline{p}^h-\bar{\alpha}\beta^h-c_U}{\underline{p}^h-\bar{\alpha}\beta^h-c_U}\right)\right]$			$(c_U+\bar{\alpha}\beta^l)Q$

Note: Closed-form expressions for $\overline{p}^\phi$, and $\underline{p}^\phi$ for $\phi\in\{l,h\}$, and $\overline{p}_U$, $\underline{p}_U$, $\overline{p}_R$, and $\underline{p}_R$ are provided in the Appendix.

(i) either she undercuts the opponent's price for both l- and h-type demand scenarios (*mass-market strategy*), (ii) or she does it for only one of the demand scenarios (*niche-market strategy*). The first alternative (mass-market strategy) enables her to win the order allocation from the buyer under both demand scenarios, $\phi\in\{l,h\}$. But in order to be able to do so, she needs to decrease her price quite significantly. On the other hand, the second alternative (niche-market strategy) allows her to charge a higher price but leaves her with a probabilistic order allocation, the likelihood of which depends on a priori beliefs for the targeted niche-market demand scenario (h-type demand for supplier R and l-type demand for supplier U).

If the likelihood of a niche-market demand scenario is very low (the case represented by C_U^1, and C_R^1 in Table 3), both suppliers would opt for mass-market strategy, which results in *head-to-head* price competition between them. As we discuss later (§ 6), in such cases, the buyer would benefit from such a mass-market strategy because the intensive price competition resulting from the head-to-head price competition between both suppliers helps equilibrium prices to decrease. On the other hand, when both suppliers can extract positive profits from their respective niche-market demand scenarios (i.e., cases C_U^2, C_R^2, and C_{UR}), instead of engaging in head-to-head competition for the same demand scenario(s), they *split* the market among each other. Specifically, in this case, supplier U undercuts supplier R for the l-type demand and supplier R undercuts supplier U for the h-type demand. As we discuss in § 6, this *weakens* the strength of price competition between the suppliers, which enables them to increase their prices. Such a scenario indeed hurts the buyer and therefore motivates him to search for a signal to credibly communicate his demand information to the suppliers, which would eventually make them engage in head-to-head price competition again.

5.2 The Equilibrium Characterization for RFQ^r under Asymmetric Information

In this section, we consider the impact of RFQ^r on equilibrium decisions as well as on the credibility of forecast information sharing between supply chain partners.

PROPOSITION 4. *The type of equilibrium as well as decisions, profits and cost under an RFQ^r are characterized for all the cases shown in Figure 4 as follows:*

- *The equilibrium under an RFQ^r is of separating type if and only if $(\beta^l,\beta^h)\in C_U$ or $(\beta^l,\beta^h)\in C_R$. The equilibrium allocation, prices, updated beliefs, and expected profits/costs for the supply chain parties for these two regions are provided in Table 4.*
- *For the remaining cases (for case C_{UR}), the equilibrium under an RFQ^r is of pooling type, i.e., $\hat{r}^\phi = r^\phi$ for $\phi = l,h$. The equilibrium allocation, prices, and expected profits/costs for the supply chain parties for the pooling cases are the same as the ones characterized in Table 3 (for case C_{UR}).*

Table 4 Equilibrium characterization of RFQ^r under asymmetric information (for the cases C_U, and C_R).

Regions		$(\beta^l,\beta^h)\in C_R: \gamma\le\beta^l\le\beta^h$	$(\beta^l,\beta^h)\in C_U$: $\beta^l\le\beta^h\le\gamma$
RFQs	$(I_F^\phi,\underline{\omega}^\phi,\bar{\omega}^\phi)$	any $(I_F^\phi,\underline{\omega}^\phi,\bar{\omega}^\phi)$ s.t. $I_F^l(1+\bar{\omega}^\phi)=\begin{cases}Q & \text{if } \phi=h\\ \frac{1+(\beta^l-c_U/\alpha)/(\beta^h-\beta^l)}{1/\alpha+(\beta^l-c_U/\alpha)/(\beta^h-\beta^l)}Q & \text{if } \phi=l\end{cases}$	any $(I_F^\phi,\underline{\omega}^\phi,\bar{\omega}^\phi)$ s.t. $I_F^l(1+\underline{\omega}^\phi)=\begin{cases}\frac{c_R-\beta^l\bar{\alpha}}{c_R-\beta^h\bar{\alpha}}Q & \text{if } \phi=h\\ Q & \text{if } \phi=l\end{cases}$
Updated Beliefs	$(\hat{r}^h,\hat{r}^l)$	$\begin{cases}(1,0) & \text{if } I_F(1+\bar{\omega})>I_F^l(1+\bar{\omega}^l)\\ (0,1) & \text{if } I_F(1+\bar{\omega})\le I_F^l(1+\bar{\omega}^l)\end{cases}$	$\begin{cases}(1,0) & \text{if } I_F(1-\underline{\omega})\ge I_F^h(1-\underline{\omega}^h)\\ (0,1) & \text{if } I_F(1-\underline{\omega})< I_F^h(1-\underline{\omega}^h)\end{cases}$
Prices	p_U^*,p_R^*	$\begin{cases}\frac{c_U}{\alpha},\left[c_U+\bar{\alpha}\beta^h\right]^{(-)} & \text{if } I_F(1+\bar{\omega})>I_F^l(1+\bar{\omega}^l)\\ \frac{c_U}{\alpha},\left[c_U+\bar{\alpha}\beta^l\right]^{(-)} & \text{if } I_F(1+\bar{\omega})\le I_F^l(1+\bar{\omega}^l)\end{cases}$	$\begin{cases}\left[\frac{c_R-\bar{\alpha}\beta^h}{\alpha}\right]^{(-)},c_R & \text{if } I_F(1-\underline{\omega})\ge I_F^h(1-\underline{\omega}^h)\\ \left[\frac{c_R-\bar{\alpha}\beta^l}{\alpha}\right]^{(-)},c_R & \text{if } I_F(1-\underline{\omega})< I_F^h(1-\underline{\omega}^h)\end{cases}$
Alloc	$q_U^{\phi*},q_R^{\phi*}$	$0,I_F^\phi(1+\bar{\omega}^\phi)$	$I_F^\phi(1-\underline{\omega}^\phi),0$
Suppliers' Profits	π_R^*,π_U^*	$\sum_{\phi=l,h}r^\phi(c_U+\bar{\alpha}\beta^\phi-c_R)I_F^\phi(1+\bar{\omega}^\phi),0$	$0,\sum_{\phi=l,h}r^\phi(c_R-\bar{\alpha}\beta^\phi-c_U)I_F^\phi(1-\underline{\omega}^\phi)$
Buyer's Cost	TC_B^{h*}	$(c_U+\bar{\alpha}\beta^h)I_F^h(1-\bar{\omega}^h)$	$c_R I_F^h(1-\underline{\omega}^h)+\beta^h\bar{\alpha}(I_F^h(1-\underline{\omega}^h)-Q)$
	TC_B^{l*}	$\beta^l(Q-I_F^l(1+\bar{\omega}^l))+(c_U+\bar{\alpha}\beta^l)I_F^l(1+\bar{\omega}^l)$	$c_R I_F^l(1+\underline{\omega}^l)$

Note: Refer to Table 3 for the equilibrium characterization of RFQ^r for the case C_{UR}, i.e., $\beta^l\le\gamma\le\beta^h$.

The main takeaway from proposition 4 is that a buyer who has private information about his true demand type can convey this information in a credible way via an RFQ^r. Below, we discuss first *how* and then *when* an RFQ^r can be used as a credible signal.

The answer to the *how*-question depends on whether an l- or h-type buyer has an incentive to imitate the RFQ^r offered by the other type. There are two cases: (i) when the extent of demand faced by both types of buyer is high, i.e., $(\beta^l,\beta^h)\in C_R$ and (ii) when it is low, i.e., $(\beta^l,\beta^h)\in C_U$. We focus on the former case to illustrate the intuition[13]. Recall from Table 2 in § 4 that in C_R, when

[13] The discussion for the other case C_U can be obtained by exchanging l-type with h-type.

the suppliers compete for the same demand type, the resulting equilibrium price offered for the l-type buyer is less than that for the h-type buyer. This implies that in the presence of asymmetric information, an h-type buyer always has an incentive to imitate the RFQ offered by an l-type buyer. So, in order for the l-type to separate himself from the h-type, he needs to design an RFQ^r that is too costly for an h-type to mimic. This can be accomplished by the l-type buyer via a *costly* self-imposed upper bound on the amount of products that he will order in the future.

We can formalize this as follows: let $(I_F^{l*}, \underline{\omega}^{l*}, \bar{\omega}^{l*})$ and $(I_F^{h*}, \underline{\omega}^{h*}, \bar{\omega}^{h*})$ be two different RFQ^rs offered by the l- and the h-type buyers, respectively. In response to this, both suppliers update their a priori beliefs accordingly and charge (p_U^{l*}, p_R^{l*}) and (p_U^{h*}, p_R^{h*}) for l- and h-type buyers, respectively. In order for these RFQs to be *credible* in equilibrium, and updated beliefs to be consistent with the buyer's decisions, equilibrium RFQ^r and prices should satisfy the following incentive compatibility (IC) constraints:

$$\text{IC constraint for } h\text{-type buyer: } TC_B^h(p_U^{h*}, p_R^{h*} | I_F^{h*}, \underline{\omega}^{h*}, \bar{\omega}^{h*}) \le TC_B^h(p_U^{l*}, p_R^{l*} | I_F^{l*}, \underline{\omega}^{l*}, \bar{\omega}^{l*})$$
$$\text{IC constraint for } l\text{-type buyer: } TC_B^l(p_U^{l*}, p_R^{l*} | I_F^{l*}, \underline{\omega}^{l*}, \bar{\omega}^{l*}) \le TC_B^{l*}(p_U^{h*}, p_R^{h*} | I_F^{h*}, \underline{\omega}^{h*}, \bar{\omega}^{h*})$$

where $TC_B^{\phi}(p_U^{\phi'*}, p_R^{\phi'*} | I_F^{\phi'*}, \underline{\omega}^{\phi'*}, \bar{\omega}^{\phi'*})$ denotes the expected total cost (defined in Equation 3) incurred by a ϕ-type buyer provided that he offers an RFQ^r designed by a ϕ'-type buyer, where $\phi \in \{l, h\}$, $\phi' \in \{l, h\}$ and $\phi \neq \phi'$. In other words, the above two conditions ensure that neither the l- nor the h-type buyer has any incentive to deviate from his respective RFQ^r even if doing so would lead to lower prices. Note that there can be multiple solutions to the above conditions. In order to eliminate the multiplicity of the equilibria, we employ the *intuitive criterion*, a commonly used equilibrium refinement concept developed for the signalling games (Cho and Kreps 1987). Indeed, this refinement enables us to determine a *unique* equilibrium RFQ^r that is both incentive compatible and least costly from both the l- and h-type buyers' perspectives.

The answer to the *when*-question depends on two things: (i) the impact of offering a separating RFQ^r on the strength of price competition and (ii) the cost of sustaining a separating equilibrium. Recall that, as shown in § 5.1, the lack of credibility may weaken the price competition, which can be restored via an RFQ^r offering. However, in order to make the RFQ^r offering credible in the eyes of suppliers, the party offering RFQ^r has to burden a cost, the *signalling cost*, which increases in the degree of informational asymmetry across the supply chain (measured by $\beta^h - \beta^l$). Hence, if the degree of information asymmetry is relatively low (i.e., C_U and C_R), the signalling cost would also be low, and the separating RFQs can be sustained in equilibrium. On the other hand, if the degree of information asymmetry is very high (i.e., C_{UR}), then, the buyer would find it too costly to sustain separating RFQs even if they strengthen the degree of competition between the suppliers.

6. The Impact of RFQ^n and RFQ^r

In this section, we first compare the effects of RFQ^n and RFQ^r on the equilibrium decisions, and subsequently, on the equilibrium costs and profits.

6.1 Impact On Equilibrium Decisions

The following proposition compares the impact of an RFQ^r on the equilibrium channel decisions with respect to an RFQ^n:

PROPOSITION 5. *The impact of an RFQ^r on equilibrium order quantities and prices with respect to an RFQ^n under asymmetric information setting is characterized as follows:*

– *Equilibrium order quantities decrease in C_U and increase in C_R under an RFQ^r, with respect to an RFQ^n.*

– *Equilibrium prices seen by both l- and h-type buyers increase in cases C_U^1 and C_R^1, and decrease in the cases C_R^2 and C_U^2 (except for l-type buyer in C_U^2) under an RFQ^n, with respect to an RFQ^n.*

As characterized in proposition 4, in order for the buyer to use an RFQ^r as a credible signal, he needs to impose either a lower or an upper bound on the order quantity. These self-imposing constraints will increase and decrease the equilibrium order quantity in regions C_R and C_U, respectively. Note that the relative cost-to-risk ratio γ between suppliers U and R also plays an important role in the format of RFQ^r offered by the buyer. Specifically, the higher the cost-to-risk ratio of supplier U with respect to R (i.e., higher values of γ), the more likely the buyer is to offer an RFQ^r with upper bounds on his order quantity in order to incentivize supplier U to engage in head-to-head competition with supplier R. This would in turn result in a lower order quantity for the buyer under an RFQ^r with respect to RFQ^n.

With regards to the effects of RFQ decisions on equilibrium prices, we need to take into account whether RFQ^n and RFQ^r lead suppliers U and R to (i) engage in head-to-head competition for the same demand scenario(s) or split the market among each other, and (ii) opt for mass- or niche-market strategies. Results are summarized in Table 5.

Table 5 **Impact of RFQ^n and RFQ^r on the strength of price competition.**

		(Competition weakens & price increases) $\Rightarrow$	
		Mass-market strategy	**Niche-market strategy**
(Competition weakens / Price increases) $\Downarrow$	**Head-to-head competition**	RFQ^n in C_U^1 and C_R^1	RFQ^r
	Split demand scenarios	Not Applicable	RFQ^n in C_U^2 and C_R^2

Table 5 shows that an RFQ^n decreases the strength of price competition between suppliers from one extreme (where they engage in head-to-head competition for mass market) to another (where each supplier targets at her respective niche-market demand scenario), whereas an RFQ^r keeps the strength of price competition in the middle (where suppliers U and R engage in head-to-head competition for the same niche market). With respect to RFQ^n, this results in a higher equilibrium price under RFQ^r for regions C_U^1 and C_R^1, and a lower equilibrium price under RFQ^r for regions C_U^2 and C_R^2 (except for l-type buyer in C_U^2).

We also analyze the impact of a priori beliefs on the equilibrium prices charged by the suppliers under both RFQ^n and RFQ^r. Note that, as shown in Figure 4, the regions C_U^2 and C_R^2, where suppliers U and R each target at their respective niche demand scenarios under an RFQ^n, increase in size in r^l and r^h, respectively. This follows intuition because in C_U^2 (resp., C_R^2), the profitability of niche demand scenario for supplier U (resp., R) increases in r^l (resp., r^h). This in turn increases the value of an RFQ^r from the buyer's perspective because it enables the suppliers to compete for the same demand scenario, resulting in lower prices for the buyer.

6.2 On Equilibrium Profits/Costs

Using the results of the previous section, the following proposition establishes the impact of an RFQ^r on the equilibrium costs and profits of the channel partners with respect to an RFQ^n:

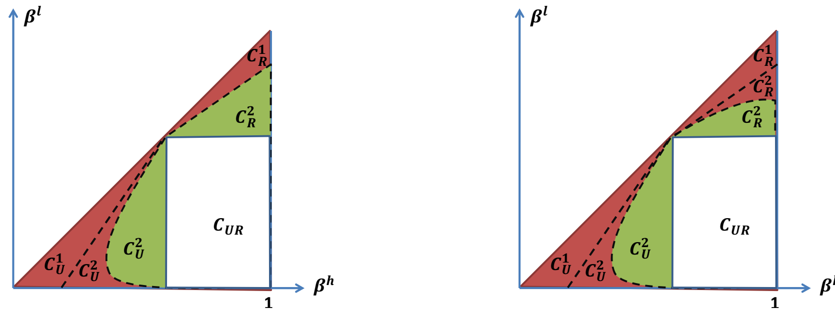
PROPOSITION 6. *The comparison between the channel partners' profits and costs under RFQ^n and RFQ^r in an asymmetric information setting is characterized in Figure 5.*

The main takeaway from the above proposition is that ultimately it is the degree of information asymmetry (i.e., $\beta^h - \beta^l$) that causes differences in expected costs and profits of channel partners between RFQ^n and RFQ^r. We elaborate on this by considering the following three cases:

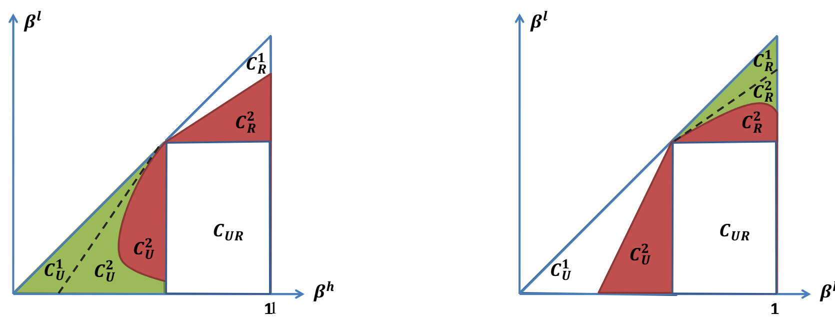
- When the degree of information asymmetry is low (i.e., regions C_U^1 and C_R^1): Note that the buyer is always worse off with an RFQ^r. This is because under an RFQ^r, the buyer faces two setbacks: an additional signalling cost and rising supply prices due to a weaker price competition between the suppliers. To sum, when the degree of information asymmetry is low, the buyer does not gain any benefit from the information visibility. On the other hand, from the suppliers' perspectives, they are better off with the buyer offering an RFQ^r, because it allows them to increase their prices.

- When the degree of information asymmetry is medium (i.e., regions C_U^2 and C_R^2): As the extent of demand facing l- and h-type buyers gets dissimilar, it becomes too costly for each supplier to offer a price low enough to cover all the demand scenarios. Consequently, the suppliers have a greater incentive to split the demand scenarios among each other, which in turn weakens the competition.

Figure 5 **Effects of RFQ^n vs. RFQ^r on supply chain partners' profit/costs in asymmetric information setting.**



Regions		h-type Buyer's Cost	l-type Buyer's Cost
C_U^1:	$(\beta^l,\beta^h) \in C_U$ and $r^l \leq 1/\zeta_U$	$RFQ^n > RFQ^r$	$RFQ^n > RFQ^r$
C_U^2:	$(\beta^l,\beta^h) \in C_U$ and $r^l > 1/\zeta_U$	$RFQ^n \geq RFQ^r$ if $\Delta_1^h \geq 0$; $RFQ^n < RFQ^r$ o.w.	$RFQ^n \geq RFQ^r$ if $\Delta_1^l \geq 0$; $RFQ^n < RFQ^r$
C_R^1:	$(\beta^l,\beta^h) \in C_R$ and $r^h \leq \zeta_R$	$RFQ^n > RFQ^r$	$RFQ^n > RFQ^r$
C_R^2:	$(\beta^l,\beta^h) \in C_R$ and $r^h > \zeta_R$	$RFQ^n < RFQ^r$	$RFQ^n \geq RFQ^r$ if $\Delta_2^l \geq 0$; $RFQ^n < RFQ^r$
C_{UR}:	$(\beta^l,\beta^h) \in C_{UR}$	$RFQ^n = RFQ^r$	$RFQ^n = RFQ^r$



Regions		Supplier U's profit	Supplier R's profit
C_U^1:	$(\beta^l,\beta^h) \in C_U$ and $r^l \leq 1/\zeta_U$	$RFQ^n < RFQ^r$	$RFQ^n = RFQ^r$
C_U^2:	$(\beta^l,\beta^h) \in C_U$ and $r^l > 1/\zeta_U$	$RFQ^n \geq RFQ^r$ if $\Delta_U \geq 0$; $RFQ^n < RFQ^r$ o.w.	$RFQ^n \geq RFQ^r$
C_R^1:	$(\beta^l,\beta^h) \in C_R$ and $r^h \leq \zeta_R$	$RFQ^n = RFQ^r$	$RFQ^n < RFQ^r$
C_R^2:	$(\beta^l,\beta^h) \in C_R$ and $r^h > \zeta_R$	$RFQ^n \geq RFQ^r$	$RFQ^n \geq RFQ^r$ if $\Delta_R \geq 0$; $RFQ^n < RFQ^r$
C_{UR}:	$(\beta^l,\beta^h) \in C_{UR}$	$RFQ^n = RFQ^r$	$RFQ^n = RFQ^r$

Note. The different colored regions in the above figure denote the following preference between RFQ^n and RFQ^r for each supply chain partner: green (light shaded) regions - prefers RFQ^r over RFQ^n; red (dark shaded) regions - prefers RFQ^n over RFQ^r; and, white regions - indifferent between RFQ^n and RFQ^r. Δ_i^ϕ (for $\phi = l, h$ for $i = 1$, and $\phi = l$, and $i = 2$), Δ_U and Δ_R are characterized in Appendix.

This creates a tradeoff situation for the buyer. Namely, the buyer can strengthen the competition by offering an RFQ^r, but he has to incur a cost to make it credible. Based on the cost-benefit analysis, Figure 5 indicates that the buyer gains more from an RFQ^r than he loses as the degree of information asymmetry grows. On the other hand, from the suppliers' perspective, Figure 5 shows that suppliers are generally better off with an RFQ^n and prefer an RFQ^r only when the degree of information asymmetry is sufficiently low. There are two reasons for this. First, RFQ^n allows the suppliers to increase their price offerings. Second, it may also increase the order quantity for them. For example, consider region C_R^2. In this region, under an RFQ^r, supplier U will always be undercut by supplier R for all demand scenarios. However, under an RFQ^n, supplier R focuses on the h-type demand and leaves the other demand scenario (l-type) for supplier U to win.

- Finally, when the degree of information asymmetry is high (i.e., region C_{UR}): As shown in proposition 4, since it is too costly for the buyer to credibly convey his demand information to the suppliers, the only equilibrium that is sustainable in C_{UR} is of pooling type, which implies that an RFQ^r has no impact either on the buyer's expected cost or on the suppliers' expected profits.

7. Conclusion

In this paper, we analyze how and when a buyer can credibly share his forecast information with his upstream suppliers, and how it impacts the equilibrium decisions and the profits/costs of channel partners. To address these questions, we develop a decentralized supply chain model with a buyer facing private demand information and two heterogeneous suppliers competing for the buyer's order quantity. We analyze two RFQ types, non-restrictive (RFQ^n) and restrictive (RFQ^r). In each case, the buyer obtains a private signal (forecast) for the demand and decides on the RFQ parameters. Then, the suppliers update their beliefs on the true forecast type, and compete on prices to earn the order from the buyer. Once the supply and demand risks are realized, and orders are shipped, the buyer clears the supply-demand mismatch, if there is any.

We first characterize the equilibrium under symmetric information and show that both RFQ^n and RFQ^r lead to same equilibrium decisions, profits and costs of the channel partners. The choice of sourcing strategy depends on the amount of forecasted demand. Specifically, the unreliable supplier (U) is preferred for low forecasted-demand scenarios, while the reliable supplier (R) is preferred for high forecasted-demand scenarios. The analyses of RFQ^n and RFQ^r under the asymmetric information setting bring new twists to every aspect of the problem, especially to the credibility of the forecast information and the strength of price competition at the supplier level. First, the fact that the suppliers hold incomplete information about the demand leads to an uncertainty on their side regarding what price to charge, which, in turn, generates an incentive for the buyer to distort his forecast information, and invalidates the credibility of an RFQ^n. We show that this distortion can be fixed, albeit at a cost, via an RFQ^r, as long as the degree of information asymmetry between channel partners is not too high.

Secondly, in the presence of incomplete information, the suppliers decide on their prices solely based on their a priori beliefs on the true demand scenario, and choose (i) whether to opt for mass- or niche market demand scenario, and (ii) whether to engage in *head-to-head competition* for the same demand scenario or split the demand scenarios between themselves. Depending on the choices made by the suppliers, the strength of price competition (resp., equilibrium price) decreases (resp., increases) from one extreme to another as the suppliers move from mass- to niche-market, and from head-to-head competition for the same market to splitting them among each other. Our results show that an RFQ^n pushes the degree of price competition to the extremes at either end, whereas an RFQ^r keeps it in the middle. Finally, a comparison of the cost/profit implications of the above two effects on the payoffs enables us to evaluate when an RFQ^r is more preferable option (and when it is not) for each channel partner.

The above-mentioned results give some managerial insights on the role of credible information sharing in competitive supply chains:

First, the degree of informational asymmetry between the buyer and the suppliers has to be in the medium range (i.e., medium level of $\beta^h - \beta^h$) in order for the buyer to justify the cost associated with providing demand visibility via an RFQ^r. This suggests that the restrictions on the order quantity can be used as an effective tool in the later stages of procurement relations between the buyer and the suppliers, when they have already somewhat established a relationship. This could offer an explanation for why Sun MicroSystems initially started with no commitments and then gradually moved to more restrictive procurement mechanisms with its suppliers for various workstation/server components.

Next, our results suggest that the buyer may need to customize the type of restriction that he provides with RFQ^r depending on the level of reliability of the supplier he is interacting with. Specifically, if the buyer is interacting with an unreliable supplier (i.e., supplier U), then he would need to impose a lower bound on the amount of products to be purchased from the supplier. Indeed, minimum capacity reservations, a common contractual form used in the semiconductor industry, where producers' yields are not too high due to the high degree of production risks, are similar to the agreements with a lower bound on the order quantity. On the other hand, if the buyer is interacting with a reliable supplier (i.e., supplier R), then he would instead offer an upper bound on the amount of products to be purchased. Indeed, as indicated in Farlow et al. (1996b), Sun MicroSystems used a specific form with only an upper bound constraint for the suppliers of relatively low risk items such as keyboards and monitors.

Finally, even though we consider specific values for the cost of internal production and the salvage value (modelled through $c_I = 1$ and $c_S = 0$, respectively), we have performed an additional analysis that extends these parameters to the general settings; it suggests that the buyer has more incentive to offer a restrictive RFQ to provide the demand visibility for the customized products, where the above transactional costs are expected to be higher. On the other hand, if the buyer can easily access the emergency sources in the case of shortfall (i.e., low c_I) or salvage the excess units without incurring too much cost (i.e., high c_S), as is the case for a number of commodity products, the buyer prefers a non-restrictive RFQ over a restrictive one.

The model presented in this paper can be extended in various directions. We assumed here that supply chain firms are risk-neutral optimizers. One possibility would be to introduce risk-aversion into the players' objectives. This extension would enable us to see the impact of the contracting decision on the risk characteristics. Another extension is to consider the impact of credible information sharing on supply chains with both upstream and downstream competitive structures. Moreover, considering a multi-period setting would allow us to capture the learning ad reputation effects. Lastly, we believe that the analysis of the impact of credible forecast sharing on competitive supply chain settings presents fruitful research opportunities and hope that our model will fuel future research in this endeavor.

Acknowledgments

The author thanks EICs for the special issue, Anil Arya, Stephen Gilbert and Brian Mittendorf, an anonymous senior editor, and three anonymous referees for constructive comments that led to significant improvements in this paper. The author is also grateful to seminar attendees at the University of British Columbia, the University of California at Irvine, the University of Chicago, the University of Miami, and Wilfrid Laurier University for many helpful comments and suggestions. The author's works were supported in part by research grants from the Natural Sciences and Engineering Research Council of Canada (NSERC RGPIN 355570-09); the Social Sciences and Humanities Research Council of Canada (SSHRC 214832); and Fonds de recherche sur la Société et la culture of Québec (FQRSC NP-132114).

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Appendix A: Proofs of Propositions

Proof of Proposition 1: Under symmetric information, the problem can be analyzed by starting from the buyer's order allocation. Let supplier U and R offer p_U and p_R per unit. Then, the buyer's expected cost can be expressed as follows: $k^{\phi}(q_U, q_R; p_U, p_R) = k_I^{\phi} \cdot (Q - q_U - q_R) + k_U^{\phi}(p_U) \cdot q_U + k_R^{\phi}(p_R) \cdot q_R$ where $k_U^{\phi}(p_U)$, $k_R^{\phi}(p_R)$, and k_I^{ϕ} are the marginal expected costs if the buyer procures one extra unit from, respectively, supplier U, supplier R, and insourcing option. We can formulate the expected marginal cost functions as follows. First, we start with $k_U^{\phi}(p_U)$. If the buyer procures one more unit from supplier U, three things can happen to this extra unit: (i) Demand occurs and supplier U delivers (with probability $\beta^{\phi}\alpha$). In this case, the buyer pays p_U dollars to the supplier U, (ii) Demand occurs but supplier U can not deliver (with probability $\beta^{\phi}(1-\alpha)$). In this case, the buyer satisfies the shortfall at c_I dollars per unit, and (iii) Demand does not occur but supplier U delivers (with probability $(1-\beta^{\phi})\alpha$). In this case, buyer pays p_U dollars to the supplier U and salvages the excess inventory at c_S per unit. Multiplying the buyer's marginal cost under each event with the event probability and letting $c_I = 1$ and $c_S = 0$, we can formulate $k_U^{\phi}(p_U)$ as follows: $k_U^{\phi}(p_U) = \beta^{\phi}\alpha p_U + \beta^{\phi}(1-\alpha)c_I + (1-\beta^{\phi})\alpha(p_U - c_S) = \alpha p_U + \beta^{\phi}(1-\alpha)$. Next, we formulate $k_R^{\phi}(p_R)$. Different from the above case, two events can occur. Multiplying buyer's marginal cost under each event with the event probability and letting $c_S = 0$, we can formulate $k_R^{\phi}(p_R)$ as follows: $k_R^{\phi}(p_R) = \beta^{\phi} p_R + (1-\beta^{\phi})(p_R - c_S) = p_R$. Finally, the expected marginal cost of using insourcing option is equal to $k_I^{\phi} = \beta^{\phi} c_I = \beta^{\phi}$ due to the fact that c_I is assumed to be 1. Note that the buyer's total expected cost is linear in q_U and q_R. Therefore, either $q_U + q_R \geq I_F(1-\underline{\omega})$ or $q_U + q_R \leq I_F(1+\bar{\omega})$ will be binding. Also, note that it is never optimal for the buyer to order more than Q. This is because salvage value c_S is assumed to be 0, hence, buyer does not have incentive to over-order. Finally, note that the buyer's expected marginal cost of insourcing option is always higher than the buyer's expected marginal cost of buying from supplier U and supplier R when the suppliers set their prices at their marginal costs due to the fact that $c_U \leq c_R \leq \beta^l \leq \beta^h$ by assumption. This implies that in equilibrium, either supplier U or supplier R receives the order from the supplier, i.e., $q_U^* + q_R^* > 0$. Taking into account all these constraints, we can specify the buyer's optimal allocation decision as follows:

$$(q_U^*(p_U, p_R), q_R^*(p_U, p_R)) = \begin{cases} (\min(\max(Q, I_F(1-\underline{\omega})), I_F(1+\bar{\omega})), 0) & \text{if } k_U^{\phi}(p_U) \leq k_R^{\phi}(p_R) \\ (0, \min(\max(Q, I_F(1-\underline{\omega})), I_F(1+\bar{\omega}))) & \text{o.w.} \end{cases} \quad (4)$$

Given that the buyer's allocation decision is given as above, supplier U and supplier R engage in Bertrand price competition, where each supplier undercuts the other one until she or her opponent (whichever happens first) reaches to her break-even price. This results in an equilibrium, in which the most cost-efficient supplier undercuts the least cost-efficient by just epsilon (i.e., infinitesimal) amount and wins the order. We use $[x]^{(-)}$ to represent a number which is infinitesimally less than x. Let $k_U^{\phi} = k_U^{\phi}(c_U/\alpha) = c_U - (1-\alpha)\beta^{\phi}$ and $k_R^{\phi} = k_R^{\phi}(c_R) = c_R$ be the buyer's marginal expected cost when U and R set their prices at their marginal costs, i.e. $p_U = c_U/\alpha$ and $p_R = c_R$, respectively. Then, in equilibrium, one of the following will be true:

1. If $k_U^{\phi} \leq k_R^{\phi}$, buyer orders from supplier U. This condition can be simplified as follows:

$$k_U^{\phi} \leq k_R^{\phi} \Leftrightarrow c_U + \beta^{\phi}(1-\alpha) \leq c_R \Leftrightarrow \beta^{\phi} \leq \frac{c_R - c_U}{1-\alpha} = \gamma$$

2. If $k_R^\phi \leq k_U^\phi$, buyer procures from R. This condition can be simplified as $\beta^\phi \geq \gamma$.

Based on the above comparisons, we can fully characterize the equilibrium procurement strategy for the buyer as given in Table 2. The corresponding equilibrium prices for the winning party can be found by equating the buyer's marginal cost associated with the winning party to the minimum marginal cost among the losing the parties. So, when $\beta^\phi \leq \gamma$, the winning party is supplier U. Therefore, U's price can be found from the following equation: $k_U^\phi(p_U) = k_R^\phi \Rightarrow p_U^* = \left[\frac{c_U}{\alpha} + \frac{k_R^\phi - k_U^\phi}{\alpha}\right]^{(-)} = \left[\frac{c_R + (1-\alpha)\beta^\phi}{\alpha}\right]^{(-)}$. If $\beta^\phi > \gamma$, then the winning party is supplier R. R's price can be found from the following equation: $k_R^\phi(p_R) = k_U^\phi \Rightarrow p_R^* = \left[c_R + k_U^\phi - k_R^\phi\right]^{(-)} = [c_U - (1-\alpha)\beta^\phi]^{(-)}$. The suppliers' profits and buyer's cost (see Table 2) can be calculated by evaluating profit and cost expressions at (p_U^*, p_R^*) and (q_U^*, q_R^*).

Proof of Proposition 2: We show that in equilibrium both h and l types offer the same initial forecast. Note that ϕ-type buyer's cost function decreases in both p_U and p_R. Hence, it is trivial to show that in equilibrium if $p_U^{l*} \neq p_U^{h*}$ and $p_R^{l*} \neq p_R^{h*}$, either l or h-type buyer can decrease his cost by mimicking the other type. Hence, it implies that $I_F^{l*} \neq I_F^{h*}$ is not sustainable on the equilibrium path. This suggests that the suppliers cannot identify the correct type of demand uncertainty, and hence uses a-priori beliefs (i.e., r^h and r^l) to decide on their prices.

Proof of Proposition 3: First, we start with C_U:

- If $(\beta^l, \beta^h) \in C_U$: In this case, supplier U can always undercut R irrespective of demand type. But since she does not know the demand type, she will rely on her a-priori beliefs. First, we show that if $r^l \leq \frac{k_R^h - k_U^h}{k_R^l - k_U^l} = \frac{\beta^h - \beta^l}{\gamma - \beta^l}$, then the following pricing policy is equilibrium: $p_U^* = \left[\frac{c_U}{\alpha} + \frac{k_R^h - k_U^h}{\alpha}\right]^{(-)} = \left[\frac{c_R + (1-\alpha)\beta^h}{\alpha}\right]^{(-)}$, and $p_R^* = c_R$. We can show that there is no profitable deviation for U and R given that the other party keeps her price constant. From R's perspective, there is no profitable deviation for her since ϕ-type buyer's cost is already less than or equal to k_R^ϕ and therefore, buyer would never assign order to R. From U's perspective, given that $p_R^* = c_R$, she has two options: (i) if she charges $p_U^* = \left[\frac{c_U}{\alpha} + \frac{k_R^h - k_U^h}{\alpha}\right]^{(-)} = \left[\frac{c_R + (1-\alpha)\beta^h}{\alpha}\right]^{(-)}$, she would win the order under both l and h-type demand, hence her profit would be equal to $k_R^h - k_U^h$, (ii) if she charges $p_U^* = \left[\frac{c_U}{\alpha} + \frac{k_R^l - k_U^l}{\alpha}\right]^{(-)} = \left[\frac{c_R + (1-\alpha)\beta^l}{\alpha}\right]^{(-)}$, she would win the order only if the demand type is l and therefore her profit would be equal to $r^l(k_R^l - k_U^l)$. But since we assume that $r^l(k_R^l - k_U^l) \leq k_R^h - k_U^h$, we can conclude that U does not have a profitable deviation. Next, we consider the case where $r^l > \frac{k_R^h - k_U^h}{k_R^l - k_U^l}$. In this case, we can show that there is always a profitable deviation from a pure strategy equilibrium. Suppose $p_U = \left[\frac{c_U}{\alpha} + \frac{k_R^l - k_U^l}{\alpha}\right]^{(-)} = \left[\frac{c_R + (1-\alpha)\beta^l}{\alpha}\right]^{(-)}$, and $p_R = c_R$. Since U obtains the order only if the demand type is l, there is a profitable deviation for R. She would simply increase her price and undercut U when demand type is h. In response to that, supplier U would also increase her price. These mutual responses would indeed increase the price of U to $\bar{p}_U = \left[\frac{c_U}{\alpha} + \frac{k_I^l - k_U^l}{\alpha}\right]^{(-)}$, and the price of R to $\bar{p}_R$, where $\bar{p}_R$ undercuts $\bar{p}_U$ for h-type demand, i.e.,

$$\bar{p}_R = \left[\alpha\bar{p}_U - c_U + c_R + k_U^h - k_R^h\right]^{(-)} = \left[c_R + k_U^h - k_R^h + k_I^l - k_U^l\right]^{(-)}$$

However, $\bar{p}_U$ and $\bar{p}_R$ also do not constitute Nash equilibrium because U can always deviate and undercut $\bar{p}_R$ by epsilon and win the order all the times. Using the undercutting argument, we can show that there is no pure strategy equilibrium. Below, we construct a mixed strategy equilibrium for U and R and define the range of prices for U and R as $\left[\underline{p}_U, \bar{p}_U\right]$, and $\left[\underline{p}_R, \bar{p}_R\right]$, respectively.

- If $(\beta^l, \beta^h) \in C_R$: In this case, supplier R can always undercut U irrespective of demand type. First, we show that if $r^h \leq \frac{k_U^l - k_R^l}{k_U^h - k_R^h}$, then the following pricing policy is equilibrium: $p_R^* = [c_R + k_U^l - k_R^l]^{(-)}$, and $p_U^* = c_U$. We can show that there is no profitable deviation for U and R given that the other party keeps her price constant. From U's perspective, there is no profitable deviation for her since ϕ-type buyer's cost is already less than or equal to k_U^ϕ and therefore, buyer would never assign order to U. From R's perspective, given that $p_U^* = c_U$, she has two options: (i) if she charges $p_R^* = [c_R + k_U^l - k_R^l]^{(-)}$, she would receive the order under both l and h-type demand, hence her profit would be equal to $k_U^l - k_R^l$, (ii) if she charges $p_R^* = [c_R + k_U^h - k_R^h]^{(-)}$, she would receive the order only if the demand type is h and therefore her profit would be equal to $r^h(k_U^h - k_R^h)$. But since we assume that $r^h \leq \frac{k_U^l - k_R^l}{k_U^h - k_R^h}$, we can conclude that R does not have a profitable deviation. Next, we consider the case where $r^h > \frac{k_U^l - k_R^l}{k_U^h - k_R^h}$. In this case, we can show that there is always a profitable deviation from a pure strategy equilibrium. Suppose $p_R = [c_R + (k_U^h - k_R^h)]^{(-)}$, and $p_R = c_U$. Since R wins the order only if the demand type is h, there is a profitable deviation for U. She would simply increase her price and undercut R when demand type is l. In response to that, supplier R would also increase her price. These mutual responses would indeed increase the price of U to $\bar{p}_U = \left[\frac{c_U}{\alpha} + \frac{k_I^l - k_U^l}{\alpha}\right]^{(-)}$, and the price of R to $\bar{p}_R$, where $\bar{p}_R$ undercuts $\bar{p}_U$ for h-type demand, i.e.,

$$\bar{p}_R = \left[\alpha \bar{p}_U - c_U + c_R + k_U^h - k_R^h\right]^{(-)} = \left[c_R + k_U^h - k_R^h + k_I^l - k_U^l\right]^{(-)}$$

Note that $\bar{p}_R \geq c_R$ because $k_U^h - k_R^h \leq 0$ and $k_I^l - k_U^l \geq 0$ due to the fact that $(\beta^l, \beta^h) \in C_R$. However, $\bar{p}_U$ and $\bar{p}_R$ also do not constitute Nash equilibrium because R can always deviate and undercut $\bar{p}_U$ by epsilon and win the order all the times. Using the undercutting argument, we can show that there is no pure strategy equilibrium. Below, we construct a mixed strategy equilibrium for U and R and define the range of prices for U and R as $\left[\underline{p}_U, \bar{p}_U\right]$, and $\left[\underline{p}_R, \bar{p}_R\right]$, respectively.

- Finally, if $(\beta^l, \beta^h) \in C_{UR}$: In this case, supplier U undercuts R when the demand type is l, whereas R undercuts U when the demand type is h. We can show that no pure strategy can be sustainable on the equilibrium. Similar to the above two sub-cases, below, we construct a mixed strategy equilibrium for U and R and define the range of prices for U and R as $\left[\underline{p}_U, \bar{p}_U\right]$, and $\left[\underline{p}_R, \bar{p}_R\right]$, respectively.

Construction of the mixed strategy equilibrium: Next, we construct a mixed strategy equilibrium, where U and R mix their prices in $\left[\underline{p}_U, \bar{p}_U\right]$, and $\left[\underline{p}_R, \bar{p}_R\right]$, respectively. Below, we construct the mixing distributions for U and R, denoted by F_U and F_R, respectively. In the construction, we need the following two functions:

$$g_R^h(p_U) = \alpha p_U - c_U + c_R + k_U^h - k_R^h \text{ and } g_U^h(p_R) = \frac{c_U + p_R - (c_R + k_U^h - k_R^h)}{\alpha}$$

Note that these functions are inverse of each other and map a $p_U \in \left[\underline{p}_U, \bar{p}_U\right]$ to a $p_R \in \left[\underline{p}_R, \bar{p}_R\right]$ such that p_U undercuts p_R (resp. p_R undercuts p_U) if and only if $p_U \leq g_U^h(p_R)$ (resp. $p_R \leq g_R^h(p_U)$). In order for a mixed strategy to be sustainable on the equilibrium, it should give same profit for all price points within the mixing range. This leads to the following equation for F_R:

$$r^h(\alpha p_U - c_U)(1 - F_R(g_R^h(p_U))) + r^l(\alpha p_U - c_U) = r^l(\alpha \overline{p}_U - c_U)$$

Note that first and second terms capture U's expected profits for the cases of $\phi = h$ and $\phi = l$. Solving this equation for F_R and transforming the variable from p_U to p_R using the inverse of $g_R^h(p_U)$, we obtain mixing distribution for R as follows:

$$F_R(p_R) = \frac{1}{r^h}\left(1 - \frac{r^l(\overline{p}_R - (c_R + k_U^h - k_R^h))}{p_R - (c_R + k_U^h - k_R^h)}\right) \text{ for } p_R \in \left[\underline{p}_R, \overline{p}_R\right]$$

Note that $F_R = 1$ when $p_R = \overline{p}_R$. We will now derive supplier U's mixing distribution. Again, using the fact that supplier R should obtain same profit within the mixing region, we can express probability distribution function F_U as follows:

$$r^h(p_R - c_R)(1 - F_U(g_U^h(p_R)) = r^h(\underline{p}_R - c_R)$$

Note that R wins the order only if $p_U \leq g_U^h(p_R)$ and $\phi = h$. Therefore, the above equation consists of only one term which represents R's expected profit when $\phi = h$. Solving this equation for F_U and transforming the variable from p_R to p_U using the inverse of $g_U^h(p_R)$, we obtain mixing distribution for U as follows:

$$F_U(p_U) = 1 - \frac{\alpha \underline{p}_U - c_U + k_U^h - k_R^h}{(\alpha p_U - c_U) + k_U^h - k_R^h} \text{ for } p_U \in \left[\underline{p}_U, \overline{p}_U\right]$$

Note that $F_U(\underline{p}_U) = 0$, and $F_U(\overline{p}_U) < 1$, which implies that there is a probability mass μ at $\overline{p}_U$ and it is equal to $\mu = 1 - F_U(\overline{p}_U) = \frac{(\alpha \underline{p}_U - c_U) + k_U^h - k_R^h}{(\alpha \overline{p}_U - c_U) + k_U^h - k_R^h}$. As we discussed before, $\overline{p}_U$ can never be greater than $\left[\frac{c_U + k_I^l - k_U^l}{\alpha}\right]^{(-)}$, otherwise l-type buyer allocate the order to insourcing option. Using the relation between p_U and p_R via g_R^h function, we can map $\overline{p}_U$ to $\overline{p}_R$. Therefore, we can set upper bounds for U and R's mixing ranges as follows: $\overline{p}_U = \frac{c_U + k_I^l - k_U^l}{\alpha}$ and $\overline{p}_R = c_R + k_U^h - k_R^h + k_I^l - k_U^l$. Also R does not deviate profitably from the specified mixed strategy equilibrium. This implies that R can not increase her profit by undercutting U for l-type demand. Using the relation $g_R^l(p_U) = (\alpha p_U - c_U) + c_R + k_U^l - k_R^l$, we can find that R starts undercutting U if she charges less than $g_R^l(\bar{p}_U) = (\alpha \bar{p}_U - c_U) + c_R + k_U^l - k_R^l = c_R + k_I^l - k_R^l$. Indeed, if she charges just epsilon below $g_R^l(\bar{p}_U)$, she will win the order with probability $r^h + r^l \frac{\underline{p}_R - c_R}{\bar{p}_R - c_R}$. Her profit would, then, be equal to

$$(g_R^l(\bar{p}_U) - c_R)\left(r^h + r^l \frac{\underline{p}_R - c_R}{\bar{p}_R - c_R}\right) = (k_I^l - k_R^l)\left(r^h + r^l \frac{\underline{p}_R - c_R}{k_U^h - k_R^h + k_I^l - k_U^l}\right) \tag{5}$$

Note that if she does not deviate, her profit would be equal to

$$r^h(\underline{p}_R - c_R) \tag{6}$$

Comparing Eqs. (5) and (6), we obtain the following condition for $\underline{p}_R$:

$$r^h(\underline{p}_R - c_R) \geq (k_I^l - k_R^l)\left(r^h + r^l \frac{\underline{p}_R - c_R}{k_U^h - k_R^h + k_I^l - k_U^l}\right)$$

Also, R's profit decreases as she decreases her price even below $g_R^l(\bar{p}_U)$ because as she decreases her price, even if she increases her chance to win the order, she lowers her profit margin and therefore loses on all the units that she receives. Finally, by using the fact that $F_R(\underline{p}_R) \geq 0$, we obtain $\underline{p}_R \geq r^l \overline{p}_R + r^h(c_R + k_U^h - k_R^h) = (c_R + k_U^h - k_R^h) + r^l(k_I^l - k_U^l)$. Combining these two inequalities, we can derive the expression for $\underline{p}_R$ as follows:

$$\underline{p}_R = c_R + k_U^h - k_R^h + \tau(k_I^l - k_U^l)$$

where $\tau = \max(r^l, \bar{\tau})$, and $\bar{\tau}$ solves the following equation:

$$r^h(k_U^h - k_R^h + \tau(k_I^l - k_U^l)) = (k_I^l - k_R^l)\left(r^h + r^l \frac{k_U^h - k_R^h + \tau(k_I^l - k_U^l)}{k_U^h - k_R^h + k_I^l - k_U^l}\right)$$

Next, using the relation between p_U and p_R via $g_R^h(\cdot)$ function, we can map $\underline{p}_R$ to $\underline{p}_U$: $\underline{p}_U = \left(\frac{c_U + \tau(k_I^l - k_U^l)}{\alpha}\right)$. Now, we obtain the equilibrium profits and cost for the suppliers and buyer. Suppliers U and R's profit on the equilibrium can be derived quickly from the construction of the mixed equilibrium strategy as follows: $\pi_U^{\theta*} = r^l(\alpha\overline{p}_U - c_U) = r^l(k_I^l - k_U^l)$ and $\pi_R^* = r^h(\underline{p}_R - c_R) = r^h(k_U^h - k_R^h) + r^h\tau(k_I^l - k_U^l)$. Now, we derive the total cost of the buyer. Buyer of type $\phi = l$ never chooses the supplier R because the construction of equilibrium, hence he allocates always to supplier U. Given that l-type buyer pays p_U, his expected cost is equal to $p^l = k_U^l(p_U)$. We can express F_U in terms p^l by using the inverse of k_U^l as follows:

$$F_U(p^l) = 1 - \frac{\underline{p} - k_R^h + k_U^h - k_U^l}{p - k_R^h + k_U^h - k_U^l} \text{ for } p \in \left[\underline{p}^l, \overline{p}^l\right]$$

where $\underline{p}^l = \tau(k_I^l - k_U^l) + k_U^l$, and $\overline{p}^l = k_I^l$. Now, l-type buyer's expected marginal cost can be found by taking the expectation of p^l with respect to $F_U(p^l)$ as follows:

$$\begin{aligned} TC^{l*} = E_{p^l} p^l = \underline{p}^l + \int_{\underline{p}^l}^{\overline{p}^l} (1 - F_U(p^l) dp^l = \underline{p}^l + \int_{\underline{p}^l}^{\overline{p}^l} \frac{\underline{p}^l + k_U^h - k_U^l - k_R^h}{p^l + k_U^h - k_U^l - k_R^h} dp^l \\ = \underline{p}^l + (\underline{p}^l + k_U^h - k_U^l - k_R^h) \ln\left(\frac{\overline{p}^l + k_U^h - k_U^l - k_R^h}{\underline{p}^l + k_U^h - k_U^l - k_R^h}\right) \end{aligned}$$

For h-type buyer, the allocation decision depends on the the comparison between p_U and p_R. As a result, h-type buyer's marginal cost is $\min(k_U^h(p_U), k_R^h(p_R))$. Therefore, we can express his cost by taking expectation of this marginal cost with respect to F_U and F_R: $TC^{h*} = E_{p_U,p_R} \min(k_U^h(p_U), k_R^h(p_R))$. To simplify the double integration, we first express p_U and p_R in terms of p^h by taking inverse of $k_U^h(p_U)$, and $k_R^h(p_R)$, respectively: $p_U = \frac{c_U + p - k_U^h}{\alpha}$ and $p_R = c_R + p - k_R^h$. Substituting above equations into $F_U(p_U)$ and $F_R(p_R)$, we can write them in terms of p^h as well: $F_U(p^h) = 1 - \frac{\underline{p}^h - k_R^h}{p^h - k_R^h}$ for $p^h \in \left[\underline{p}^h, \overline{p}^h\right]$ and $F_R(p^h) = \frac{1}{r^h}\left(1 - \frac{r^l(\overline{p}^h - k_U^h)}{p^h - k_U^h}\right)$ for $p^h \in \left[\underline{p}^h, \overline{p}^h\right]$, where $\overline{p}^h = k_U^h + k_I^l - k_U^l$, and $\underline{p}^h = k_U^h + \tau(k_I^l - k_U^l)$. Now, TC^{h*} can rewritten as follows:

$$TC^{h*} = E_{p_1^h, p_2^h} \min(p_1^h, p_2^h) \text{ where } p_1^h \sim F_U(p^h) \text{ and } p_2^h \sim F_R(p^h)$$

Let $F(p^h)$ be the cumulative distribution of minimum of two random variables, p_1^h and p_2^h. Using the fact that $x \geq p^h$ is equivalent to $x \geq p_1^h$ and $x \geq p_2^h$, we can write down $F(p^h)$ as follows:

$$F(p^h) = 1 - (1 - F_U(p^h)) \times (1 - F_R(p^h)) = 1 - \frac{r^l(\underline{p} - k_R^h)(\overline{p}^h - p^h)}{r^h(p^h - k_R^h)(p^h - k_U^h)}$$

Finally, we can formulate the closed-form expression for TC^{h*} as follows:

$$TC^{h*} = \underline{p}^h + \int_{\underline{p}^h}^{\overline{p}^h} (1 - F(p^h)) dp^h = \underline{p}^h + \int_{\underline{p}^h}^{\overline{p}^h} \frac{r^l(\underline{p}^h - k_R^h)(\overline{p}^h - p^h)}{r^h(p^h - k_R^h)(p^h - k_U^h)} dp^h = \underline{p}^h + \frac{r^l}{r^h}(\underline{p}^h - k_R^h) \int_{\underline{p}^h}^{\overline{p}^h} \frac{\overline{p}^h - p^h}{(p^h - k_R^h)(p^h - k_U^h)} dp^h$$

$$= \underline{p}^h + \frac{r^l}{r^h}(\underline{p}^h - k_R^h) \int_{\underline{p}^h}^{\overline{p}^h} \left[\frac{A}{p^h - k_R^h} + \frac{B}{p^h - k_U^h} \right] dp^h = \underline{p}^h + \frac{r^l}{r^h}(\underline{p}^h - k_R^h) \left[A \ln\left(\frac{\overline{p}^h - k_R^h}{\underline{p}^h - k_R^h} \right) + B \ln\left(\frac{\overline{p}^h - k_U^h}{\underline{p}^h - k_U^h} \right) \right]$$

where the second line above is obtained by expanding the integrand into its partial fractions with $A = \frac{\overline{p}^h - k_R^h}{k_R^h - k_U^h}$ and $B = \frac{\overline{p}^h - k_U^h}{k_U^h - k_R^h}$.

Proof of Proposition 4: We first characterize the separating equilibria in C_U and C_R:

- $(\beta^l, \beta^h) \in C_U$: Recall that in case C_U, it is l-type who has incentive to mimic and distort his forecast information in order to get a lower price from the suppliers. Therefore, in a separating equilibrium, h-type buyer needs to provide a lower bound constraint on the amount of products that will be requested from the suppliers in order to deter l-type from mimicking. Therefore, the suppliers can infer the buyer's type by comparing the level of lower bound constraints provided by l- and h-type buyers. If the level of lower bound constraint is less than a threshold, the suppliers infer that the true demand of l-type; otherwise, it is of h-type. Note that a binding lower bound constraint is of no use to l-type. Therefore, $I_F^l(1-\underline{\omega}^l) = 0$. This implies that in order to deter l-type from mimicking himself, h-type has to provide $I_F^h(1-\underline{\omega}^h) > Q$ that satisfies the following incentive compatibility condition: $(\alpha p_U^l + (1-\alpha)\beta^l)Q \le I_F^h(1-\underline{\omega}^h)\alpha p_U^h + Q(1-\alpha)\beta^l$, where lhs and rhs of the above inequality denote the expected total cost for l-type buyer when he provides $I_F^l(1-\underline{\omega}^l) = 0$ and $I_F^h(1-\underline{\omega}^h) > Q$, respectively. Simplifying the above inequality provides a threshold on $I_F^h(1-\underline{\omega}^h)$ as follows: $I_F^h(1-\underline{\omega}^h) \ge \frac{p_U^l}{p_U^h} Q$. Similarly, h-type buyer must not also mimic l-type buyer in equilibrium, which implies that $(\alpha p_U^l + (1-\alpha)\beta^h)Q \ge I_F^h(1-\underline{\omega}^h)\alpha p_U^h + Q(1-\alpha)\beta^h$. Simplifying the above inequality provides an upper bound on $I_F^h(1-\underline{\omega}^h)$ as follows: $I_F^h(1-\underline{\omega}^h) \le \frac{p_U^l}{p_U^h} Q$. Combining above two conditions leads a unique separating equilibrium with $I_F^h(1-\underline{\omega}^h) = \frac{p_U^l}{p_U^h} Q = \frac{c_R - (1-\alpha)\beta^l}{c_R - (1-\alpha)\beta^h} Q$. Note that total expected cost of the h-type buyer can be expressed as $\alpha p_U^h I_F^h(1-\underline{\omega}^h) + (1-\alpha)\beta^h Q$, where $p_U^h = \frac{c_U + k_R^h - k_U^h}{\alpha} + \left[\frac{(1-\alpha)\beta^h(1-1/I_F^h(1-\underline{\omega}^h))}{\alpha}\right]$. On the other hand, l-type buyer's expected cost is $\alpha p_U^l + (1-\alpha)\beta^l$, where $p_U^l = \frac{c_U}{\alpha} + \left[\frac{k_R^l - k_U^l}{\alpha}\right]^{(-)}$. Finally, suppliers update their beliefs on the probability of the true demand type by using the following function:

$$(\hat{r}^h, \hat{r}^l) = \begin{cases} (1,0) & \text{if } I_F(1-\underline{\omega}) \ge I_F^h(1-\underline{\omega}^h) \\ (0,1) & \text{if } I_F(1-\underline{\omega}) < I_F^h(1-\underline{\omega}^h) \end{cases}$$

- $(\beta^l, \beta^h) \in C_R$: Recall that in case C_R, h-type has incentive to mimic l-type and distort his forecast information in order to get a lower price from the suppliers. Therefore, in a separating equilibrium, l-type needs to commit to a maximum order quantity that is too costly for h-type buyer to mimic. So, l-type buyer provides an upper bound constraint $I_F^l(1+\bar{\omega}^l)$ on the amount of products requested from the suppliers. Therefore, the suppliers can infer the buyer's type by comparing the level of upper bound constraints provided by l- and h-type buyers. If the level of upper bound constraint is less than a threshold, the suppliers infer that the true demand of l-type; otherwise, it is of h-type. Note that a binding upper bound constraint is of no use to h-type. Therefore, $I_F^h(1+\bar{\omega}^h) = Q$. This implies that in order to deter h-type from mimicking himself, l-type has to provide $I_F^l(1+\bar{\omega}^l) < Q$ that satisfies the following incentive compatibility condition: $p_R^h Q \le I_F^l(1+\bar{\omega}^l)p_R^l + (Q - I_F^l(1+\bar{\omega}^l))\beta^h$, where lhs and rhs of the above inequality denote the expected total cost for h-type buyer if he provides $I_F^h(1+\bar{\omega}^h) = Q$ and $I_F^l(1+\bar{\omega}^l) < Q$, respectively. Simplifying the above inequality provides a threshold for $I_F^l(1+\bar{\omega}^l)$ for it to be a credible signal: $I_F^l(1+\bar{\omega}^l) \leq \frac{\beta^h - p_R^h}{\beta^h - p_R^l}Q$. Similarly, l-type buyer must not also mimic h-type buyer, which implies that $p_R^h Q \geq I_F^l(1+\bar{\omega}^l)p_R^l + (Q - I_F^l(1+\bar{\omega}^l))\beta^l$. Simplifying the above inequality provides a lower bound on $I_F^l(1+\bar{\omega}^l)$ as follows: $I_F^l(1+\bar{\omega}^l) \geq \frac{\beta^l - p_R^h}{\beta^l - p_R^l}Q$ Note that $\frac{\beta^l - p_R^h}{\beta^l - p_R^l}$ is less than $\frac{\beta^h - p_R^h}{\beta^h - p_R^l}$ due to the fact that $\beta^l \leq \beta^h$ and $p_R^l \leq p_R^h$. Therefore, any solution that satisfies the following condition also satisfies the incentive compatibility conditions for l- and h-type buyers: $Q\frac{\beta^l - p_R^h}{\beta^l - p_R^l} \leq I_F^l(1+\bar{\omega}^l) \leq Q\frac{\beta^h - p_R^h}{\beta^h - p_R^l}$. But note that since h-type buyer's expected cost is independent of $I_F^l(1+\bar{\omega}^l)$, whereas l-type buyer's expected cost decreases in $I_F^l(1+\bar{\omega}^l)$, $I_F^l(1+\bar{\omega}^l) = Q\frac{\beta^h - p_R^h}{\beta^h - p_R^l}$ is the least-costly credible signal for the l-type buyer. We can simplify this solution as follows:

$$I_F^l(1+\bar{\omega}^l) = \left[\frac{\beta^h - p_R^h}{\beta^h - p_R^l}\right] Q = \left[\frac{1 + (\beta^l - c_U/\alpha)/(\beta^h - \beta^l)}{1/\alpha + (\beta^l - c_U/\alpha)/(\beta^h - \beta^l)}\right] Q$$

Since the suppliers correctly infer the true demand type, the equilibrium prices will become exactly same as symmetric information setting. Furthermore, the expected cost for l-type buyer will be equal to $p_R^l I_F^l(1+\bar{\omega}^l) + \beta^l(Q - I_F^l(1+\bar{\omega}^l))$, where $p_R^l = c_R - k_U^l - k_R^l$. On the other hand, expected cost for h-type buyer is equal to $p_R^h Q$, where $p_R^h = c_R - k_U^h - k_R^h$. Finally, suppliers update their beliefs about the probability of true type of demand by using the following function:

$$(\hat{r}^h, \hat{r}^l) = \begin{cases} (1,0) & \text{if } I_F(1+\bar{\omega}) > I_F^l(1+\bar{\omega}^l) \\ (0,1) & \text{if } I_F(1+\bar{\omega}) \leq I_F^l(1+\bar{\omega}^l) \end{cases}$$

Next, we show that separating equilibrium is not sustainable in C_{UR}. Recall that under symmetric information scenario, supplier R wins the order if the true forecast type is h and U wins the order if it is l. The equilibrium prices for h-type buyer are $p_R^h = c_R + k_U^h - k_R^h$ and $p_U^h = c_U/\alpha$ and those for l-type buyer are $p_R^l = c_R$ and $p_U^l = c_U/\alpha + (k_R^l - k_U^l)/\alpha$. Since $k_U^h - k_R^h \geq 0$ and $k_R^l - k_U^l \geq 0$, we can conclude that $p_R^h \geq p_R^l$ and $p_U^h \leq p_U^l$. This implies that h-type buyer has incentive to mimic l-type, whereas l-type buyer has incentive to mimic h-type. In order to deter both types from imitating each other's strategies, l-type buyer needs to provide an upper bound constraint $I_F^l(1+\bar{\omega}^l) < Q$, whereas h-type buyer provides a lower bound constraint $I_F^h(1-\underline{\omega}^h) > Q$. We can confirm that if $I_F^l(1+\bar{\omega}^l)$ is offered by the l-type buyer, the resulting equilibrium prices will be equal to $p_R^l = c_R$ and $p_U^l = c_U/\alpha + (k_R^l - k_U^l)/\alpha$. However, if $I_F^h(1-\underline{\omega}^h)$ is offered by the h-type buyer, there exists a profitable deviation from the above symmetric equilibrium prices $p_R^h = c_R + k_U^h - k_R^h$ and $p_U^h = c_U/\alpha$. This can be shown as follows. Given $p_R^h = c_R + k_U^h - k_R^h$ and $p_U^h = c_U/\alpha$, supplier U is undercut by R for the first Q units because $k_R(p_R^h) \cdot Q < k_U^h(p_U^h) \cdot Q$, where the lhs and rhs denote for buyer's expected total cost for the first Q units if he procures from U and R, respectively. However, U undercuts R for the remaining $I_F^h(1-\underline{\omega}^h) - Q$ units because $\alpha p_U^h(I_F^h(1-\underline{\omega}^h) - Q) \leq p_R^h(I_F^h(1-\underline{\omega}^h) - Q)$, where the lhs and rhs denote for buyer's expected residual cost for the remainder $I_F^h(1-\underline{\omega}^h) - Q$ units if he procures from U and R, respectively. Therefore, supplier U has incentive to increase her price from $p_U^h = c_U/\alpha$ to the price p_R^h that undercuts supplier R. Anticipating this increase, supplier R also has incentive to increase her price because p_R^h was intended to undercut supplier U assuming that U would charge $p_U^h = c_U/\alpha$. This argument proves that there does not exist a sustainable price pair for supplier U and R in equilibrium when h-type buyer commits himself to a maximum order quantity $I_F^h(1-\underline{\omega}^h) > Q$.

Proof of Proposition 5: We first compare the equilibrium prices under RFQ^n between symmetric and asymmetric information settings:

- $(\beta^l, \beta^h) \in C_U$: We divide the analysis into two sub-cases:

—If $r^l \le \frac{k_R^h - k_U^h}{k_R^l - k_U^l}$: The comparison of equilibrium prices between Proposition 1 and Proposition 3 shows that h-type buyer would pay same price under both symmetric and asymmetric settings. However, l-type pays less in asymmetric information setting.

—If $r^l > \frac{k_R^h - k_U^h}{k_R^l - k_U^l}$: As shown in Proposition 1, h-type pays $\left[\frac{c_U}{\alpha} + \frac{k_R^h - k_U^h}{\alpha}\right]^{(-)}$ to the supplier U under symmetric information setting. However, as shown in Proposition 3, under asymmetric information, she pays at least $\underline{p}_U$ to the supplier U and $\underline{p}_R$ to the supplier R, where both prices are greater than their counterparts in the symmetric information scenario. Hence, the equilibrium price seen by h-type buyer in asymmetric information setting is always greater than that in symmetric information setting. Next, we consider l-type buyer. Under asymmetric information scenario, he only procures from U and pays at least $\underline{p}_U = \frac{c_U}{\alpha} + \tau\frac{k_I^l - k_U^l}{\alpha}$ and at most $\bar{p}_U = \frac{c_U}{\alpha} + \frac{k_I^l - k_U^l}{\alpha}$. From Proposition 1, we know that under symmetric information, l-type pays exactly $p_U^* = \left[\frac{c_U}{\alpha} + \frac{k_R^l - k_U^l}{\alpha}\right]^{(-)}$. Hence, since p_U^* can be shown to be between $\underline{p}_U$ and $\bar{p}_U$, the equilibrium price seen by l-type buyer under asymmetric information can be either more or less than that under symmetric information.

- $(\beta^l, \beta^h) \in C_R$: We divide the analysis into two sub-cases:

—If $r^h \le \frac{k_U^l - k_R^l}{k_U^h - k_R^h}$: The comparison of equilibrium prices between Proposition 1 and Proposition 3 shows that l-type buyer would pay same price under both symmetric and asymmetric settings. However, h-type pays less in asymmetric information setting.

—If $r^h > \frac{k_U^l - k_R^l}{k_U^h - k_R^h}$: As shown in Proposition 1, both h- and l-type buyer pays exactly c_U in symmetric information setting and more than c_U in asymmetric information setting. Hence, the prices seen by both l- and h-type increase with asymmetric information.

- $(\beta^l, \beta^h) \in C_{UR}$: The proof for C_{UR} is very similar to the proof for C_U. More specifically, h-type always pays less more under asymmetric information setting, whereas l-type may pay more or less depending on how p_U^* compares to $\underline{p}_U$ and $\bar{p}_U$.

Next, we compare the order quantities under RFQ^r between symmetric and asymmetric settings. Note that as characterized in Proposition 4, $I_F^h(1 - \underline{\omega}^h) = \frac{c_R - (1-\alpha)\beta^l}{c_R - (1-\alpha)\beta^h} Q > Q$ and $I_F^l(1 + \bar{\omega}^l) = \frac{1 + (\beta^l - c_U/\alpha)/(\beta^h - \beta^l)}{1/\alpha + (\beta^l - c_U/\alpha)/(\beta^h - \beta^l)} Q < Q$. This implies that the equilibrium order quantity under asymmetric information setting is more (resp., less) than that under symmetric information in C_U (resp., C_R).

Proof of Proposition 6: In this proposition, we prove the impact of RFQ^n and RFQ^r on the expected cost and profits. First, note that RFQ^n and RFQ^r models yield same equilibrium in region C_{UR}. Therefore, we consider only C_U and C_R:

- $(\beta^l, \beta^h) \in C_U$: We divide the analysis into two sub-cases:

—If $(\beta^l, \beta^h) \in C_U^1$, i.e., $r^l \le \frac{k_R^h - k_U^h}{k_R^l - k_U^l}$: The comparison of equilibrium prices and order quantities between Proposition 3 and Proposition 4 implies that both l and h-type buyers would strictly benefit from RFQ^n

because of the following different reasons. Specifically, l-type benefits from RFQ^n because it allows him to hide behind h-type buyer and lower the price charged by supplier U. And, h-type benefits because it allows him to get a competitive price without incurring a costly signal. On the other side, supplier U is strictly worse off with RFQ^n because she cannot price-differentiate l-type from h-type, which causes her to charge a uniform price low enough to cover both demand scenarios. Finally, supplier R is indifferent between RFQ^n and RFQ^r .

—If $(\beta^l, \beta^h) \in C_U^2$, i.e., $r^l > \frac{k_R^h - k_U^h}{k_R^l - k_U^l}$: In this sub-case, each model (RFQ^n and RFQ^r) has its own pros and cons for both l- and h-type buyer. Consider h-type buyer. A RFQ^r enables him to get a competitive price from supplier U but he has to incur a signalling cost. Therefore, whether he benefits from a RFQ^r depends on the comparison between its cost (due to signalling) and benefit (due to reduction in price). More specifically, if $\Delta_1^h = TC_{QF}^h - TC_{NC}^h \geq 0$, he is better off with RFQ^n; otherwise, he benefits from a RFQ^r, where TC_N^h, and TC_S^h are characterized in Propositions 3 and 4, respectively. Now, consider l-type buyer. Recall that l-type buyer does not incur any signalling cost under RFQ^r. However, as we have shown in Proposition 5, a RFQ^r may actually increase or decrease the price seen by l-type compared to RFQ^n. If it increases, i.e., $\Delta_1^l = TC_S^l - TC_N^l \geq 0$, he is better off with RFQ^r; otherwise, he benefits from a RFQ^r, where TC_N^l, and TC_S^l are characterized in Propositions 3 and 4, respectively. Next, we consider the suppliers U and R. First of all, supplier R is always better off with RFQ^n because she would always be undercut by supplier U when demand information is credible signalled (i.e., RFQ^r), however, she would obtain non-zero expected profit under RFQ^n. On the other hand, supplier U's profit may increase or decrease with RFQ^n. Namely, off $\Delta_U = \pi_U^{N*} - \pi_U^{S*} \geq 0$, where where π_U^{N*}, and π_U^{S*} are characterized in Propositions 3 and 4, respectively, she would benefit from RFQ^n even though she shares the order with R because RFQ^n enables her to increase her price.

- $(\beta^l, \beta^h) \in C_R$: Similarly, we divide the analysis into two sub-cases:

—If $(\beta^l, \beta^h) \in C_R^1$, i.e., $r^h \leq \frac{k_U^l - k_R^l}{k_U^h - k_R^h}$: The proof for this sub-case is very similar to C_U^1, hence, it is omitted.

—If $(\beta^l, \beta^h) \in C_R^2$, i.e., $r^h > \frac{k_U^l - k_R^l}{k_U^h - k_R^h}$: The proof for this sub-case is very similar to C_U^2, except for h-type buyer. He is always better off with a RFQ^r because (i) first, he does not incur any signalling cost and (ii) second, he has to pay more under RFQ^n compared to RFQ^r as shown in Proposition 5.