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Dynamic Bargaining in a Supply Chain with Asymmetric Demand Information

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We analyze a dynamic bargaining game in which a seller and a buyer negotiate over quantity and payment to trade for a product. Both firms are impatient, and they make alternating offers until an agreement is reached. The buyer is privately informed about his type, which can be high or low: the high type's demand is stochastically larger than the low type's. In the dynamic negotiation process, the seller can screen, whereas the buyer can signal information through their offers, and the buyer has an *endogenous* and *type-dependent* reservation profit. With rational assumptions on the seller's belief structure, we characterize the perfect Bayesian equilibrium of the bargaining game. Interestingly, we find that both quantity distortion and information rent may be avoided depending on the firms' relative patience, and the seller may reach an agreement with either the high type or the low type first, or with both simultaneously. Furthermore, we explore our model to characterize the effect of demand forecasting accuracy on firm profitability. We find that improved demand forecast benefits the buyer but hurts the seller when the buyer's forecasting accuracy is low. However, once the buyer's forecasting accuracy exceeds a threshold, both firms will benefit from further improvement of the forecast. This observation makes an interesting contrast to previous findings based on the one-shot principal–agent model, in which improvement of forecasting accuracy mostly leads to a win–lose outcome for the two firms, and the buyer has an incentive to improve his forecasting accuracy only when it is extremely low.

Keywords: dynamic bargaining; asymmetric information; screening; signaling; forecasting accuracy
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1. Introduction

Asymmetric information often arises in the process of supply chain contracting. For instance, retailers with point-of-sale data are better positioned to forecast future market demand than manufacturers. Retailers' advantageous access to demand information may allow them to obtain favorable pricing from manufacturers. Likewise, manufacturers may hold proprietary cost or inventory information, which gives them to an edge in negotiating with retailers. To alleviate the effect of information asymmetry, the supply chain literature shows that by using structured contracts, firms can induce their opponents to reveal private information. But most of the existing supply chain studies adopt the principal–agent framework. Under this framework, the uninformed principal has the dominating power to dictate contractual terms, whereas the informed agent takes a rather passive role, for he can either accept the principal's offer or walk away from the deal. This framework seems to be at odds with the fact that procurement contract negotiations are commonly observed in a range of industries including the semiconductor, medical, automobile, agricultural, and construction industries (see, e.g., Bajari et al. 2009). In a typical negotiation, firms go through rounds of offers and counteroffers to reach an agreement on price, quantity, or delivery schedule. This negotiation process provides an opportunity for firms to learn about each other's private information. Apparently, the static principal–agent framework offers little insight into firms' dynamic negotiation behaviors and their incentives to hide or reveal information as a negotiation unfolds.

To understand dynamic negotiations in the supply chain, we adopt a *noncooperative bargaining* approach to study a newsvendor contracting problem under asymmetric demand information. In our model, a buyer intends to procure a product from a seller for a future sale with uncertain demand. Relative to the seller, the buyer has better information about the demand state,

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which is one of two types: the high type's demand is stochastically larger than the low type's. The buyer and the seller negotiate over both quantity and payment in a dynamic alternating-offer game, with the seller making the initial offer. Both parties are impatient, which is reflected by their time preferences or their perceived risks of negotiation breakdown.

Given the game structure of alternating offers and one-sided asymmetric information, the dynamic bargaining game features both signaling (from the perspective of the buyer) and screening (from the perspective of the seller). A distinctive element of the model is that the informed buyer has an *endogenous type-dependent* reservation profit, which depends on the two parties' negotiation strategies. In our model, the high-type buyer may have an incentive to mimic the low type, but not vice versa. When she believes that the buyer is likely to be the high type, the seller will demand a high payment. Hence, to avoid being misidentified and paying too much to the seller, the low-type buyer may significantly downward distort his order quantity when making a counteroffer so as to hinder the high type from mimicking. From the seller's perspective, she has the choice of *screening* the types through sequential agreement. To screen, the seller can make an offer acceptable to only one type, thereby forcing the other type to counteroffer and reveal his information. This screening strategy subjects the seller to a reduced profit as a result of potential distortion, rents, and delay in reaching an agreement. And thus the seller may also offer a contract acceptable to both buyer types to strike a deal immediately.

We characterize the bargaining outcome as a perfect Bayesian equilibrium. We find that an agreement is reached after at most two rounds of negotiations. The equilibrium structure is driven by two key factors: the firms' relative patience and the prior probability of the high-type buyer. In general, relatively high buyer patience or high prior probability of the high type tends to give rise to a separating equilibrium in which the seller settles with the two types sequentially in two consecutive rounds. In contrast, relatively low buyer patience or low prior probability of the high type tends to result in a pooling equilibrium in which the seller reaches an agreement with both buyer types in the first round.

This dynamic bargaining game gives rise to interesting outcomes that sharply contrast with those under the static principal–agent framework. First, one-sided asymmetric information does not necessarily induce quantity distortion. In particular, when the buyer has a relatively high patience level, both buyer types may agree to the first-best order quantity of their own. Second, the buyer's private information is not necessarily revealed to the seller in equilibrium. This happens when the seller finds it too costly to screen the buyer's type because of the severe quantity distortion needed and thus prefers to offer a contract acceptable to both buyer types. Third, the high-type buyer does not always earn an information rent. For instance, the low type may signal his information through his counteroffer, which leaves the high type no choice but to accept the seller's offer at his first-best order quantity and payment. The seller may also choose to settle with the low type first by offering a screening contract with downward distortion. In this case, the high type reveals his information by rejecting the contract and thus forgoes any information rent.

We further explore the dynamic bargaining model to analyze the effect of demand forecasting accuracy on firm profitability. We find that the buyer's increased forecasting accuracy will dampen the high type's incentive to mimic the low type. Moreover, improved demand forecast benefits the buyer but hurts the seller when the buyer's forecasting accuracy is low. When the buyer's forecasting accuracy exceeds a certain level, however, further improvement can lead to increased profits for both firms. Moreover, such a win–win outcome is likely to arise for either a high-margin, low-demand product or a low-margin, high-demand product. These findings differ from those derived using the one-shot principal–agent framework. For instance, Taylor and Xiao (2010) find that when the supply chain efficiency gain from better demand forecast is disproportionately captured by the manufacturer, the retailer has no incentive to improve forecasting accuracy except when it is extremely low. Furthermore, their model predicts that improved demand forecast mostly leads to a win–lose outcome for the two firms.

The remainder of our paper is organized as follows. Section 2 reviews the related literature, and §3 introduces the model. Section 4 presents the analysis of the bargaining equilibrium. Based on the equilibrium analysis, we derive managerial insights in §5 and investigate the effect of demand forecasting accuracy in §6. Section 7 concludes the study.

2. Literature Review

Our paper lies at the intersection of two literatures: noncooperative bargaining theory and supply chain contracting under asymmetric information. The theory of bargaining traces its lineage back to Nash (1950), who models cooperative bilateral bargaining as an optimization problem and selects a Pareto-efficient outcome—namely, the Nash bargaining solution. As a seminal paper of the noncooperative bargaining literature, Rubinstein (1982) shows that in an infinite-horizon alternating-offer game there exists a unique subgame perfect equilibrium in which a Pareto-efficient agreement is reached in the first period. Several papers subsequent to Rubinstein (1982) incorporate information

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asymmetry in dynamic negotiations (for a comprehensive survey, see Ausubel et al. 2002). Rubinstein (1985a) considers a setting where one party has private knowledge about his own time preference, which can be one of two types. Unlike the complete-information game, he finds that there is a continuum of pure-strategy sequential equilibria. By imposing restrictions on the uninformed party's belief, he selects a unique equilibrium. In general, dynamic bargaining games with asymmetric information do not have unique equilibrium, and the choice of beliefs matters to the equilibrium outcomes (see, e.g., Rubinstein 1985b, Bikhchandani 1992). Grossman and Perry (1986) extend Rubinstein (1985a) by allowing a continuous type distribution. They conclude that there can be significant delay in reaching an agreement. In contrast, Admati and Perry (1987) allow the informed party to choose when to make a counteroffer. This enables the informed party to signal his type by delaying his counteroffer. Gul and Sonneschein (1988) and Ausubel and Deneckere (1992), however, suggest that delay in settlement may not always happen. In particular, when the time interval between offers becomes sufficiently small, the uniformed party is willing to give up most of the trade surplus and thus settles a deal with the informed party immediately. This is the so-called Coase conjecture in dynamic bargaining processes under asymmetric information.

Most of the existing literature on dynamic bargaining under asymmetric information, including the aforementioned ones, studies *one-dimensional* bargaining problems in which two players negotiate over how to divide a *fixed* pie (i.e., trade surplus). An important feature of such problems lies in the fact that an efficient type of the informed party *always* has an incentive to imitate an inefficient type, and thus it is impossible for the uninformed party to settle a deal with an inefficient type before she does so with an efficient type. The problem becomes very different in *two-dimensional* bargaining settings in which two contractual terms are to be negotiated—one term endogenously determines the trade surplus and the other determines how to split it. In this case, the efficient type of the informed party may or may not lie depending on the players' *relative patience levels*. These considerations impose significant analytical challenges. Several papers investigate two-dimensional bargaining problems under certain simplifying assumptions. For example, Wang (1998) considers a one-sided offer game in which the uninformed party can offer contract menus, whereas the informed party can only choose to accept one contract or reject the entire menu. He shows that the equilibrium coincides with the optimal mechanism obtained from the static principal–agent model. This observation, however, does not hold in an alternating-offer game. Sen (2000) analyzes a problem in which the uninformed party offers contract menus while the informed party counteroffers a single contract. By imposing a series of conditions on equilibrium beliefs, he derives a unique stationary equilibrium that is independent of the history of offers. In this equilibrium, the uninformed party may settle with both types by offering a contract menu or with only the efficient type by offering a single contract in the first round. Inderst (2002) studies a similar problem with the assumption that the informed party's counteroffer is always the first-best contract. His analysis of the uniformed party's screening problem suggests that system inefficiency reduces as the informed party becomes more patient relative to the uninformed party. Inderst (2003) further extends the model to allow both parties to offer contract menus. He focuses on a special case where the informed party will always truthfully reveal his type. Consequently, the first-best contract menu is offered and agreed to in the first round.

In contrast to the above studies, we do not impose restrictive assumptions on the contracts offered by the two parties engaged in the negotiation, and we consider the entire feasible range of their patience levels such that the informed party may or may not have an incentive to reveal his private information. We show that information can be revealed through not only signaling by the informed party but also screening by the uninformed party or through both approaches. Signaling and screening are generally costly in the sense that they imply a reduced profit as a result of deviation from the first-best contracts. The combination of these two can give rise to interesting equilibrium behaviors. For example, in our study, when she shares only part of the information revelation cost, the uninformed party may strike a deal with an inefficient type before doing so with an efficient type.

Our paper also contributes to the growing research area that applies bargaining theory to operations management (OM) problems (e.g., Van Mieghem 1999; Wu 2004; Plambeck and Taylor 2005; Gurnani and Shi 2006; Nagarajan and Bassok 2008; Kuo et al. 2011; Feng and Lu 2012, 2013a, b). The majority of these research studies adopt the cooperative approach and apply the Nash bargaining solution (see also a comprehensive survey by Nagarajan and Sošić 2008). To the best of our knowledge, theoretical exploration of dynamic noncooperative bargaining under asymmetric information is absent in the OM literature.

Aside from bargaining, our paper naturally contributes to the literature of supply chain contracting under asymmetric information. The vast majority of contracting papers adopt the principal–agent framework to study either a screening or a signaling problem (see reviews by Cachon 2003, Chen 2003). Papers with screening models often feature asymmetric information

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on demand, cost, or inventory. They aim to design efficient contracts to achieve coordination between supply chain members (e.g., Corbett 2001, Ha 2001, Corbett et al. 2004, Cachon and Zhang 2006, Burnetas et al. 2007, Hutze and Özer 2008, Zhang 2010). Papers with signaling models have studied how private demand information can be credibly shared between supply chain members (e.g., Cachon and Lariviere 2001, Özer and Wei 2006) and how information accuracy and disclosure affect firm profitability (e.g., Taylor and Xiao 2010, Kostamis and Duenyas 2011). In contrast to these studies, our dynamic bargaining model features both screening and signaling. More importantly, the balanced negotiation power between the supply chain firms in our model gives rise to interesting contracting outcomes that contrast sharply with previous findings derived from the principal–agent model (see our detailed discussion in §1).

Very few papers in the supply chain literature study dynamic principal–agent models with asymmetric information. Zhang and Zenios (2008) and Zhang et al. (2010) study dynamic screening models with Markovian property. Oh and Özer (2013) investigate a supplier's mechanism design problem to screen a manufacturer's private demand information under dynamic evolutions of demand forecasts. In contrast, our bargaining game with alternating offers features both screening and signaling in a dynamic setting.

3. The Model

We consider a buyer (he) who procures a product from a seller (she) for a selling event. The buyer charges a fixed retail price r per unit, and the seller incurs a unit production cost c. To ensure trade always occurs in equilibrium, we assume $r > c$. The buyer's stocking decision and the seller's production need to be carried out before the demand is realized. There is no replenishment opportunity afterward, and thus any excess demand is lost. In the case of overage, the leftover inventory has zero value. Such a setting is appropriate for a seasonal product with a long replenishment lead time and a short selling horizon.

We assume that the buyer privately obtains a demand signal, $I = i$, before deciding on the stocking level. Ex ante, the signal can be either high ($i = H$) with probability $\beta \in (0, 1)$ or low ($i = L$) with probability $1 - \beta$. The demand conditional on $I = i$ is a nonnegative random variable X_i with a continuous and strictly increasing distribution $F_i(\cdot)$ over $\mathscr{X} \subseteq \mathbb{R}^+$ and a density function $f_i(\cdot)$. Signal H implies a stochastically larger demand than signal L; i.e., $F_H(x) \le F_L(x)$ for all $x \in \mathscr{X}$. Except for this demand signal, all model elements are assumed to be common knowledge.

After observing the signal, the buyer negotiates with the seller over a quantity q to be delivered by the seller and a transfer payment T to be paid to the seller. We adopt an alternating-offer game for the negotiation process and index each round of negotiation by τ ($\tau = 1, 2, \ldots$). If no agreement has been reached prior to round τ, then one party offers a contract to the other party, and the latter responds with either acceptance or rejection. If the offer is accepted, then the corresponding contract is executed; if, however, the offer is rejected, then the negotiation evolves to the next round, in which the roles of the two parties are exchanged. Specifically, we assume that the negotiation starts with the seller making an offer in the first round.

We use $\delta_B \in (0, 1)$ and $\delta_S \in (0, 1)$ to denote the buyer's and the seller's patience in the negotiation, respectively. The patience level δ_k, $k = B, S$, can be interpreted as a discount factor (that captures all the costs due to delay in agreement) and/or a perceived risk of negotiation breakdown (Binmore et al. 1986). To make it explicit, suppose that firm k has a discount rate α_k and believes that the negotiation will be terminated in exponentially distributed time at rate λ_k. Then, $\delta_k = e^{-(\alpha_k+\lambda_k)\Delta t}$, where Δt is the length of one round of negotiation. In our subsequent analysis, we focus on the pure-strategy perfect Bayesian equilibrium, in which the seller and both buyer types participate in the trade.

4. The Bargaining Equilibrium

In this section, we conduct equilibrium analysis and start by establishing the first-best benchmark.

4.1. The First-Best Benchmark

The first-best benchmark is the bargaining equilibrium under complete information. Let $\bar{F}_i(x) = 1 - F_i(x)$, $i \in \{H, L\}$. Given any quantity q, the expected revenue of the i-type buyer is $R_i(q) = r\,\mathbb{E}[\min(q, X_i)] = r\int_0^q \bar{F}_i(x)\,dx$. Subtracting the seller's production cost cq, we obtain the total trade surplus, $\pi_i(q) = R_i(q) - cq$, which is maximized at $\hat{q}_i \equiv \bar{F}_i^{-1}(c/r)$. Define $\hat{\pi}_i \equiv R_i(\hat{q}_i) - c\hat{q}_i$ as the maximum trade surplus when the buyer's type is i. Under complete information, the order quantity must be equal to $\hat{q}_i$, and the bargaining problem boils down to finding an equilibrium payment $\hat{T}_i$ to allocate $\hat{\pi}_i$. As such, the complete-information bargaining game becomes the classical Rubinstein (1982) strategic bargaining problem, and the equilibrium is characterized as follows.

Proposition 1. *Under complete information, there exists a unique subgame perfect equilibrium in which the seller offers* $(\hat{q}_i^S, \hat{T}_i^S) \equiv (\hat{q}_i, ((1-\delta_B)/(1-\delta_B\delta_S))\hat{\pi}_i + c\hat{q}_i)$ *given the buyer's type* $i \in \{H, L\}$, *which is accepted immediately by the buyer. In equilibrium, the seller's profit is* $\hat{\pi}^S = ((1-\delta_B)/(1-\delta_B\delta_S))[\beta\hat{\pi}_H + (1-\beta)\hat{\pi}_L]$, *and the i-type buyer's profit is* $\hat{\pi}_i^B = (\delta_B(1-\delta_S)/(1-\delta_B\delta_S))\hat{\pi}_i$.

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All proofs are provided in Online Appendix A (see online appendices at http://ssrn.com/abstract=2403991). The above proposition provides the solution for a negotiation initiated by the seller, i.e., with the seller making the first offer. For a buyer-initiated negotiation, we can similarly obtain the solution $(\hat{q}_i^B, \hat{T}_i^B) \equiv (\hat{q}_i, ((\delta_S(1-\delta_B))/(1-\delta_B\delta_S))\hat{\pi}_i + c\hat{q}_i)$. Notice that the seller's share of the trade surplus is equal to $(1-\delta_B)/(1-\delta_B\delta_S)$ when she makes the first offer, whereas it becomes $(\delta_S(1-\delta_B))/(1-\delta_B\delta_S)$ when the buyer makes the first offer. The higher share in the former setting is due to the seller's first-mover advantage. These solutions will be useful for our subsequent analysis.

4.2. The Buyer's Truth-Telling Conditions

With private demand information, the buyer may choose to hide it to gain an advantage in the negotiation. It is well known that in the classical principal–agent setting (e.g., Taylor and Xiao 2010), an H-type buyer always has an incentive to mimic an L type in the sense that the former can make more profit under the latter's first-best contract than under his own. An L-type buyer, by contrast, always tells the truth. In our dynamic negotiation setting, whereas an L-type buyer stays truth telling, an H-type buyer may or may not mimic an L type depending on his patience level relative to that of the seller's. This is stated in the next proposition. We use $\succ$ and $\prec$ to denote the firms' preference. Specifically, $(q, T)_\tau \succ_k (\prec_k)(q', T')_{\tau'}$ means that firm k's profit from contract (q, T) in round τ is strictly higher (lower) than that from contract (q', T') in round τ', where $k = S, H, L$ represents respectively, the seller, the H-type buyer, and the L-type buyer. We also use $\succcurlyeq$ and $\preccurlyeq$ to denote the preference in the weak sense.

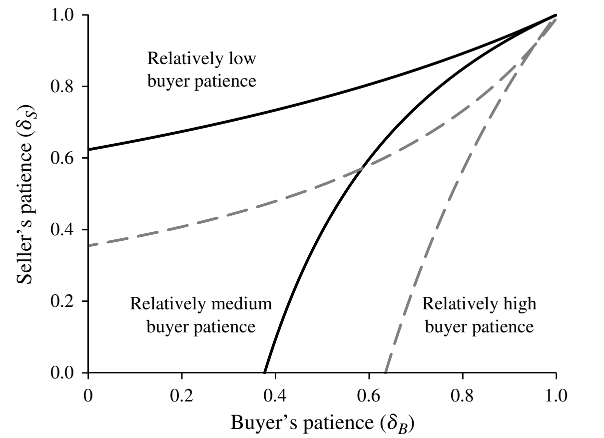
Proposition 2. *In any round τ, there exist two thresholds $\underline{\delta}_B(\delta_S) < \bar{\delta}_B(\delta_S)$ (both of which increase in δ_S) such that*

(i) *if it is the seller's turn to make an offer, then $(\hat{q}_L^S, \hat{T}_L^S)_\tau \succ_L (\hat{q}_H^S, \hat{T}_H^S)_\tau$, and when $\delta_B < (>) \bar{\delta}_B(\delta_S)$, $(\hat{q}_L^S, \hat{T}_L^S)_\tau \succ_H (\prec_H) (\hat{q}_H^S, \hat{T}_H^S)_\tau$;*

(ii) *if it is the buyer's turn to make an offer, then $(\hat{q}_L^B, \hat{T}_L^B)_\tau \succ_L (\hat{q}_H^B, \hat{T}_H^B)_\tau$, and when $\delta_B < (>) \underline{\delta}_B(\delta_S)$, $(\hat{q}_L^B, \hat{T}_L^B)_\tau \succ_H (\prec_H) (\hat{q}_H^B, \hat{T}_H^B)_\tau$.*

Proposition 2 suggests that the L-type buyer never has an incentive to lie, whereas the H type is willing to truthfully reveal his private information if he has a relatively high patience level. This departs from the behaviors observed in principal–agent models wherein the efficient type always misreports his type because a truth-telling agent obtains zero profit. In contrast, both buyer types in this dynamic negotiation process earn a portion of the trade surplus. As a result, the H type has to weigh the benefit of mimicking, i.e., reduced payment to the seller, against the cost of quantity distortion, i.e., reduced trade surplus. The balance tips toward truth telling when the buyer is sufficiently patient, i.e., when his share of trade surplus is sufficiently large. Furthermore, because the buyer gains a larger share of the trade surplus when he makes an offer than when he responds to the seller's offer, the H-type buyer is more likely to truthfully reveal his type when making an offer, suggesting $\underline{\delta}_B(\delta_S) < \bar{\delta}_B(\delta_S)$. These two thresholds define three regions, as depicted in Figure 1. In our subsequent analysis, we characterize the bargaining outcomes for these three regions.

Figure 1 **The Buyer's Truth-Telling Conditions in the Space of $\{\delta_B, \delta_S\}$**



Notes. $r = 100$, $c = 20$, and $\beta = 0.5$. The demand is a mix of two normal random variables with distributions $F_l(x) = \Phi((x-40)/10)$ and $F_h(x) = \Phi((x-80)/10)$, where $\Phi(\cdot)$ is the standard normal distribution function. Specifically, $F_i(x) = \alpha_i(\gamma)F_h(x) + (1-\alpha_i(\gamma))F_l(x)$, $i \in \{H, L\}$, where $\alpha_H(\gamma) = \gamma$ and $\alpha_L(\gamma) = 1-\gamma$, with $\gamma = 0.9$ for the solid line and $\gamma = 0.7$ for the dashed line.

4.3. The Seller's Belief Structure

When negotiating with the buyer, the seller needs to form a belief about the buyer's type based on his actions. Notice that in this alternating-offer game, rejecting an offer is immediately followed by a counteroffer in the next round. Thus, the seller's belief update should be based on the buyer's counteroffer. Facing the H type's incentive to mimic, the L type may find it beneficial to signal his type by offering a contract unattractive to the H type. Intuitively, the seller's belief needs to take into account these incentives. We establish three criteria on the seller's belief structure as follows.

Criterion 1. *Suppose that the seller with a belief $\beta \in (0, 1)$ offers a contract (q^S, T^S) in round $\tau - 1$, but no agreement has been reached, and the buyer counteroffers (q^B, T^B) in round τ. If $(q^B, T^B)_\tau \succcurlyeq_S (\hat{q}_i, \hat{T}_i^B)_\tau$, $(q^B, T^B)_\tau \succcurlyeq_i (q^S, T^S)_{\tau-1}$, but $(q^B, T^B)_\tau \preccurlyeq_j (q^S, T^S)_{\tau-1}$, $i, j \in \{L, H\}$ and $i \neq j$, then the seller updates her belief to that the buyer is type i with probability one.*

According to Criterion 1, the seller will be convinced that the buyer is of one specific type if his contract offer is more attractive to himself but less attractive to

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the other buyer type than the contract offered by the seller in the previous round. In comparing the buyer's contract offers, it is important to make sure that they should yield the seller a profit no less than she receives under complete information, so that it is acceptable to the seller if she believes the buyer is of that type. Based on Criterion 1, we can define two sets of contracts, $\mathscr{C}_i^{(q^S,T^S)}$, $i \in \{L, H\}$. Whenever receiving a counteroffer $(q^B, T^B) \in \mathscr{C}_i^{(q^S,T^S)}$, the seller should conclude that the buyer is type i.

Criterion 1 follows the same spirit as Assumptions (B1) and (B4) in Rubinstein (1985a) for a one-dimensional asymmetric information bargaining model. However, for the two-dimensional bargaining problem here, besides comparing the buyer's counteroffer with the seller's offer in the previous round, the buyer might be able to find an alternative to signal his type (i.e., if the counteroffer is suboptimal for the other buyer type), which is captured by Criterion 2.

Criterion 2. *Suppose that the seller with a belief $\beta \in (0, 1)$ offers a contract in round $\tau - 1$, but no agreement has been reached, and the buyer counteroffers (q^B, T^B) in round τ. If $(q^B, T^B)_\tau \succcurlyeq_S (\hat{q}_i, \hat{T}_i^B)_\tau$ and there exists an alternative contract (q, T) such that $(q, T)_\tau \succcurlyeq_S (\hat{q}_j, \hat{T}_j^B)_\tau$ and $(q, T)_\tau \succcurlyeq_j (q^B, T^B)_\tau$, but $(q, T)_\tau \preccurlyeq_i (q^B, T^B)_\tau$, $i, j \in \{L, H\}$ and $i \neq j$, then the seller updates her belief to that the buyer is type i with probability one.*

By Criterion 2, the seller, regardless of the history, is convinced that the buyer is type i if his counteroffer guarantees the seller the first-best profit, whereas the j type can be better off with a different contract. Let $\mathscr{C}_i$, $i \in \{L, H\}$, denote the set of contracts satisfying Criterion 2. Whenever receiving a counteroffer $(q^B, T^B) \in \mathscr{C}_i$, the seller should conclude that the buyer is type i.

Criterion 3. *Suppose that the seller with a belief $\beta \in (0, 1)$ offers a contract (q^S, T^S) in round $\tau - 1$, but no agreement has been reached, and the buyer counteroffers $(q^B, T^B) \notin \mathscr{C}_L^{(q^S,T^S)} \cup \mathscr{C}_H^{(q^S,T^S)} \cup \mathscr{C}_L \cup \mathscr{C}_H$ in round τ. If either $(q^B, T^B)_\tau \preccurlyeq_L (q^S, T^S)_{\tau-1}$, or there exists an alterative contract (q, T) such that $(q^B, T^B)_\tau \preccurlyeq_L (q, T)_\tau$, $(q, T)_\tau \preccurlyeq_H (q^B, T^B)_\tau$, and either $(q, T) \in \mathscr{C}_L^{(q^S,T^S)} \cup \mathscr{C}_L$ or $(q, T)_\tau \succcurlyeq_S (q^B, T^B)_\tau$, then the seller updates her belief to that the buyer is type H with probability one; otherwise, the seller's belief remains unchanged.*

A contract (q^B, T^B) other than those specified in Criteria 1 and 2 does not credibly reveal the buyer's type. Given that it is the H-type buyer who has an incentive to mimic the L type, Criterion 3 verifies whether the offer (q^B, T^B) can possibly come from the L-type buyer. This would not be possible if the L-type buyer can be better off by accepting the seller's offer or by offering an alternative contract. Specifically, the alternative contract should be more (less) attractive to the L (H) type than (q^B, T^B). Also, this contract either signals the buyer's type to be L by Criteria 1 and 2 or provides the seller a higher profit. If the above conditions hold, then the L-type buyer would have no incentive to reject the seller's previous offer and then counteroffer (q^B, T^B); therefore, the seller should believe this offer comes from the H-type buyer. Otherwise, no credible information can be inferred from the contract (q^B, T^B), and the seller's initial belief should not be updated. In our subsequent equilibrium analysis, Criteria 1 and 2 are applied to characterize separating offers, whereas Criterion 3 is applied to identify potential pooling offers.

Finally, we assume that once the seller's belief about the buyer's type becomes probability one, she will not revise her belief any more regardless of subsequent actions the buyer takes. This avoids the complexity of having tentative beliefs.

4.4. Bargaining Outcomes

In theory, the bargaining process with alternating offers is an infinite-horizon game; i.e., each party may reject the other's offer without ever reaching an agreement. An immediate question is, how long, if ever, does it take to end the game in equilibrium? The next lemma answers this question.

Lemma 1. *In equilibrium, an agreement is reached after at most two rounds of negotiation, and*

(i) *the buyer will reject any offer (q, T) made by the seller with $T - cq > ((1-\delta_B)/(1-\delta_B\delta_S))\hat{\pi}_H$;*

(ii) *the seller will accept any offer (q, T) made by the buyer with $T - cq \geq ((\delta_S(1-\delta_B))/(1-\delta_B\delta_S))\hat{\pi}_H$ and reject any offer (q, T) with $T - cq < ((\delta_S(1-\delta_B))/(1-\delta_B\delta_S))\hat{\pi}_L$.*

With private information, the buyer has no incentive to delay agreement because of his impatience (i.e., $\delta_B < 1$). The seller, however, faces a trade-off between information extraction and profit loss as a result of potential delay in agreement or negotiation breakdown. As a result, the seller may take the risk of not striking a deal immediately if it results in information revelation through the buyer's counteroffer. Lemma 1 also implies that the seller obtains a profit no higher (lower) than that from negotiating with the H-type (L-type) buyer under complete information.

Lemma 2. *Suppose in an equilibrium that the seller's initial offer (q^S, T^S) is rejected and followed by a counteroffer (q^B, T^B).*

(i) *Regardless of (q^S, T^S),*

(a) *when $\delta_B \geq \underline{\delta}_B(\delta_S)$, the seller believes that the buyer is type i if $(q^B, T^B) = (\hat{q}_i, \hat{T}_i^B)$, $i = L, H$;*

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(b) *when* $\delta_B < \underline{\delta}_B(\delta_S)$, *the seller believes that the buyer is type* H *if* $(q^B, T^B) = (\hat{q}_H, \hat{T}_H^B)$ *and the buyer is type* L *if* $(q^B, T^B) = (q^D, T^D)$, *where* $q^D < \hat{q}_L$ *and*

$$\begin{cases} R_H(q^D) - T^D = \dfrac{1-\delta_S}{1-\delta_B\delta_S}\hat{\pi}_H, \\ T^D - cq^D = \dfrac{\delta_S(1-\delta_B)}{1-\delta_B\delta_S}\hat{\pi}_L. \end{cases} \tag{1}$$

(ii) *If* (q^S, T^S) *satisfies* $R_H(q^S) - T^S \geq (\delta_B(1-\delta_S)/(1-\delta_B\delta_S))\hat{\pi}_H$, *then the seller believes that the buyer is type* L *if* $(q^B, T^B) = (q^M, T^M)$, *where* $q^D \leq q^M \leq \hat{q}_L$ *and*

$$\begin{cases} R_H(q^M) - T^M \\ \quad = \min\{[R_H(q^S) - T^S]/\delta_B, R_H(\hat{q}_L) - \hat{T}_L^B\}, \\ T^M - cq^M = \dfrac{\delta_S(1-\delta_B)}{1-\delta_B\delta_S}\hat{\pi}_L. \end{cases} \tag{2}$$

Lemma 2 describes some characteristic equilibrium paths along which the buyer's private information is revealed. In part (i), the buyer voluntarily *signals* his type via his counteroffer while guaranteeing the seller her first-best profit. When the buyer is sufficiently patient, signaling can be done by simply offering the first-best contract (part (i(a))). When the buyer's patience level is low, however, signaling becomes costly for the L-type buyer because he must distort his order quantity to avoid being imitated by the H type (part (i(b))). Part (ii) describes a *combination of signaling and screening*. In this case, the seller sweetens her offer to the H type with an information rent but makes sure the offer is unacceptable to the L type. The L type, in turn, makes a counteroffer with moderate quantity distortion to signal his information (the extent of quantity distortion is lower than that in part (i(b)). Therefore, the seller and the L-type buyer share the cost of information revelation in this case.

With Lemmas 1 and 2 and the seller's belief structure presented in §4.3, we are now ready to derive the equilibrium for the three scenarios of the relative patience levels of the two firms (recall Figure 1). For expositional convenience, we use $\{A, A\}$ to represent the case when both buyer types accept the seller's initial offer, $\{R, A\}$ when the H type rejects the seller's initial offer and the L type accepts, and $\{A, R\}$ when the H type accepts the seller's initial offer and the L type rejects. Wherever appropriate, we also use the suffix *Sig*, *Scr*, or *Mix* to denote costly signaling by the L-type buyer, costly screening by the seller, or a combination of the two, respectively.

4.4.1. Relatively High and Medium Buyer Patience. We first derive the bargaining outcome for the cases in which the buyer's patience is relatively high or medium, i.e, the regions with $\delta_B \geq \underline{\delta}_B(\delta_S)$, in Figure 1. In this case, the buyer, when making a counteroffer, will be truth telling and give the first-best contract. The equilibrium outcome is then determined by whether or not the seller prefers to delay agreement by making the initial offer acceptable to only one buyer type.

Proposition 3. *When* $\delta_B \geq \bar{\delta}_B(\delta_S)$, *there exist* $\underline{\beta}^h(\delta_B, \delta_S)$ *and* $\bar{\beta}^h(\delta_B, \delta_S)$ *such that the perfect Bayesian bargaining equilibrium is given as follows.*

(i) $\{R, A\}$: *When* $\beta \leq \underline{\beta}^h(\delta_B, \delta_S)$, *the seller offers* $(\hat{q}_L, \hat{T}_L^S)$. *If the buyer is type* L, *he accepts the offer; otherwise, he rejects and counteroffers* $(\hat{q}_H, \hat{T}_H^B)$, *which the seller accepts.*

(ii) $\{A, A\}$: *When* $\underline{\beta}^h(\delta_B, \delta_S) < \beta < \bar{\beta}^h(\delta_B, \delta_S)$, *the seller offers* (q^I, T^I), *and both buyer types accept the offer, where* (q^I, T^I) *solves*

$$T^I = R_H(q^I) - \frac{\delta_B(1-\delta_S)}{1-\delta_B\delta_S}\hat{\pi}_H = R_L(q^I) - \frac{\delta_B(1-\delta_S)}{1-\delta_B\delta_S}\hat{\pi}_L.$$

(iii) $\{A, R\}$: *When* $\beta \geq \bar{\beta}^h(\delta_B, \delta_S)$, *the seller offers* $(\hat{q}_H, \hat{T}_H^S)$. *If the buyer is type* H, *he accepts the offer; otherwise, he rejects and counteroffers* $(\hat{q}_L, \hat{T}_L^B)$, *which the seller accepts.*

Moreover, $\bar{\beta}^h(\delta_B, \delta_S) > \underline{\beta}^h(\delta_B, \delta_S)$ *when* $\delta_S < \sqrt{\hat{\pi}_L/\hat{\pi}_H}$, *and* $\bar{\beta}^h(\delta_B, \delta_S) = \underline{\beta}^h(\delta_B, \delta_S)$ *otherwise.*

Proposition 3 says that the seller's negotiation strategy depends on his initial belief about the buyer type. When β is small (i.e., $\beta \leq \underline{\beta}^h(\delta_B, \delta_S)$), settling with the L type immediately is most beneficial. Likewise, when β is large (i.e., $\beta \geq \bar{\beta}^h(\delta_B, \delta_S)$), settling with the H type immediately is most beneficial. When β is in the middle range, offering a contract acceptable to only one of the two types carries a substantial risk of delaying agreement if the buyer turns out to be the "wrong" type. Therefore, offering a contract acceptable to both buyer types emerges as the best strategy for the seller. In this case, the seller chooses a quantity that is in between the first-best quantities of the two buyer types. Moreover, it is the seller who bears all the efficiency loss of quantity distortion, as the buyer obtains his first-best profit.

When the buyer's patience level moves from the relatively high to the relatively medium range, there is a subtle change in the equilibrium structure. This is because now the H-type buyer prefers the first-best contract offered to the L-type buyer (recall Proposition 2). It becomes costly for the seller to *screen* the L-type buyer if she attempts to reach an agreement with only the L-type buyer in the first round. Such screening is done by distorting the quantity and yet leaving the L-type buyer his first-best profit. The seller, while bearing the loss of quantity distortion when trading with the L type, obtains the first-best profit from the H-type buyer, because the latter is forced to reveal his information. Such a strategy is profitable to the seller only when the probability of an H-type buyer is sufficiently high. Otherwise, the seller should

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offer a contract acceptable to both buyer types. These results are summarized in the next proposition.

Proposition 4. *When $\underline{\delta}_B(\delta_S) \le \delta_B < \bar{\delta}_B(\delta_S)$, there exist $\underline{\beta}^m(\delta_B, \delta_S)$ and $\bar{\beta}^m(\delta_B, \delta_S)$ such that the perfect Bayesian bargaining equilibrium is given as follows.*

(i) $\{A, A\}$: *When $\beta \le \underline{\beta}^m(\delta_B, \delta_S)$, the seller offers $(\hat{q}_L, \hat{T}_L^S)$, and both buyer types accept the offer.*

(ii) $\{R, A\}$-*Scr*: *When $\underline{\beta}^m(\delta_B, \delta_S) < \beta < \bar{\beta}^m(\delta_B, \delta_S)$, the seller offers (q^I, T^I) that solves*

$$T^I = R_H(q^I) - \frac{\delta_B(1-\delta_S)}{1-\delta_B\delta_S}\hat{\pi}_H + \epsilon = R_L(q^I) - \frac{\delta_B(1-\delta_S)}{1-\delta_B\delta_S}\hat{\pi}_L$$

for some sufficiently small $\epsilon > 0$. If the buyer is L type, he accepts the offer; otherwise, he rejects and counteroffers $(\hat{q}_H, \hat{T}_H^B)$, which the seller accepts.

(iii) $\{A, R\}$: *When $\beta \ge \bar{\beta}^m(\delta_B, \delta_S)$, the seller offers $(\hat{q}_H, \hat{T}_H^S)$. If the buyer is H type, he accepts the offer; otherwise, he rejects and counteroffers $(\hat{q}_L, \hat{T}_L^B)$, which the seller accepts.*

4.4.2. Relatively Low Buyer Patience. When the buyer's patience level is relatively low (i.e, $\delta_B < \underline{\delta}_B(\delta_S)$), the H-type buyer would have an incentive to mimic the L type even when making offers. According to Lemma 2, there can be different ways to mitigate the H type's misreporting incentive, depending on whether the L-type buyer prefers to signal his information and to what extent the seller is willing to bear the cost of screening. The buyer's response to the seller's initial offer depends on the profit the seller anticipates to earn (see Lemmas 5 and 6 in Online Appendix A). In equilibrium, the anticipated seller profit should be consistent with the true profit the seller earns, and similarly, the seller's belief of the buyer's type should be consistent with the buyer's optimal strategy. We use a fixed-point approach to derive the equilibrium, which is stated in the following proposition.

Proposition 5. *When $\delta_B < \underline{\delta}_B(\delta_S)$, there exist $\underline{\beta}^l(\delta_B, \delta_S)$ and $\bar{\beta}^l(\delta_B, \delta_S)$ such that the perfect Bayesian bargaining equilibrium is given as follows.*

(i) $\{A, A\}$: *When $\beta \le \underline{\beta}^l(\delta_B, \delta_S)$, the seller offers $(\hat{q}_L, \hat{T}_L^S)$, and both types accept the offer.*

(ii) $\{A, R\}$-*Sig*: *When $\beta \ge \bar{\beta}^l(\delta_B, \delta_S)$, the seller offers $(\hat{q}_H, \hat{T}_H^S)$. If the buyer is H type, he accepts the offer; otherwise, he rejects and counteroffers (q^D, T^D) that solves Equation (1) and the seller accepts.*

(iii) *When $\underline{\beta}^l(\delta_B, \delta_S) < \beta < \bar{\beta}^l(\delta_B, \delta_S)$, the equilibrium is characterized by one of the following cases:*

(a) $\{A, R\}$-*Mix*: *The seller offers $(\hat{q}_H, \bar{T}_H^S)$. If the buyer is H type, he accepts the offer; otherwise, he rejects and counteroffers (q^M, T^M) that solves Equation (2) and the seller accepts, where $\bar{T}_H^S$ satisfies*

$$\beta(\bar{T}_H^S - c\hat{q}_H) + (1-\beta)\frac{\delta_S^2(1-\delta_B)}{1-\delta_B\delta_S}\hat{\pi}_L = \frac{1}{\delta_S}\left[\hat{\pi}_L - \left(R_L(q^M) - cq^M - \frac{\delta_S(1-\delta_B)}{1-\delta_B\delta_S}\hat{\pi}_L\right)\right].$$

(b) $\{R, A\}$-*Mix*: *The seller offers (q^X, T^X). If the buyer is L type, he accepts the offer; otherwise, he rejects and counteroffers $(\hat{q}_H, \hat{T}_H^B)$, which the seller accepts, where (q^X, T^X) satisfies $q^X < q^D$, $R_H(q^X) - T^X + \epsilon = ((\delta_B(1-\delta_S))/(1-\delta_B\delta_S))\hat{\pi}_H$, and*

$$R_L(q^X) - T^X = \delta_B \max\left\{R_L(q^D) - T^D, \hat{\pi}_L - \delta_S \cdot \left[\beta\frac{\delta_S^2(1-\delta_B)}{1-\delta_B\delta_S}\hat{\pi}_H + (1-\beta)(T^X - cq^X)\right]\right\}$$

for some sufficiently small $\epsilon > 0$.

A high likelihood of having an L-type buyer (i.e., $\beta \le \underline{\beta}^l(\delta_B, \delta_S)$) induces the seller to be content with a pooling outcome by offering the first-best contract of the L type. The H type will pretend to be an L type and accept this contract. When β is sufficiently large, however, the seller prefers a separating outcome by settling a deal with the two buyer types sequentially, i.e., in two rounds. There can be three separating equilibrium outcomes, depending on the seller's screening incentive and the L type's signaling incentive.

With a high likelihood of having an H-type buyer (i.e., $\beta \ge \bar{\beta}^l(\delta_B, \delta_S)$), the seller prefers to reach an agreement with the H-type buyer first and have the L-type buyer signal his information in the next round. This is done by the seller demanding the first-best profit under an H signal when making her initial offer. Only when the buyer significantly distorts his order quantity in his counteroffer and leaves the seller the first-best profit of trading with an L type (i.e., offers (q^D, T^D)) should the seller be convinced that the buyer is L type. This leads to the equilibrium $\{A, R\}$-*Sig*, in which the L-type buyer bears all the cost of information revelation via signaling. The seller, however, is always guaranteed the first-best profit regardless of which type she ends up trading with.

When β is in an intermediate range, the seller may have to pay a screening cost to induce either the H-type or the L-type buyer to reach an early agreement. This leads to equilibrium $\{A, R\}$-*Mix* and $\{R, A\}$-*Mix*. Specifically, in the $\{A, R\}$-*Mix* equilibrium, the seller prefers to settle with the H-type buyer first, but the L-type buyer does not have a strong incentive to signal his information (i.e., he is not willing to offer (q^D, T^D)). As a result, the seller has to surrender some information rent to the H-type buyer so that he accepts an offer in the first round. In the L-type buyer's counteroffer, the order quantity is distorted to an extent less than the distortion in $\{A, R\}$-*Sig* (i.e., $q^D < q^M < \hat{q}_L$). In the $\{R, A\}$-*Mix* equilibrium, the seller prefers to settle with the L-type buyer first. To do so, she has to incur a screening cost by distorting the L type's order quantity (i.e., $q^X < q^D < \hat{q}_L$) to prevent the H-type buyer from accepting it. In the meantime, the seller's offer should

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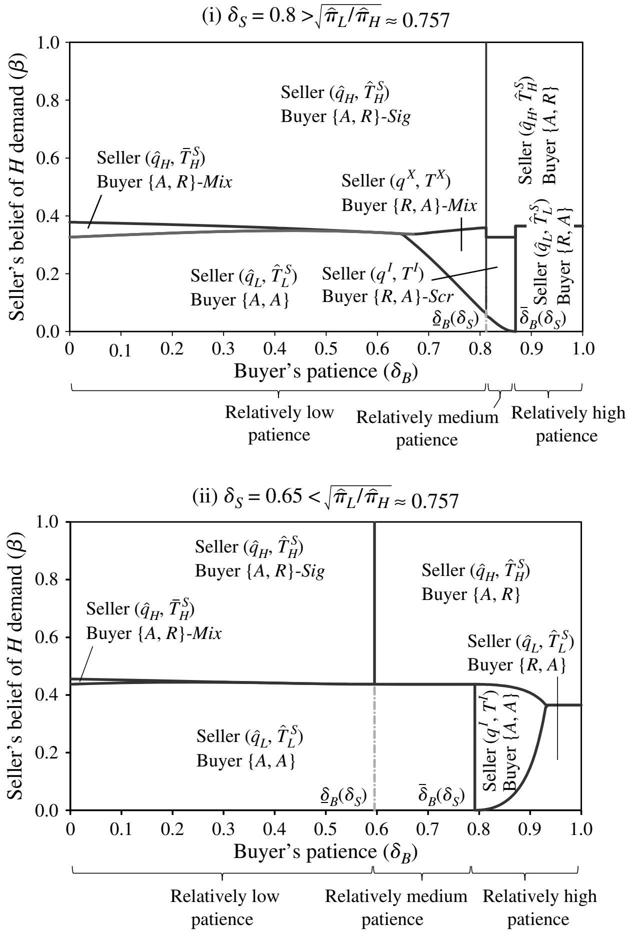
Figure 2 **Summary of Equilibria in the Space of $\{\delta_B, \beta\}$, as Characterized in Propositions 3–5**



Notes. $r = 100$ and $c = 20$. The demand is a mix of two normal random variables with distributions $F_l(x) = \Phi((x-30)/10)$ and $F_h(x) = \Phi((x-55)/10)$, where $\Phi(\cdot)$ is the standard normal distribution function. Specifically, $F_i(x) = \alpha_i(\gamma)F_h(x) + (1-\alpha_i(\gamma))F_l(x)$, $i \in \{H, L\}$, where $\alpha_H(\gamma) = \gamma$ and $\alpha_L(\gamma) = 1-\gamma$ with $\gamma = 0.9$.

be attractive enough for the L-type buyer so that he makes a higher profit than he would by a counteroffer. The seller's screening cost is lower if the L-type buyer has a stronger incentive to signal his information in his intended counteroffer. By accepting the seller's offer, the L-type buyer reveals his information and incurs a signaling cost because he makes a profit lower than his first-best profit. Under both $\{A, R\}$-*Mix* and $\{R, A\}$-*Mix*, the loss as a result of information revelation is shared by the seller paying a screening cost and the L-type buyer paying a signaling cost.

5. Insights and Comparison with the Principal–Agent Framework

We illustrate the regions of the equilibria characterized by Propositions 3–5 in Figure 2. We also summarize the key features of the equilibrium outcomes in Table 1 on the basis of which we will discuss the managerial insights.

5.1. Order Quantity

Under complete information, the equilibrium order quantity always equals the newsvendor quantity for the entire supply chain. Under asymmetric information, however, the equilibrium order quantity can be substantially distorted depending on the information structure and the two parties' relative patience levels.

Corollary 1. *The L-type buyer's order quantity is distorted*

(i) *downward when $\delta_B < \underline{\delta}_B(\delta_S)$ and $\beta > \underline{\beta}^l(\delta_B, \delta_S)$;*

(ii) *downward when $\underline{\delta}_B(\delta_S) \le \delta_B < \bar{\delta}_B(\delta_S)$ and $\underline{\beta}^m(\delta_B, \delta_S) < \beta < \bar{\beta}^m(\delta_B, \delta_S)$;*

(iii) *upward when $\delta_B \ge \bar{\delta}_B(\delta_S)$, $\delta_S < \sqrt{\hat{\pi}_L/\hat{\pi}_H}$, and $\underline{\beta}^h(\delta_B, \delta_S) < \beta < \bar{\beta}^h(\delta_B, \delta_S)$.*

Corollary 1 suggests that the distortion in the L-type buyer's order quantity depends on the H-type buyer's incentive to hide his private information. When the H-type buyer prefers to pretend to be L type in either accepting or making an offer, the L-type buyer's order quantity can be smaller than the first-best level. When the H-type buyer is willing to truthfully reveal his type, the L-type buyer's order quantity can be higher than the first-best level. Whereas an upward quantity distortion does not hurt the L-type buyer, a downward distortion may lower his profit, as shown in Table 1.

Corollary 2. *The H-type buyer's order quantity is downward distorted when one of the following conditions is satisfied*:

(i) *$\delta_B < \underline{\delta}_B(\delta_S)$ and $\beta \le \underline{\beta}^l(\delta_B, \delta_S)$;*

(ii) *$\underline{\delta}_B(\delta_S) \le \delta_B < \bar{\delta}_B(\delta_S)$ and $\beta \le \underline{\beta}^m(\delta_B, \delta_S)$;*

(iii) *$\delta_B \ge \bar{\delta}_B(\delta_S)$, $\delta_S < \sqrt{\hat{\pi}_L/\hat{\pi}_H}$, and $\underline{\beta}^h(\delta_B, \delta_S) < \beta < \bar{\beta}^h(\delta_B, \delta_S)$.*

Corollary 2 indicates that unlike the L type, the H-type buyer's order quantity does not have upward distortion but can be distorted downward at any buyer patience level. Table 1 also shows that the H-type buyer may earn an information rent when his order quantity is distorted downward.

To understand how dynamic negotiation affects contracting outcomes and firm behaviors, we compare the results obtained from our model with those from the one-shot principal–agent framework (see Online Appendix B). The latter predicts that the H-type buyer's quantity is always at the first-best level, whereas the L type's is always distorted downward. As β increases, the downward distortion becomes more severe. In contrast, under dynamic negotiations, the buyer earns a portion of the trade surplus and, more importantly, has an option to counteroffer. Therefore, quantity distortion does not always occur as a result of the buyer's ability to signal with counteroffers and the H-type buyer's

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Table 1 Characteristics of the Equilibria in Propositions 3–5

Buyer's patience	Equilibrium	Information revealed?	Screening? (seller)	Signaling? (L type)	L type's quantity	H type's quantity	Seller's profit	L type's profit	H type's profit
High	(A, A)	No	—	—	$q_L = q^I > \hat{q}_L$	$q_H = q^I < \hat{q}_H$	$\pi^S < \hat{\pi}^S$	$\pi_L^B = \hat{\pi}_L^B$	$\pi_H^B = \hat{\pi}_H^B$
	(A, R)	Yes	—	—	$q_L = \hat{q}_L$	$q_H = \hat{q}_H$	$\pi^S < \hat{\pi}^S$	$\pi_L^B = \hat{\pi}_L^B$	$\pi_H^B = \hat{\pi}_H^B$
	(R, A)	Yes	—	—	$q_L = \hat{q}_L$	$q_H = \hat{q}_H$	$\pi^S < \hat{\pi}^S$	$\pi_L^B = \hat{\pi}_L^B$	$\pi_H^B = \hat{\pi}_H^B$
Medium	(A, A)	No	—	—	$q_L = \hat{q}_L$	$q_H = \hat{q}_L < \hat{q}_H$	$\pi^S < \hat{\pi}^S$	$\pi_L^B = \hat{\pi}_L^B$	$\pi_H^B > \hat{\pi}_H^B$
	(A, R)	Yes	—	—	$q_L = \hat{q}_L$	$q_H = \hat{q}_H$	$\pi^S < \hat{\pi}^S$	$\pi_L^B = \hat{\pi}_L^B$	$\pi_H^B = \hat{\pi}_H^B$
	(R, A)-*Scr*	Yes	Yes	—	$q_L = q^I < \hat{q}_L$	$q_H = \hat{q}_H$	$\pi^S < \hat{\pi}^S$	$\pi_L^B = \hat{\pi}_L^B$	$\pi_H^B = \hat{\pi}_H^B$
Low	(A, A)	No	—	—	$q_L = \hat{q}_L$	$q_H = \hat{q}_L < \hat{q}_H$	$\pi^S < \hat{\pi}^S$	$\pi_L^B = \hat{\pi}_L^B$	$\pi_H^B > \hat{\pi}_H^B$
	(A, R)-*Sig*	Yes	—	Yes	$q_L = q^D < \hat{q}_L$	$q_H = \hat{q}_H$	$\pi^S < \hat{\pi}^S$	$\pi_L^B < \hat{\pi}_L^B$	$\pi_H^B = \hat{\pi}_H^B$
	(A, R)-*Mix*	Yes	Yes	Yes	$q_L = q^M < \hat{q}_L$	$q_H = \hat{q}_H$	$\pi^S < \hat{\pi}^S$	$\pi_L^B < \hat{\pi}_L^B$	$\pi_H^B > \hat{\pi}_H^B$
	(R, A)-*Mix*	Yes	Yes	Yes	$q_L = q^X < \hat{q}_L$	$q_H = \hat{q}_H$	$\pi^S < \hat{\pi}^S$	$\pi_L^B < \hat{\pi}_L^B$	$\pi_H^B = \hat{\pi}_H^B$

reduced incentive to lie. When quantity distortion does occur, it may be either upward or downward, and it can arise for both buyer types. Furthermore, the order quantity is generally nonmonotone with respect to β (see the examples in Online Appendix C).

5.2. Information Flow

In this dynamic negotiation process, the demand information possessed by the buyer may or may not be revealed to the seller, depending on whether a separating or a pooling equilibrium is reached. From Propositions 3–5, we can obtain the following corollary.

Corollary 3. *The demand information is concealed from the seller in equilibrium when one of the following conditions is satisfied*:

(i) $\delta_B < \underline{\delta}_B(\delta_S)$ *and* $\beta \le \underline{\beta}^l(\delta_B, \delta_S)$;

(ii) $\underline{\delta}_B(\delta_S) \le \delta_B < \bar{\delta}_B(\delta_S)$ *and* $\beta \le \underline{\beta}^m(\delta_B, \delta_S)$;

(iii) $\delta_B \ge \bar{\delta}_B(\delta_S)$, $\delta_S < \sqrt{\hat{\pi}_L/\hat{\pi}_H}$, *and* $\underline{\beta}^h(\delta_B, \delta_S) < \beta < \bar{\beta}^h(\delta_B, \delta_S)$.

Otherwise, *the demand information is revealed*.

Both firms' relative patience and the buyer's type distribution affect the information flow in the supply chain. In general, the buyer's private information is revealed when β is large because the seller benefits from inducing a separating equilibrium. The buyer's private demand information is also revealed if the buyer is relatively patient and thus has little incentive to lie. These outcomes are driven by the buyer's incentive to increase the trade surplus of which he takes a share thanks to his ability to counteroffer. In contrast, under the principal–agent setup, information revelation is always induced by the seller's take-it-or-leave-it offer and does not depend on the buyer's type distribution.

5.3. Firm Profits

We compare the firms' equilibrium profits with those under the first-best benchmark, as shown in Table 1. Two observations stand out contrasting the predictions of the principal–agent framework. First, the H type does not always earn an information rent at any level of buyer patience. Second, the L type may earn his first-best profit, usually in a pooling equilibrium or when the seller chooses to settle with him first. Again, these different outcomes hinge on the fact that under dynamic negotiations the buyer has an option to counteroffer and thus signal his type to the seller, thereby alleviating information asymmetry. It also derives from the fact that the H type has a reduced incentive to lie because of the more balanced profit allocation between the two contracting parties compared with the principal–agent framework.

Finally, it is worth pointing out that when δ_B increases, the equilibrium may move from a pooling region to a separating region with the H-type buyer's order quantity increased from $\hat{q}_L$ to $\hat{q}_H$, which may lead to an improvement in the seller's profit. In other words, *the seller may benefit from increased buyer patience*.

6. The Impact of Buyer's Demand Forecasting Accuracy

In this section, we apply the dynamic bargaining model to investigate how the buyer's demand forecasting accuracy affects the bargaining outcome and the firms' profitability. To that end, we model the demand as a mix of two random variables, i.e., $X = \mathbb{I}_{\{J=l\}} X_l + \mathbb{I}_{\{J=h\}} X_h$, where J indicates the true underlying state of the demand, and X_l and X_h have distributions $F_l(\cdot)$ and $F_h(\cdot)$, respectively. The probability of the h state is $\Pr\{J = h\} = \alpha \in (0, 1)$. Both the seller and the buyer know $F_l(\cdot)$, $F_h(\cdot)$, and α. Before negotiating with the seller, the buyer privately obtains a forecast $I \in \{H, L\}$ with an accuracy level $\gamma \equiv \Pr\{I = L \mid J = l\} = \Pr\{I = H \mid J = h\} \in [0.5, 1]$.

Clearly, this model is a special case of the base model analyzed earlier. The buyer's type is identified by his forecast $I \in \{H, L\}$. The seller's initial belief that the

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buyer is type H and the conditional probabilities of the h demand state are given by

$$\beta(\gamma) = \Pr(I = H) = \alpha\gamma + (1-\alpha)(1-\gamma),$$

$$\alpha_H(\gamma) = \Pr(J = h \mid I = H) = \frac{\alpha\gamma}{\alpha\gamma + (1-\alpha)(1-\gamma)},$$

$$\alpha_L(\gamma) = \Pr(J = h \mid I = L) = \frac{\alpha(1-\gamma)}{\alpha(1-\gamma) + (1-\alpha)\gamma}.$$

When $\gamma = 0.5$, the buyer does not gain any additional information by observing I; i.e., $\alpha_i(0.5) = \alpha$, $i \in \{L, H\}$. When $\gamma = 1$, the buyer knows the true state precisely; i.e., $\alpha_H(1) = 1$ and $\alpha_L(1) = 0$. The two buyer types' demand distributions are

$$F_i(x) = \alpha_i(\gamma)F_h(x) + (1 - \alpha_i(\gamma))F_l(x), \quad i \in \{H, L\}.$$

We assume that $F_h(x) \le F_l(x)$ so that state h has a stochastically larger demand distribution than state l. It follows that $F_H(x) \le F_L(x)$. Furthermore, $F_H(\cdot)$ is decreasing in γ, and $F_L(\cdot)$ is increasing in γ, which means that as the forecasting accuracy improves, the "difference" between the two types' demand distributions is enlarged.

6.1. The Impact on Bargaining Equilibrium

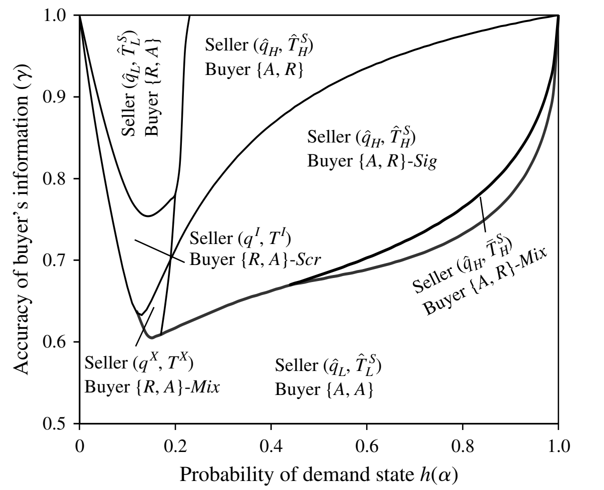
To understand how the buyer's forecasting accuracy affects the bargaining outcome,[1] we first need to understand how it affects the buyer's incentive to reveal information.

Proposition 6. *$\underline{\delta}_B(\delta_S)$ and $\bar{\delta}_B(\delta_S)$ are decreasing in γ.*

Proposition 6 says that when the buyer's forecasting accuracy improves (i.e., when γ increases), he becomes more likely to reveal his forecast signal when negotiating with the seller (recall Figure 1). This is because a more accurate forecast will lead to more distinct first-best order quantities of the two types, making it more costly for the H type to imitate the L type.

In Figure 3, we plot the equilibrium outcome in the space of α and γ. When γ is low, the H-type buyer has a strong incentive to mimic the L-type buyer. Because the buyer's private demand information is not accurate (thus, $F_H(\cdot)$ and $F_L(\cdot)$ are quite similar), the best strategy for the seller is to offer $(\hat{q}_L, \hat{T}_L^S)$ and settle with both types in the first round. As γ increases, the difference between the two demand distributions enlarges and the H-type buyer's imitating incentive reduces, it turns out to be profitable for the seller to settle with one type at a time. Depending on the value of α, the seller's initial contract offer may be acceptable to only the H-type or L-type buyer. When γ becomes

Figure 3 **The Bargaining Equilibrium in the Space of $\{\alpha, \gamma\}$**



Notes. $r = 100$ and $c = 10$. The demand is a mix of two normal random variables with distributions $F_l(x) = \Phi((x - 30)/10)$ and $F_h(x) = \Phi((x - 100)/10)$, where $\Phi(\cdot)$ is the standard normal distribution function. In this scenario, $\delta_B = 0.8$ and $\delta_S = 0.9$.

sufficiently large, the buyer is willing to truthfully reveal his private information via his counteroffer, and the distortions in the order quantities eventually vanish in the equilibrium.

6.2. The Impact on Firm Profitability

In the next proposition, we characterize the change of the seller's and the buyer's equilibrium profits with respect to γ.

Proposition 7. (i) *Under complete information, both the seller's and the buyer's expected profits increase in γ.*

(ii) *Under asymmetric information,* (a) *the seller's expected profit always decreases in γ in the $\{A, A\}$ equilibrium region with her initial offer $(\hat{q}_L, \hat{T}_L^S)$;* (b) *in the $\{A, R\}$, $\{A, R\}$-Sig, or $\{R, A\}$ equilibrium regions, the seller's expected profit increases in γ when δ_S is larger than a threshold $\hat{\delta}_S$.*

(iii) *Under asymmetric information,* (a) *the buyer's expected profit always increases in γ in the $\{A, A\}$ equilibrium region with the seller's initial offer (q^I, T^I);* (b) *in the $\{A, R\}$, $\{R, A\}$, or $\{R, A\}$-Scr equilibrium regions, the buyer's expected profit increases in γ when δ_B is larger than a threshold $\hat{\delta}_B$.*

Under complete information, better demand forecast leads to improved supply chain performance. The seller's and the buyer's profits are proportional to the total supply chain surplus and thus increase in the forecasting accuracy. This is indicated in Proposition 7, part (i). Under asymmetric information, however, the impact of the buyer's private demand forecast on the supply chain performance and on the two parties' profits depends critically on their relative patience levels and varies across different equilibrium regions. Parts (ii)

[1] For our purpose of assessing the effect of forecasting accuracy (e.g., Taylor and Xiao 2010), we ignore the cost of obtaining a forecast signal, which may lead to complex analysis without dramatically altering the insights.

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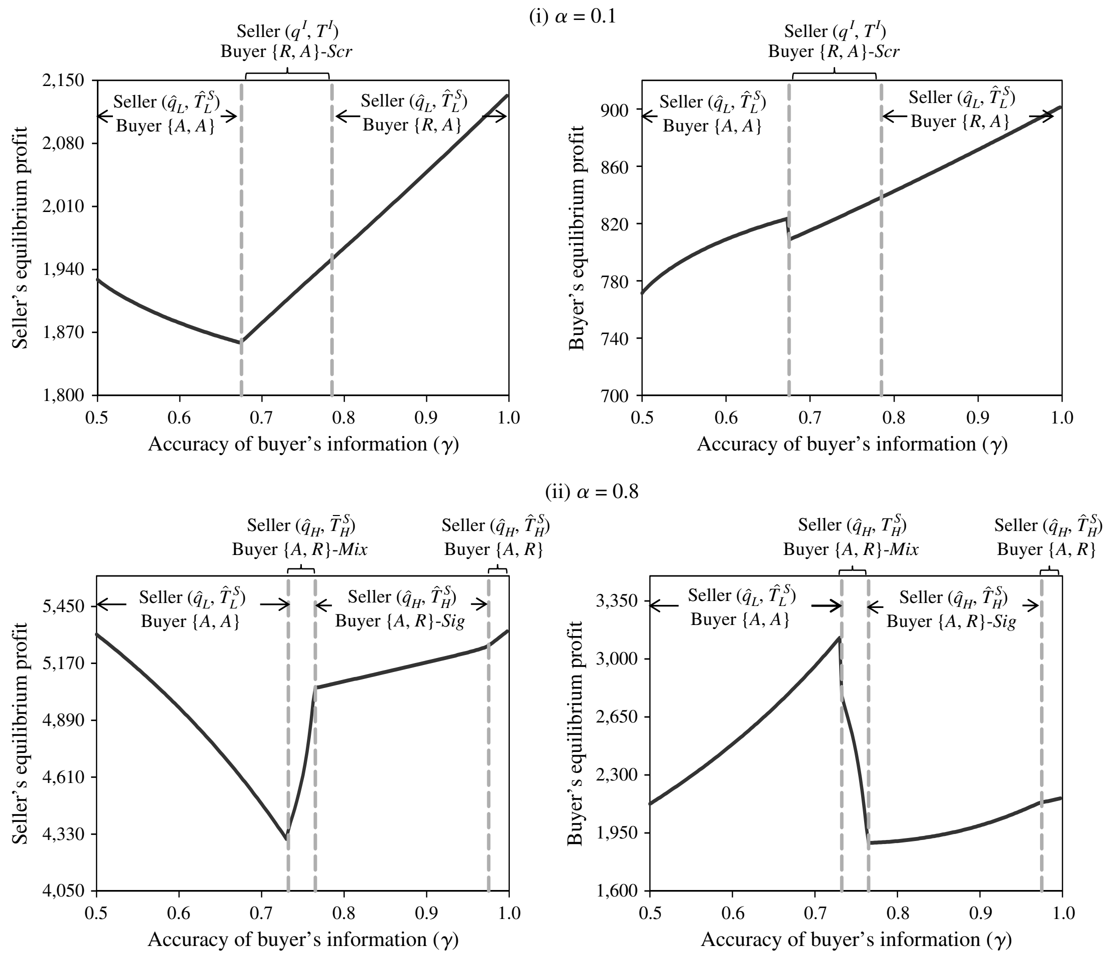
Figure 4 **The Firms' Equilibrium Profits as a Function of γ**



Note. The examples are computed based on the parameter settings of Figure 3.

and (iii) of Proposition 7 indicate that in the $\{A, A\}$ equilibrium region, the seller's profit decreases, but the buyer's profit increases as the buyer's forecasting capability improves. In the separating equilibrium regions, both parties' profits may increase as the forecasting accuracy improves, leading to a win–win outcome. To provide further insights, we conduct a numerical analysis and illustrate our main findings in Figure 4.

6.2.1. The Seller's Profit. When γ exceeds a threshold, the bargaining equilibrium moves from the pooling region to the separating regions. The seller starts making more profit from the H-type buyer than from the L-type buyer. Because the H type's imitating incentive is weakened as γ increases, the seller pays a reduced information rent to screen the buyer and thus obtains an increased profit (see Figure 4).

6.2.2. The Buyer's Profit. When γ is small, the equilibrium is in the pooling region. The H-type buyer benefits from imitating the L type. This benefit increases rapidly as the buyer's forecasting accuracy improves, leading to an increased expected buyer profit. The profit improvement is more substantial when α is large because it becomes more likely for the buyer to receive an H demand forecast (see the two right panels in Figure 4).

When the buyer's forecasting accuracy improves to a certain level, the H-type buyer can no longer misreport his type, and the equilibrium moves from the pooling region to the separating region. At this point, we observe a substantial drop in the buyer's expected profit over the equilibrium region of $\{A, R\}$-*Mix*. However, beyond this region, the buyer's expected profit is increasing in γ within most of the separating regions (except $\{A, R\}$-*Mix*).[2] This is because the buyer's misreporting incentive is weakened, leading to reduced quantity distortion. The buyer benefits from not only

[2] In the $\{A, R\}$-*Mix* equilibrium region reported in the figure, the seller and the buyer share the cost of information revelation. However, as γ increases, the buyer is more likely to receive an H signal, which makes the seller less willing to concede in the negotiation. As a result, the L-type buyer has to significantly distort his order quantity to signal, which results in a smaller expected buyer profit.

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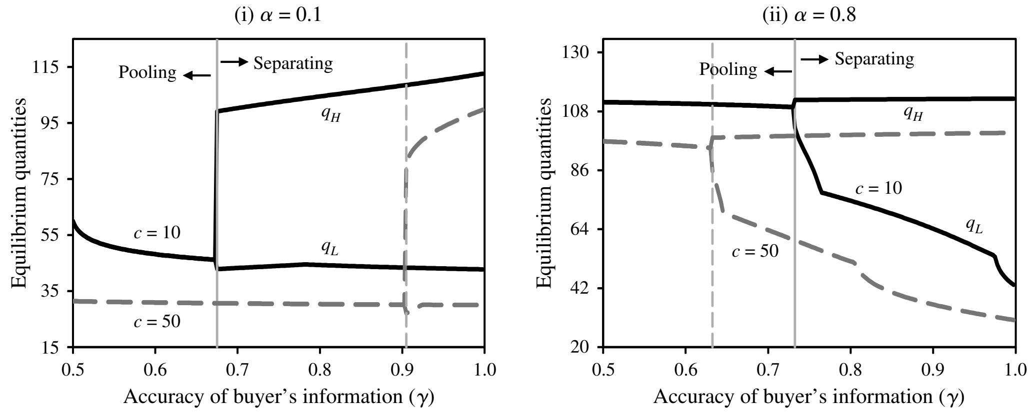
Figure 5 The Effect of Profit Margin on the Equilibrium Quantities



Notes. The examples are computed based on the parameter settings of Figure 3. The solid lines are plotted for the case when $c = 10$ and the dashed lines for $c = 50$.

improved supply chain efficiency but also a reduced cost to signal his private information.

6.3. The Role of Profit Margin

We find that the impact of improved demand forecast is influenced by the profit margin. To understand this, we conduct a numerical analysis in which we fix the buyer's retail price r and vary the seller's production cost c (the insights are similar when we fix c and vary r).

We observe that when α (i.e., the prior probability that the demand is in the h state) is small, the pooling equilibrium region expands as the profit margin decreases (see an illustration in Figure 5). Recall from the previous subsection that better demand forecast hurts the seller but benefits the buyer in the pooling equilibrium region. Hence, this observation implies that in a market with a low prior demand, the seller (the buyer) is more likely to be hurt by (to benefit from) better demand forecast when the profit margin becomes smaller. To understand the intuition, we note that when α is small, as the profit margin decreases, the difference between the first-best order quantities under the two demand forecasts decreases, which gives the buyer more incentive to lie and thus leads to a wider region for the pooling equilibrium. We shall comment that the profit margin affects the underage and overage costs, and thus affects the expected mismatch cost. When α is small, the firms contract at a small quantity when the forecast is not accurate, under which underage happens more often than overage. Hence, the benefit of better demand forecast tends to be larger when the profit margin increases.

This effect works in the opposite direction when α is large, and we observe from our experiments that the pooling equilibrium region shrinks as the profit margin decreases. Furthermore, the separating regions with quantity distortion also shrink. As a result, an improved demand forecast is more likely to benefit both parties.

6.4. Comparison to the Principal–Agent Model

The observations from Proposition 7 and our numerical study make an interesting contrast to those derived by Taylor and Xiao (2010), who use the principal–agent framework to solve a contracting problem similar to ours and obtain a menu of contracts that fully separate the buyer types. They uncover a surprising phenomenon—the buyer with private demand information benefits from better forecast only when his forecasting accuracy is extremely low. In this case, the seller must pay an increased information rent to screen the buyer, thereby suffering a reduction in profit. When the buyer's forecasting accuracy is high, however, the buyer loses from improved forecast while the seller gains. This is because the buyer's order quantity becomes closer to his first-best level, and the seller, who has the dominating power to dictate the contract terms, can reap most of the efficiency gain from better forecast. Taken together, Taylor and Xiao's results suggest that improved forecasting accuracy generally leads to a win–lose outcome for the supply chain.

In our dynamic bargaining game, by contrast, the contract terms are determined by a process of alternating offers between the buyer and the seller, which alleviates both the effect of information rent and disproportionate allocation of efficiency gain from better forecasting. Specifically, in most of the separating equilibrium regions, the seller's profit increases as the forecasting accuracy improves. The dynamic bargaining process allows the buyer to signal his private information through counteroffers. This in turn reduces the amount of information rent the seller has to pay to extract the buyer's private information. As a result, the seller gains from a better forecast. The buyer also gains from a better forecast in most of the separating equilibrium regions because he shares the efficiency

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gain. This explains the finding that under dynamic negotiations within a wide range of parameter space, both firms benefit from improved forecasting accuracy.

7. Concluding Remarks

In this paper, we study a dynamic bargaining process in a supply chain with asymmetric demand information. We characterize the perfect Bayesian equilibrium of the bargaining game and compare firms' profitability with the first-best benchmark. Note that our analysis is general enough to be applied to other buyer–seller trading problems under asymmetric information (privately observed cost, price, quality, etc.) with two-dimensional bargaining parameters as long as the marginal channel profit under one type dominates that under the other (i.e., $\pi'_H(q) > \pi'_L(q)$).

Applying the framework of dynamic bargaining to a classical supply chain problem allows us to draw novel insights into contracting under asymmetric information. Unlike the static principal–agent setup in which the seller (or the buyer) offers a take-it-or-leave-it contract to the buyer (or the seller), the dynamic bargaining model assigns more balanced power to both firms and allows them to interact strategically through rounds of offers and counteroffers. Furthermore, because firms are impatient, a key trade-off arises between delaying agreement and allowing information communication through making offers. Therefore, firms' patience plays an essential role in determining the bargaining outcome. We analyze the supply chain material and information flows as well as how the buyer's demand forecasting accuracy affects the firms' bargaining behaviors and their profitability. We find that the results under dynamic bargaining can be drastically different from those obtained using the one-shot principal–agent framework. The key insight is that the balanced power between firms under dynamic negotiations not only gives more distributed profit allocation but also raises the supply chain efficiency—the buyer has more incentive to improve demand forecasting accuracy, leading to a win–win outcome. With these results, we hope our paper will draw interest to the area of dynamic bargaining in supply chains, which has not gained enough attention in the literature of operations management.

Finally, we comment on the assumption that the two parties negotiate over a single contract. Our model can be extended to the one in which the seller offers a contract menu and the buyer (with private information) counteroffers a single contract (see Online Appendix D). Despite the seller's ability to better screen the buyer with contract menus, she may still prefer to reach an agreement with the two buyer types sequentially, for which the equilibrium exhibits similar patterns to those of our model. This is because sequential separation of the two types may allow the seller to avoid paying an information rent to the high type and/or eliminating the costly quantity distortion by the low type. Alternatively, one may let both players offer contract menus. Complications arise in characterizing the seller's belief structure because when the seller sees a contract menu offered by the buyer, she has to consider the buyer's preference over each contract within the menu. Inderst (2003) considers a model of alternating menu offers, but he does not use belief refinement to find the equilibrium. Instead, he imposes restrictive conditions on the model parameters to ensure a truth-telling outcome. Further research along this line requires a careful analysis of the seller's belief and a complete characterization of the equilibrium space.

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