# Demand Learning and Agreement Delay in Technology Adoption


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| Journal: | *Manufacturing and Service Operations Management* |
| Manuscript ID | MSOM-16-416 |
| Manuscript Type: | Innovative Operations |
| Keywords: | Technology Management and Process Design, Game Theory, Pricing and Revenue Management |
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# Demand Learning and Agreement Delay in Technology Adoption

**Abstract**

Negotiations associated with technology adoption can take months or years and agreements are often made close to deadlines. Existing theories attribute agreement delay and the deadline effect in bilateral negotiations to either asymmetric information or behavioral constraints. However, high-technology industries are often characterized by deep cooperation, effective communications, rational decisions, and uncertain demand for new technologies. We study the drivers and consequences of agreement delay in this context with a bilateral, dynamic bargaining model featuring uncertain demand facing the seller, information symmetry, and a deadline. We discover that incentives to learn about the seller's demand drive delay of agreements. With better information, the seller can possibly sell the manufacturing capacity to higher-value buyers; the buyer can also benefit from learning because the seller must make concessions if they find the demand to be weak. Thus, delay can be efficient and benefit both negotiators. However, we also show a sufficient condition under which delay hurts the buyer. Although extending the deadline can improve the joint payoff, close deadlines are preferred by the buyer when the buyer has a sufficiently low bargaining power or when the seller with a strong bargaining power is very likely to have excessive capacities.

[*Keywords*: technology adoption; bargaining; demand learning; delayed agreement; revenue management]

# 1 Introduction

Drawn-out negotiations and delayed agreements are common when new manufacturing or component technologies are adopted along supply chains. Existing theories generally attribute this delay and the so-called "deadline effect" (i.e., agreements are prone to be achieved close to the deadline) to asymmetric information (e.g., Cramton 1984), random delay of price offers (Ma and Manove 1993), or history-dependent preferences (Fershtman and Seidmann 1993 and Li 2007). Without these conditions, agreements should be immediately reached in bilateral negotiations (e.g., Robinstein 1982 and Muthoo 1999). However, high-technology industries such as the microprocessor market are often characterized by deep cooperation, efficient communications, and professional decisions. Hence, we are still uncertain as to why firms in such industries often cannot reach agreements until the last minute.

A recent example involves Apple, Inc. and Taiwan Semiconductor Manufacturing Company (TSMC) in the microprocessor market. According to *The Wall Street Journal*, since July of 2014, Apple and TSMC have collaborated on designing and testing the 14/16-nanometer A9 processor that would power 2015 iPhones and iPads (Luk 2014). Hundreds of TSMC engineers were sent to Apple headquarters to work on the project. Apple finally decided to award nearly one-third of the A9 processor orders to TSMC around April of 2015, after vacillating between GlobalFoundries and TSMC for more than half a year (Hughes 2015). It was reported, however, that the price was still unsettled for this deal even in August of 2015 when TSMC already had its 14/16-nanometer FinFET Process capacity ready and the new iPhone was due to be launched soon (Lien and Shen 2015). According to an August 2015 article in DigiTimes.com, Apple requested price cuts from both its A9 processor suppliers, Samsung Electronics and TSMC. TSMC, however, was not inclined to drop prices given that its 16-nanometer FinFET process had been adopted by downstream buyers such as Broadcom, Freescale Semiconductor, Nvidia, and MediaTek, among others, who could be potential users of TSMC's capacity.

Although infrequent, such delayed agreements are not unusual in high-technology industries. In another example, although Nvidia officially named Samsung to be its manufacturing partner in early 2015 and aimed to adopt Samsung's 14nm low-power plus fabrication process, the deal was still not finalized in June 2015, due to prolonged negotiations (Shilov 2015). According to an article from kitguru.net,

> "Nvidia's chip designers are working on chips to be made by Samsung, whereas other people are negotiating over pricing. If talks take too much time, then the start of volume production may be delayed, but since Nvidia will need Samsung's production services only in 2016, it still has weeks or even months to negotiate a deal."

More recently, Apple decided to switch from LCD (liquid crystal display) to OLED (organic light-emitting diode) panels for its 2017 iPhone and entered into negotiations with Samsung in November 2015 for the supply of the new panels (Singh 2015). Although Samsung had already signed a previous contract to supply OLED panels for the Apple watch, the iPhone contract was signed in April, 2016, after negotiations that lasted for several months (Ungureanu 2016). In fact, according to our interactions with practitioners, many other examples of delayed price agreement exist in high-technology industries but have not been covered by news reports.

The aforementioned examples motivate us to think about the following questions. Why do firms fail to reach an immediate agreement (e.g., within a day or so) when they have symmetric information and make concessions when rejections to their price offers are anticipated? Does delay benefit or hurt firms in high-technology industries? What is the impact of a deadline? As far as we are concerned, no clear answers to these questions can be found in the literature. Traditional strategic bargaining models that build on Robinstein (1982) and assume information symmetry often predict immediate agreement. The reason is that delay is costly and unnecessary because the consequences can be rationally expected and avoided by making concessions as long as both players benefit from the trade. In addition, traditional models normally assume that outside options are fixed and known; hence, no new information can be collected over time and thus delay will always hurt both firms.

An important feature of high-technology industries not captured by traditional models is that demand for new technologies is uncertain and thus the seller's outside option is unknown to both the buyer and seller at the outset of negotiations. The demand of a new technology depends on the number of firms that decide to adopt the technology. Normally, as these adoption decisions are publicly announced or reported by the media (e.g., Luk 2014 and Ungureanu 2016), both the buyer and seller learn about the demand over time. As a result, both parties may have incentives to delay the agreement. On the one hand, if many new buyers adopt the technology after the start of the negotiation with the focal buyer, the seller then would like to charge more for production capacity. On the other hand, the buyer may also benefit from better information regarding the demand because the seller may have to make concessions if they find that the demand is weak. Therefore, demand learning is a critical component of negotiation in high-technology industries.

Other important features of high-technology industries, especially the semicondutor industry, include price negotiations, expensive and inflexible production capacities, and inflexible procurement quantities. Because manufacturing facilities are costly and construction lead times are long, suppliers often build up their capacities based on demand forecasts and the capacities are inflexible during a selling season. OEM buyers often take advantage of this situation and drive hard bargains. Lacking full pricing power, suppliers are unable to set the price in a take-it-or-leave-it fashion and have to engage in negotiations. Normally, the purchase quantity is not a term for negotiation. This is because final products are often made of a large number of components, it is difficult for buyers to manipulate the procurement quantity of a particular one. Readers are referred to Karabuk and Wu (2003) and Zhang et al. (2016) for detailed descriptions of the semiconductor industry.

In this research, we focus on a setting wherein an OEM decides to adopt the technology offered by a supplier for the next generation of product and has determined the production plan of the final product as well as the purchase quantity of the focal component. (Although buyers in principle can allocate their purchase requirements among alternative suppliers, they do so at a very early stage in the planning process because products offered by different sellers differ in technical features and influence the design of the buyer's products. The change of order allocation later on can thus incur huge costs due to change of production plan and renegotiations.) Therefore, the buyer's only task is to negotiate with the supplier for the price before a fixed deadline. Motivated by the microprocessor market, we build a strategic bargaining model that has the following features: (1) the buyer and seller always have symmetric information; (2) a deadline for the negotiation exists; (3) the seller has a fixed capacity; (4) the market condition is unknown at the outset; (5) new adopters of the technology appear sequentially and randomly; and (6) the belief about the market condition is updated over time. Using this model, we learn that the delay of agreement is driven by incentives to learn, and learning can benefit both the seller and buyer. Contradicting most existing models that show delay is inefficient and that extending the deadline can hurt the participants, we show that expected payoffs can be improved by extending the deadline given that delay is costly and that the "deadline effect" exists—that is, agreements are frequently achieved either at the beginning or near the deadline. Of course, extending the deadline can sometimes hurt the negotiators, and we show when such situations occur. Particularly, the buyer can suffer from extending the deadline when his bargaining power is really low or when high demand for the technology is very unlikely (and the seller is likely to have excessive capacities). In addition, we find that the tendency of delay increases as more technology adopters appear and the belief of high demand gets stronger, which offers a partial explanation to the agreement delay between Apple and TSMC. These results hold even if we allow the value of the technology to depend on the market condition, or if we extend the model in a number of other ways.

## 2 Related Literature

This paper is related to three streams of research in the literature: sales management in new product or technology diffusion and adoption; bargaining with delay of agreements; and bargaining in supply chains. As far as we know, our paper is the first to explicitly model the process of B2B bargaining during new technology diffusion and adoption.

The literature of sales management in new product or technology diffusion and adoption is primarily based on the diffusion model proposed by Bass (1969). Robinson and Lakhani (1975) conducted the first study of a dynamic pricing problem of a seller who faces a price-dependent demand process, which is represented by an extended Bass model. Krishnan et al. (1999) then proposed the generalized Bass model and developed an optimal pricing path that is consistent with empirical data. These two papers assume that the seller has the absolute pricing power and thus they do not consider bargaining. More recently, Ho et al. (2002), Kumar and Swaminathan (2003), and Shen et al. (2011) studied the management of demand and sales dynamics in new product diffusion under supply constraint. In their models, a seller can turn down the request of a customer who then either waits or exits the market and thus delay of sales is possible. While Ho et al. (2002) showed that it is never optimal to refuse to satisfy any customers when a firm has inventory, Kumar and Swaminathan (2003) and Shen et al. (2011) argued that production constraints may in fact lead a firm to reject customer orders even when the firm has the inventory. However, this unintuitive but optimal behavior of denying customers disappears when the firm can dynamically set prices. Different from all of these studies, our paper is based on a strategic bargaining model and we focus on the time of agreement between a seller and a major buyer while they jointly learn about the demand of the new technology. Although learning models (e.g., Jensen 1982 and McCardle 1985) have been used in the literature of technology adoption to predict delay of adoption, they mostly focus on single-firm problems. To the best of our knowledge, our work is the first to consider bilateral negotiations in technology adoption. Our model suggests that even though agreement delay allows learning and thus can increase supply chain efficiency, delay may hurt one of the negotiating parties under certain circumstances.

Delay in reaching agreements has been frequently observed in practice and studied in the literature. So far, four causes of delay have been discussed in the literature: information asymmetry, random delay of price offers, history-dependent preferences, and multi-person sequence game. Cramton (1984) was among the earliest to study the phenomenon that trade often occurs after a costly delay and attributed the delay to the need for participants to learn each other's valuation under incomplete information. Later, Admati and Perry (1987) and Cramton (1992) proposed that bargainers can signal the strength of their bargaining positions by delaying. Fuchs and Skrzypacz (2010) studied a model that combines information asymmetry and the arrival of new buyers. They assumed that the seller has an indivisible good to sell, the seller does not know the value of the good for the focal buyer, and the negotiation will be terminated when a new buyer randomly arrives. Because the type of buyer is unknown, the seller gradually lowers the asking price and thus the agreement is delayed until a buyer accepts the price. In this model, the agreement delay is mainly driven by information asymmetry, and there is no learning about an outside option, which is the main feature of our model. In the latest paper in this stream, Feng et al. (2015) predicted a delay in price-quantity contract settlement in supply chains wherein the demand information is known only to the buyer. In all of the aforementioned papers, delay is driven by information asymmetry and an infinite horizon is assumed. Roth et al. (1988) considered bargaining with deadlines and documented some experimental evidence of last-minute agreements. Based on this observation, Ma and Manove (1993) proposed a continuous-time, alternating-offer model with a deadline and symmetric information. They assumed that players can decide when to make an offer or counteroffer but only after an exogenous, random delay due to information transmission and processing. Their model predicts that players adopt strategic delay early in the game and reach an agreement late in the game if at all. Because the player who makes an offer closer to the deadline is less likely to be rejected, the delay in the model is driven by the desire to obtain a stronger bargaining power. However, long and random communication lead time is not an appropriate assumption in high-technology industries. Recently, Damiano et al. (2012) studied a concession game wherein two players jointly decide between two alternatives and the value of each option is different for the two players and is privately known. They showed that delay of agreement can hurt or benefit the players and there exists an optimal deadline. The cause of delay in their model is again information asymmetry. Under the assumption of symmetric information, the models proposed by Fershtman and Seidmann (1993) and Li (2007) both predict delay of agreement; however, their models deviate from the assumption of rational behavior and rely on history-dependent commitment or preferences. Cai (2000) studied delay of agreement in multilateral bargaining with symmetric information. In the model, if weak players who reach agreements earlier can be forced to accept much smaller shares than tough players who reach agreements later, then delay can arise; in other words, the sequence matters. Assuming symmetric information, we contribute to this literature by offering a new explanatory factor of delay: learning about the existence of other buyers. Furthermore, while nearly all of the previous studies argue that delay is inefficient, we offer a counter argument that delay can benefit both parties.

The literature on multilateral bargaining in B2B markets or supply chains has emerged in recent years and this stream of research normally focuses on how profit is allocated among supply chain members. Depending on the game structure that is used, two streams of research mainly exist in this literature. One stream assumes that the multilateral bargaining happens sequentially and considers the impact of the bargaining sequence and coalitions. In an assembly-chain setting, Nagarajan and Bassok (2008) considered suppliers who form multilateral bargaining coalitions and compete for a position in the bargaining sequence. Different from sequential models in which bargaining power is manifested in the position in the sequence, simultaneous multilateral-negotiation models focus on the static equilibrium in which the profit allocation is determined by a negotiator's contribution to the entire system. Guo and Iyer (2013) compared simultaneous and sequential multilateral bargaining games in a channel system with one manufacturer and two competing retailers. They show that the manufacturer's choice of timing of bargaining—i.e., simultaneous versus sequential bargaining—should depend on the dispersion in retail prices. Dukes et al. (2006) and Lovejoy (2010) used simultaneous bargaining models to study the impact of a channel or chain structure. In a retail setting, Aydin and Heese (2015) studied an assortment problem of a retailer who engages in simultaneous bilateral negotiations with all manufacturers for a given assortment. Our model falls into the realm of sequential bargaining, but we supplement the literature by studying the situation wherein the number of participants is uncertain. In addition, we focus on the demand-learning process and efficient capacity allocation during technology adoption.



# 3 The Base Model

Supplier $\mathcal{A}$ sells a new component or process technology with a fixed capacity to multiple OEM (original equipment manufacturer) buyers over multiple periods. Due to heterogeneity in development cycles, the buyers may decide to adopt the new technology at different times. In the semiconductor industry, buyer adoption decisions are often called design-wins of the seller, and such decisions indicate future demand. Without loss of generality, we assume that a major buyer, $\mathcal{B}$, is the first adopter and starts a negotiation with seller $\mathcal{A}$ in period 1. While $\mathcal{A}$ and $\mathcal{B}$ are negotiating, design-wins may be achieved with other buyers. We define each period to be short enough so that at most one design-win can be achieved at the beginning of a period. Because the number of buyers is finite, the arrival process of design-wins will end. When potential adopters exist, a new design-win will be achieved in a period ($t > 1$) with probability $\alpha \in (0, 1)$.

Motivated by the Apple-TSMC as well as the Nvidia-Samsung example, we focus on a setting wherein $\mathcal{B}$ has decided to adopt the technology for the next generation of product and the overall production plan as well as the launch date of the new product has been determined. Hence, there is a deadline for $\mathcal{B}$ to reach an agreement. However, the time of agreement will not affect the production plan or the launch date of the final product. We consider that $\mathcal{B}$ has to reach an agreement by period $T \geq 1$; otherwise, $\mathcal{B}$ has to give up the technology and receive a fixed payoff that is normalized to zero. Note that seller $\mathcal{A}$ may continue the selling after period $T$. Because the final product is made of different components, it is difficult for $\mathcal{B}$ to change the procurement quantity of a particular one. We thus consider that $\mathcal{B}$ demands $Q > 0$ units of capacity from $\mathcal{A}$ and partial fulfillment is not accepted.

We focus on the negotiation between $\mathcal{A}$ and $\mathcal{B}$, which proceeds as follows. In each period, one party, either $\mathcal{A}$ or $\mathcal{B}$, is randomly selected to propose a price. If the other party accepts the price, an agreement is reached. Otherwise, both parties wait until the next period and the process repeats. Such a random-proposer bargaining game is common in the economics literature. Similar settings can be found in Binmore (1987), Fershtman and Seidmann (1993), and Muthoo (1999). We assume that buyer $\mathcal{B}$'s relative power of bargaining is measured by $\beta \in (0,1)$ such that $\mathcal{B}$ proposes the price in any period with probability $\beta$. This is because the proposer can set the price to the reservation price of the other party when an agreement is possible and thus seize a larger share of the surplus. To be consistent with the classic strategic bargaining models (e.g., Rubinstein 1982 and Muthoo 1999), we do not allow the players to quit the negotiation in the base model unless the bargaining breaks down. We define break-downs later in this section and the option of quitting will be discussed in Section 6.4.

The total number of adopters, $N$, including buyer $\mathcal{B}$, is unknown at the beginning. Two possible market conditions exist: an average market, wherein $N = N_L \geq 1$, or a good market, wherein $N = N_H > N_L$. Therefore, both $\mathcal{A}$ and $\mathcal{B}$ can learn about the market condition by counting the arrival of design-wins. Once the critical number, $N_L + 1$, is observed, both parties can be sure that the market is good. It is a common prior belief that $\Pr\{N = N_H\} = \gamma \in (0,1)$. Let $N_t$ denote the total number of adopters that have appeared by period $t$ and we have $N_1 = 1$. According to the Bayes' theorem, we know that

$$\Pr\{N = N_H | N_t < N_L, t > 0\} = \gamma;$$

$$\Pr\{N = N_H | N_t > N_L, t > 0\} = 1;$$

$$\Pr\{N = N_H | N_{t'-1} < N_L, N_{t'} = N_L, N_{t'+t} = N_L, t \geq 0\} = \frac{\gamma(1-\alpha)^t}{1-\gamma+\gamma(1-\alpha)^t}.$$

Hence, the belief about the market condition in period $t$ depends on the history, $\{N_k\}_{k=1}^t$. Let $\theta_t = \Pr\left\{N = N_H | \{N_k\}_{k=1}^t\right\}$ be the belief in period $t$ and $\pi$ be seller $\mathcal{A}$'s opportunity cost per unit of the capacity demanded by buyer $\mathcal{B}$. In other words, $\mathcal{A}$ can obtain an expected profit of $Q\pi$ if the capacity is not sold to buyer $\mathcal{B}$. For the sake of tractability, we assume that $\pi = 0$ in an average market and $\pi = \pi_0 > 0$ in a good market. Before $N$ or the market condition is known, the per-unit opportunity cost in period $t$ is thus $\pi_t^e = \theta_t \cdot \pi_0$.

Although a two-point distribution of the market condition is a simplification, it can actually be mapped to certain realistic situations. For example, in practice, potential adopters can usually be classified into two types: strategic partners and market followers. Strategic partners will definitely adopt the technology, and market followers will adopt the technology if the market believes that the technology is promising. In this case, the firms can be sure that the market condition is good if one of the market followers decides to adopt the technology. Readers are referred to Section 6.3 for further discussion. In addition, notice that negotiations between the supplier and other buyers during the process will not influence the negotiation with $\mathcal{B}$ as long as $\pi = 0$ or $N_t \leq N_L$. Once the market condition is known to be good, no more delay is necessary and the supplier has to decide whether to reach an agreement with $\mathcal{B}$ or terminate the negotiation.

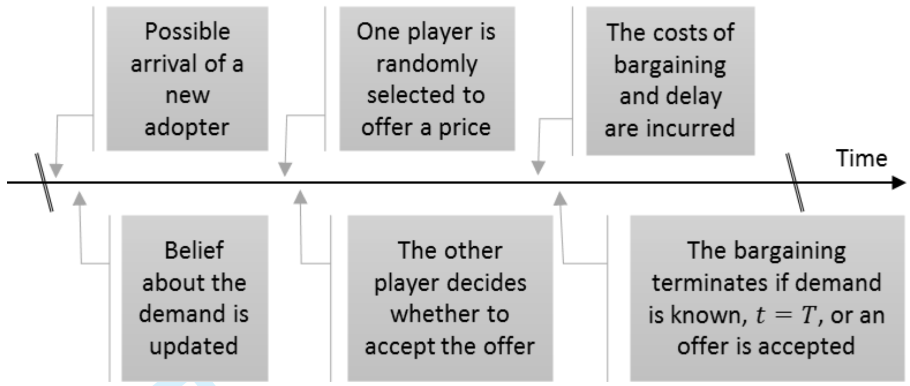
For the buyer, it is publicly known that each unit of the capacity has a fixed value of $v > 0$. For the seller, we set the marginal production cost to zero because a positive production cost will not qualitatively change the results. Even if the production cost depends on whether an agreement is reached, the difference can be capture by the supplier's opportunity cost. In addition, bargaining and delaying the agreement are costly for both the seller and buyer because bargaining consumes labor hours and delaying the agreement may cause delay of other business activities such as marketing and pricing. It costs the seller $c_S > 0$ and the buyer $c_B > 0$ per period unless an agreement has been reached or the bargaining breaks down. Both $c_S$ and $c_B$ are public information.

Finally, the negotiation terminates either when an agreement is achieved or the negotiation breaks down. The negotiation breaks down either (1) when the deadline is reached, or (2) when the market condition is known yet an agreement is not achieved. The timing of events in a period is summarized in Figure 1.

# 4 Model Analysis

This is a non-stationary, strategic bargaining model with symmetric information and two-sided learning. We know that the result of a bargaining game depends on the bargaining powers, the value of trade, and the outside options. The bargaining powers (i.e., $\beta$ and $1 - \beta$) and the value

Figure 1: The Timing of Events in Period $t$






of trade (i.e., $vQ$) are fixed in this game, but the outside options may change as the players learn about the market. As described in the previous section, the buyer's outside option is 0 and the seller's outside option is $\pi_t^e = \theta_t \cdot \pi_0$ per unit of capacity. Clearly, an agreement can be reached in period $t$ only if $v \geq \theta_t \cdot \pi_0$; however, an agreement may not be reached even if $v \geq \theta_t \cdot \pi_0$. Our goal in this section is to understand how $\theta_t$ evolves and when an agreement can be reached. Because the bargaining has a deadline, we will use a backward induction to solve this dynamic game.

First, notice that $\theta_t$ is a function of $\{N_k\}_{k=1}^t$ and from the firms' perspective the evolution of $\{N_k\}_{k=1}^t$ in turn depends on $\theta_t$. Hence, define the state in period $t$ as $s_t = \{N_t, \theta_t\}$. We know that when $N_t < N_L$, the arrival process of design-wins is always on and there is no learning. Hence, for $N_t < N_L$, the state evolves in the following way:

$$N_{t+1} = \begin{cases} N_t + 1 & \text{w.p. } \alpha \\ N_t & \text{w.p. } 1 - \alpha \end{cases} \quad \text{and } \theta_{t+1} = \theta_t = \gamma.$$

The learning takes place when $N_t \geq N_L$. Specifically, $N_{t+1} = N_t + 1$ if $N = N_H$ and a new adopter arrives. Once $N_t > N_L$, we can confirm that $N = N_H$; otherwise, we update the belief. Hence, for $N_t \geq N_L$, the transition takes the following form:

$$N_{t+1} = \begin{cases} N_t + 1 & \text{w.p. } \alpha\theta_t \\ N_t & \text{w.p. } 1 - \alpha\theta_t \end{cases} \quad \text{and } \theta_{t+1} = \begin{cases} 1 & \text{if } N_{t+1} > N_L \\ \frac{(1-\alpha)\theta_t}{(1-\alpha)\theta_t + 1 - \theta_t} & \text{if } N_{t+1} = N_L \end{cases}.$$

With the previously stated transition rules, we can try to understand the bargaining process.

### 4.1 The Bargaining Process

Let $U_t^B$ and $U_t^S$ be the expected payoff for the buyer and seller, respectively, in period $t$ ($\geq 1$) given that no agreement is reached. Accordingly, the lowest price acceptable for the seller in period $t$ is $U_t^S/Q$ and the highest price acceptable for the buyer is $v - U_t^B/Q$. Thus, an agreement can be reached in period $t$ if and only if $U_t^S \leq vQ - U_t^B$ or, equivalently,

$$U_t^S + U_t^B \leq vQ. \tag{1}$$

In the following, we focus on the derivation of $U_t^S + U_t^B$ to determine whether an agreement is reached or delayed in period $t$.

If an agreement cannot be reached by period $T$, the buyer will receive an payoff of 0 in period $T+1$ and the seller will receive an expected payoff of $\theta_T \cdot \pi_0 \cdot Q$. Hence, we have $U_T^B = 0$ and $U_T^S = \theta_T \cdot \pi_0 \cdot Q$, and we can do a backward induction for period $t \leq T-1$ as follows. In any period $t+1$, either the buyer or the seller proposes the price. If the buyer makes the offer, the best price to offer is $\min\left\{v - U_{t+1}^B/Q, U_{t+1}^S/Q\right\}$ and the buyer's payoff is $\max\left\{U_{t+1}^B, vQ - U_{t+1}^S\right\}$. If the seller makes the offer, the buyer's payoff is always $U_{t+1}^B$ because the price offered by the seller (i.e., $\max\left\{v - U_{t+1}^B/Q, U_{t+1}^S/Q\right\}$) will not be lower than $\mathcal{B}$'s highest acceptable price (i.e., $v - U_{t+1}^B/Q$). Therefore, the no-agreement payoff for the buyer in period $t$ is

$$U_t^B\left(N_t, \theta_t\right) = \mathbf{E}\left[\beta \max\left\{U_{t+1}^B, vQ - U_{t+1}^S\right\} + (1-\beta)\, U_{t+1}^B | N_t, \theta_t\right] - c_B. \tag{2}$$

Similarly, the no-agreement payoff for the seller in period $t$ is

$$U_t^S\left(N_t, \theta_t\right) = \mathbf{E}\left[\beta U_{t+1}^S + (1-\beta)\max\left\{U_{t+1}^S, vQ - U_{t+1}^B\right\} | N_t, \theta_t\right] - c_S. \tag{3}$$

Combining (2) and (3), we have

$$U_t^B + U_t^S = \mathbf{E}\left[\max\left\{U_{t+1}^B + U_{t+1}^S, vQ\right\} | N_t, \theta_t\right] - c_S - c_B. \tag{4}$$

Using this iteration formula, we can derive the following results. Lemma 1 suggests that if bargaining is too costly for either party or the capacity is of high value to the buyer, an agreement will be reached immediately. This result is independent of bargaining power $\beta$. We then derive a necessary condition for the delay of agreement by introducing Proposition 1. Note that all of the technical proofs are presented in the supplementary.

**Lemma 1.** *An agreement can be reached in period $t < T$ if and only if*

$$c_S + c_B \geq \mathbf{E}\left[\max\left\{0, U_{t+1}^B + U_{t+1}^S - vQ\right\} |N_t, \theta_t\right]. \tag{5}$$



**Proposition 1.** *If $vQ + c_S + c_B \geq \pi_0 Q$, the agreement is never delayed.*

To study possible delays of the agreement, we now assume that $\pi_0 Q > vQ + c_S + c_B$ for the rest of our analysis. In preparation, define

$$\begin{aligned}\delta_t\left(N_t, \theta_t\right) =& U_t^B\left(N_t, \theta_t\right) + U_t^S\left(N_t, \theta_t\right) + c_S + c_B - vQ \\ =& \mathbf{E}\left[\max\left\{0, U_{t+1}^B + U_{t+1}^S - vQ\right\} |N_t, \theta_t\right] \\ =& \mathbf{E}\left[\max\left\{0, \delta_{t+1} - c_S - c_B\right\} |N_t, \theta_t\right].\end{aligned} \tag{6}$$

Accordingly, we know that $\delta_t\left(N_t, \theta_t\right) \geq 0$ and $U_t^B + U_t^S = vQ - c_S - c_B + \delta_t$ for period $t \leq T-1$. In light of Lemma 1, an agreement can be reached if and only if

$$\delta_t \leq c_S + c_B. \tag{7}$$

Hence, $\delta_t$ can be viewed as the *tendency* of delay in period $t$. Again, it is important to notice that $\delta_t$ is independent of the bargaining power $\beta$.

We now perform a backward induction on $U_t^B + U_t^S$, starting from period $T$, and the procedures are illustrated in Table 1. From the table, we can see that the key is to determine the value of $\delta_t$ for each period $t$ and then we know the dynamics of the bargaining process. However, it is difficult to determine the values directly. Given that $\delta_t$ can be written iteratively as a function of $\delta_{t+1}$, we will try to derive some structural properties of $\delta_t$ and the bargaining process in the next section.

Table 1: Backward Induction on $U_t^B + U_t^S$ Given $\pi_0 Q > vQ + c_S + c_B$

| Period | Case: $N_t < N_L$ | Case: $N_t = N_L$ | Case: $N_t > N_L$ |
|---|---|---|---|
| $T$ | $\pi_0 \gamma Q$ | $\pi_0 \theta_T Q$ | $\pi_0 Q$ |
| $T-1$ | $Q \cdot \max\left\{\pi_0 \gamma, v\right\} - c_S - c_B$ | $Q \cdot \max\left\{\pi_0 \theta_{T-1}, v + \alpha \theta_{T-1}\left(\pi_0 - v\right)\right\}$<br>$-c_S - c_B$ | $\pi_0 Q$ |
| $T-2$ | For $N_{T-2} < N_L - 1:$<br>$vQ - c_S - c_B$<br>$+\left[\left(\pi_0 \gamma - v\right) Q - c_S - c_B\right]^+$<br>For $N_{T-2} = N_L - 1:$<br>$vQ - c_S - c_B + \delta_{T-2}\left(N_L - 1, \gamma\right)$ | $vQ - c_S - c_B + \delta_{T-2}\left(N_L, \theta_{T-2}\right)$ | $\pi_0 Q$ |
| $\ldots$ | $\ldots$ | $\ldots$ | $\ldots$ |
| $t$ | For $N_t < N_L - (T - t - 1):$<br>$vQ - c_S - c_B$<br>$+\left[\left(\pi_0 \gamma - v\right) Q - c_S - c_B\right]^+$<br>For $N_t \geq N_L - (T - t - 1):$<br>$vQ - c_S - c_B + \delta_t\left(N_t, \gamma\right)$ | $vQ - c_S - c_B + \delta_t\left(N_L, \theta_t\right)$ | $\pi_0 Q$ |

Note:

$$\delta_{T-1}\left(N_L - 1, \gamma\right) = Q \cdot \max\left\{0, \pi_0 \gamma - v\right\}$$
$$\delta_{T-1}\left(N_L, \theta_{T-1}\right) = Q \cdot \max\left\{\pi_0 \theta_{T-1} - v, \alpha \theta_{T-1}\left(\pi_0 - v\right)\right\}$$
$$\delta_{T-2}\left(N_L - 1, \gamma\right) = (1 - \alpha) \max\left\{0, \delta_{T-1}\left(N_L - 1, \gamma\right) - c_S - c_B\right\} + \alpha \max\left\{0, \delta_{T-1}\left(N_L, \gamma\right) - c_S - c_B\right\}$$
$$\delta_{T-2}\left(N_L, \theta_{T-2}\right) = \theta_{T-2} \alpha \left(\pi_0 - v\right) Q + \left(1 - \theta_{T-2} \alpha\right) \max\left\{\delta_{T-1}\left(N_L, \frac{(1-\alpha)\theta_{T-2}}{1 - \alpha \theta_{T-2}}\right) - c_S - c_B, 0\right\}$$
$$x^+ = \max\{0, x\}$$

## 4.2 Delay of the Agreement

Given that $\pi_0 Q > vQ + c_S + c_B$, we can easily prove that $U_t^B + U_t^S \leq \pi_0 Q$ for any $t$, $N_t$, and $\theta_t$, using (4) and induction. It means that the total no-agreement payoff should be bounded by $\pi_0 Q$, the total opportunity loss for the seller in a good market. With this observation, we can proceed to prove the following result.

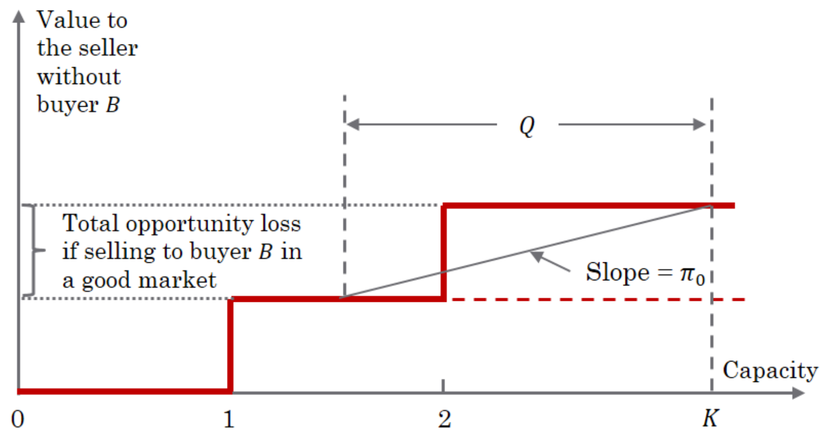
**Proposition 2.** *$\delta_t(N_t, \theta_t)$ is an increasing function of $\pi_0$ given any possible $t$, $N_t$, and $\theta_t$.*

Note that $\pi_0$ carries the influence from several factors, including the capacity level, the difference in demand between the two market conditions, other buyers' valuation of the component, and their bargaining powers. It is reasonable to expect that the tendency of delay increases as the supplier's opportunity cost increases. This is because higher opportunity cost implies higher benefit the supplier could obtain from learning and thus better allocation of the capacity. On the other hand, the buyer has an high incentive to learn about the market condition when $\pi_0$ is high because if they agree immediately the joint surplus (i.e., $vQ - \pi_0\theta_t Q$) is small and thus the buyer has to pay a high price. Thus, from the buyer's standpoint, the downside of delay is limited but the upside is high. Although this logic also applies to the next result, the proof is more complicated.

**Proposition 3.** *$\delta_t(N_t, \theta_t)$ is an increasing function of $\theta_t$ given any possible $t$ and $N_t$.*

Proposition 3 reveals the influence of the belief about market potential on the delay tendency. It suggests that the higher the chance that the demand is high for the new technology, the more likely that the agreement will be delayed. Proposition 3 offers a partial explanation to the delay of agreement between Apple and TSMC. Given that the 16-nanometer FinFET process technology was believed to be popular in the market, the agreement on price was delayed due to a high no-agreement payoff for TSMC. From Apple's perspective, it was better to wait and see if the belief could be weakened in the end. However, it turned out that Apple did not benefit from waiting and the bargaining might have broken down if Apple had not changed the strategy. According to an online article (Clover 2015), Apple in the end significantly increased the order size from TSMC (from nearly 1/3 to about 60%) such that the average unit value of the demanded capacity was reduced for TSMC. We have learned from Proposition 1 that, as long as the total opportunity loss is held constant for the seller, the agreement will be reached immediately if $Q$ is large enough,

Figure 2: The effect of $Q$ on $\pi_0$




*Note*. In this example, $N_L = 2$ and $N_H = 3$. $K$ is the total capacity level. Each buyer will purchase one unit of capacity and they do not accept partial fulfillments. The bold line is the value of capacity without selling to buyer $\mathcal{B}$. We can see that as long as $K - 2 < Q \leq K - 1$, the total opportunity loss ($\pi_0 Q$) is a constant.



because when $\pi_0 Q$ is held constant, $\pi_0$ decreases as $Q$ increases. According to Proposition 2, $\delta_t$ is reduced as $\pi_0$ is reduced. In Figure 2, we use a simple example to illustrate why $\pi_0 Q$ can be held constant and how $\pi_0$ will be reduced if $Q$ is increased.

The next result concerns how the number of new adopters (i.e., the number of arrivals during the bargaining process) influences the tendency of delay. We know that learning and updating of beliefs take place only when $N_t = N_L$. However, we show that even when there is no learning, the number of new adopters matters to the tendency of delay.

**Proposition 4.** *$\delta_t (N_t, \gamma) \geq \delta_t (N_t - 1, \gamma)$ for any $t < T$ and $N_t < N_L$.*

Proposition 4 adds to the explanation of the agreement delay between Apple and TSMC. As more downstream buyers adopted the 16-nanometer FinFET process, it became easier for TSMC to reject Apple's price-cut requests. This may not be directly related to belief about the market potential of the technology. According to our model, as more buyers arrive, it becomes easier or less costly for both the buyer and seller to wait for the learning stage or the threshold point (i.e., $N_t = N_L$) and thus the tendency of delay is high.

How do bargaining costs influence the delay of agreements? We know that the agreement is delayed in period $t$ if and only if $\delta_t (N_t, \theta_t) > c_S + c_B$. However, the tendency of delay itself is a function of $c_S + c_B$. Hence, it is necessary to know how $\delta_t (N_t, \theta_t)$ depends on $c_S + c_B$ in order to understand the impact of the bargaining costs. In preparation, we define $c_* = c_S + c_B$ as the total cost of bargaining per period. We then show in the following proposition that as the bargaining costs increases, agreement delay will be less and less likely.

**Proposition 5.** *$\delta_t(N_t, \theta_t)$ is a decreasing function of $c_*$ given any possible $t$, $N_t$, and $\theta_t$.*

### 4.3 The Condition for Participation

In the previous section, we investigated the factors that are associated with the tendency of delay given that the firms have participated in the negotiation. We now study the condition under which the firms would like to enter the negotiation at the outset. In preparation, we define $U_0^S$ and $U_0^B$ as the expected payoffs associated with the target capacity for the seller and buyer, respectively, at the beginning of period 1 given that the firms participate in the negotiation. It is clear that, $U_0^S + U_0^B = \max\left\{U_1^B + U_1^S, vQ\right\} - c_*$. Additionally, the outside payoffs associated with the target capacity at the beginning of period 1 are $\pi_0\gamma Q$ for the seller and 0 for the buyer. Hence, the firms would like to enter into negotiation as long as $U_0^S + U_0^B \geq \pi_0\gamma Q$ and if side payments are allowed. Clearly, if the total value of this transaction is too low, the firms would never start the negotiation given that negotiation is costly. The following proposition gives a sufficient condition for both firms to participate.

**Proposition 6.** *If $vQ \geq \pi_0\gamma Q + c_*$ and side payments are allowed, firms will negotiate.*

Hence, the firms would never negotiate if $v$ is too low and would never delay the agreement if $v$ is too high. To avoid the trivial case of no participation or no delay, it is sufficient to assume

$$\pi_0\gamma + \frac{c_*}{Q} \leq v < \pi_0 - \frac{c_*}{Q}, \tag{8}$$

which is possible when $\gamma < 1 - \frac{2c_*}{\pi_0 Q}$. Given this condition, it is possible for the firms to achieve a total expected payoff ($U_0^S + U_0^B$) that is higher than $vQ - c_*$ and $\pi_0\gamma Q$ by delaying the agreement and collecting more information during the negotiation because the firms would achieve different results given different market conditions. If the demand state is known to be "low," the firms would reach an agreement and receive a total payoff of $vQ$ minus the bargaining costs; if the demand state is known to be "high," the bargaining would break down and the firms would receive a total payoff of $\pi_0 Q$ minus the bargaining costs. Therefore, in expectation, the total payoff with more information could be higher than that given by no negotiation or an immediate agreement.

The logic behind the condition for participation also applies to the choice of quitting the negotiation or staying in any period if quitting is allowed. Details about the choice of quitting will be discussed in Section 6.4. We will see that firms would never choose to quit if $vQ \geq \pi_0 \gamma Q + c_*$. Therefore, agreement delay under this condition is entirely driven by the value of learning.

### 4.4 The Impact of a Deadline

Due to inflexible production schedules, deadlines often exist for price negotiations. In addition, in order to avoid stalling or delay of agreements, a commonly used bargaining tactic is to commit to a deadline (e.g., Moore 2004). Based on previous analyses, we know that firms could benefit from delay by collecting more information about the market condition. Hence, the existence of a deadline may hurt the firms that are in such a situation. In this section, we analyze the impact of a deadline in technology adoption. In particular, we examine how a change in deadline will affect the firms' expected payoffs and participation.

In preparation, we assume that $\pi_0 \gamma < v < \pi_0$, which is weaker than (8). Additionally, let $u_0(T, N_L, N_H, \gamma) = U_0^S + U_0^B$ denote the joint expected payoff of a bargaining game given that the deadline is period $T$, the number of buyers is $N_L$ ($N_H$) in an average (a good) market, and the prior belief about a good market is $\gamma$. Recall that $U_0^S + U_0^B = \max\left\{U_1^B + U_1^S, vQ\right\} - c_*$ and that $U_1^B + U_1^S = \mathbf{E}\left[\max\left\{U_2^B + U_2^S, vQ\right\}\right] - c_*$, wherein the expectation is on $\{N_2, \theta_2\}$. If we treat the bargaining game starting from period 2 as a new bargaining game, then the joint expected payoff of this new bargaining game is thus $u_0(T', N_L', N_H', \gamma') = \max\left\{U_2^B + U_2^S, vQ\right\} - c_*$, wherein the deadline $T' = T - 1$, prior belief $\gamma' = \theta_2$, the total number of adopters in an average market $N_L' = N_L - N_2 + 1$, and in a good market $N_H' = N_H - N_2 + 1$. Therefore, we have $u_0(T, N_L, N_H, \gamma) = \max\left\{\mathbf{E}\left[u_0(T-1, N_L - N_2 + 1, N_H - N_2 + 1, \theta_2)\right], vQ\right\} - c_*$. In particular, for any $T \geq 2$,

$$u_0(T, N_L, N_H, \gamma) = -c_* + \max\left\{\begin{array}{c}\left(1 - \alpha \cdot \gamma^{(2-N_L)^+}\right) \cdot u_0(T-1, N_L, N_H, \gamma) + \\ \alpha \cdot \gamma^{(2-N_L)^+} \cdot u_0\left(T-1, (N_L-2)^+ + 1, N_H - 1, \frac{(1-\alpha)^{(2-N_L)^+} \cdot \gamma}{(1-\alpha)^{(2-N_L)^+} \cdot \gamma + 1 - \gamma}\right)\end{array}, vQ\right\}, \quad (9)$$

where $x^+ = \max\{0, x\}$. Now we can analyze how $u_0$ changes with $T$, using the above iterative relationship (9) and induction. It reveals that the closer the deadline, the lower the expected payoff a firm can obtain from participating in the negotiation, which confirms our conjecture.

**Proposition 7.** *$u_0(n+1, N_L, N_H, \gamma) \geq u_0(n, N_L, N_H, \gamma)$ for $\forall N_L, N_H, \gamma$ and $n \geq 1$.*

We then compare our result with those from the literature. On one hand, our model suggests that the existence of a finite deadline brings inefficiency to the bargaining game and technology adoption. In this regard, our result is consistent with the literature. On the other hand, our model offers a new insight regarding how a change in deadline affects firm payoffs. Most studies (e.g., Ma and Manove 1993, Fershtman and Seidmann 1993, and Damiano et al. 2012) suggest that extending a deadline hurts the players because delay is costly and players tend to reach an agreement close to the deadline without bringing additional benefits to the system. However, our model indicates that extending the deadline benefits the system by better allocating the production capacity among buyers with different valuations. Therefore, both negotiating parties can be better off by extending the deadline if side payments are allowed.

A related question emerges immediately. When are side payments necessary? In other words, if side payments are not allowed, when will the buyer or supplier suffer from extending the deadline? To answer this question, now let's look at the impact of a deadline from a single firm's standpoint. To avoid the trivial cases, we assume that $\pi_0\gamma < v < \pi_0$. We then proceed as follows. First, setting $T = 1$, we do not allow delay of the agreement. In this case, we know that $U_1^B = 0$ and $U_1^S = \pi_0\gamma Q$. The transaction price is expected to be $\bar{p} = \beta \min\{v, \pi_0\gamma\} + (1-\beta)\max\{v, \pi_0\gamma\} = \beta\pi_0\gamma + (1-\beta)v$ and thus the buyer's (*ex ante*) expected payoff is $U_0^B = (v - \bar{p})\,Q - c_B = \beta Q\,(v - \pi_0\gamma) - c_B$. Next, we allow delay by setting $T > 1$. Let $U_0^B(T)$ denote the buyer's expected payoff given a general $T$. We compare $U_0^B(T)$ with $U_0^B(T-1)$. We find that the impact of $T$ on $U_0^B(T)$ depends on the bargaining power and the seller's outside option.

**Proposition 8.** *For any $T > 1$ and $\pi_0\gamma < v < \pi_0$, we have $U_0^B(T) < U_0^B(T-1)$ if $\gamma\pi_0 Q \leq (c_B - \beta c_*)/\beta$.*

It is immediately observed that $\gamma\pi_0 Q \leq (c_B - \beta c_*)/\beta$ holds if $\beta \to 0$. Hence, given all other parameters, extending the deadline will hurt the buyer if $\beta$ is small enough. This is very intuitive. When $\beta$ is too small, the buyer will either pay a very high price (close to $v$) to purchase the component or receive the outside payoff of zero. In this case, the cost of delay will outweigh the benefit of learning for the bueyer. Note that this logic also applies to the supplier and thus when $\beta$ approaches 1 the supplier will suffer from extending the deadline. Given that the joint payoff always (weakly) increases with $T$, the buyer must benefit from extending the deadline when the supplier suffers.

In addition, an interesting observation is that extending the deadline can hurt the buyer when the seller has a weak outside option. For example, if $c_B = c_S$ and $\beta = 1/3$, we have $U_0^B(T) < U_0^B(T-1)$ if $\gamma\pi_0 Q \leq c_B$. Hence, even if the buyer has a decent bargaining power, he cannot benefit from learning if the seller's expected outside option value is too low. This result is interesting because in this case we expect the buyer to obtain a significant portion of the surplus as well as the benefit of learning. However, notice that the buyer can benefit from learning only when they find that the market is likely to be weak and thus the seller's opportunity cost ($\gamma\pi_0 Q$) is weakened. Given that $\gamma\pi_0 Q$ is low in the first place, the benefit of learning will be marginal for the buyer and thus will be outweighed by the cost of delay.

Therefore, we learn that the buyer and seller will have a conflict of interest in terms of setting a deadline when either party has a sufficiently weak bargaining power or when the seller's expected opportunity cost and the buyer's bargaining power are both sufficiently low. When the buyer is too weak in terms of bargaining power, the seller should use side payments to subsidize the buyer and set the deadline as far in the future as possible so that the capacity can be better allocated. Surprisingly, when the initial belief $\gamma$ for a good market is too low, the seller should also consider subsidizing the buyer with side payments as long as the seller's bargaining power is sufficiently high. If side payments are not allowed and firms are able to commit to an arbitrary deadline prior to the negotiation, we should expect the negotiation to terminate sooner when these conditions are satisfied.

## 4.5 The Time of Agreement

Given that the firms participate in the negotiation and delay is possible, when can the firms eventually reach an agreement? To answer this question, let's first check how the delay tendency is affected by the length of the negotiation window. We can use ~~Proposition 8~~ to show that the tendency of delay in any period increases as the deadline is extended. In other words, the longer the negotiation window, the more likely the agreement is delayed. In fact, Proposition 9 implies that if $\pi_0\gamma < v < \pi_0$ , we then have $\delta_{t-1}(N_t, \gamma) \geq \delta_t(N_t, \gamma)$ for any $t < T$ and $N_t < N_L$. This is because shortening the negotiation window by one period is equivalent to passing one period without observing a new adopter and without updating the belief.

**Proposition 9.** *Given that $\pi_0\gamma < v < \pi_0$, $\delta_t(N_t, \theta_t)$ is an increasing function of $T$ given any possible $t$, $N_t$, and $\theta_t$.*

Combining all the previous propositions, we arrive at two conclusions. First, reaching an agreement is possible in any period $t \leq T$. If the agreement cannot be reached in the first period, the delay tendency can be weakened as time passes and thus the agreement can be reached in any subsequent period. Second, agreements—if not reached at the beginning, are likely to be reached after some periods of learning. Although Proposition 9 suggests that the tendency of delay can be weakened over time, this effect will be reduced or even eliminated according to Proposition 4 as new adopters appear. Once the critical point is reached, the learning starts and the delay tendency will be continually reduced conditioning on that the bargaining does not break down. Therefore, the overall pattern of the frequency of agreement should be "U"-shaped, which is supported by our simulations.

## 5 Numerical Examples and Simulation

Through theoretical analysis, we understand that the delay of agreement in our model is driven by the benefit of learning about the demand, and that the tendency of delay can be influenced by a number of factors. Here we try to use numerical examples to gain a better understanding of how the bargaining actually proceeds under different parameter settings and calculate the expected payoffs. To this end, we first use a large number of random instances to simulate the bargaining process given that the participation condition is strictly satisfied. Second, we investigate how the firms' respective expected payoffs, $U_0^B$ and $U_0^S$ (as well as $U_0^B + U_0^S$) change with the parameters. In our numerical examples, the default parameter setting is as follows: $\pi_0 = 10$, $v = 6$, $\alpha = 0.5$, $\beta = 0.5$, $\gamma = 0.4$, $Q = 1$, $N_L = 5$, $c_S = c_B = 0.01$, and $T = 10$.

In the first study, we examine eight different parameter settings. We generate 1,000 random instances for each setting and plot a histogram showing the distribution of the time of termination (i.e., agreement or breakdown). For the simulation, we build a tree of all the possible results of the game under a fixed parameter setting, calculate the expected no-agreement payoffs at each node of the tree, and generate random market conditions and buyer arrivals to obtain "sample paths" of the game. The results are presented in Figure 3. In aggregate, an interesting observation is that, in most cases, the agreement is either reached in the first few periods or close to the deadline, depending on the parameter setting. This observation is consistent with the result of Propositions 2, 3 and 4: the tendency of delay increases as more buyers arrive and an agreement can be achieved only when belief of a good market becomes low enough through learning. We particularly test the impact of $\alpha$, $\beta$, $\gamma$, and $N_L$.

The time of agreement is influenced by $\alpha$ (i.e., the probability of a new arrival given that the arrival process is still on) in a non-monotonic way. When $\alpha$ is low (= 0.2), the agreement is always reached in period 1, because the low arrival rate of buyers makes it costly to learn about the demand given a fixed cost of bargaining per period. When the benefit of learning is low, firms can reach agreement immediately. In contrast, a higher $\alpha$ (= 0.5, as shown in the second row of Figure 3) allows easier learning and thus delay occurs. As $\alpha$ becomes larger, the time of agreement shifts rapidly from the first few periods to the last few periods, skipping periods in the middle. If we combine the instances under different parameter settings, the distribution should be U-shaped. Interesting, when $\alpha$ is extremely large (=0.9), the time of agreement is shifted forward, because the learning is highly effective when $\alpha$ is extremely large, and thus the firms do not need to wait as long to learn about the demand.

From the second row of Figure 3, we can see that $\beta$ (i.e., the relative bargaining power of the buyer) has little impact on the bargaining process other than determining the split of the surplus. As a result, the second row of Figure 3 in fact serves as the baseline scenario with the default parameter setting. Next, from the second and third rows, we can see that the agreement becomess delayed for longer periods as the prior belief ($\gamma$) of a good market increases, which is consistent with Proposition 3. Lastly, from the second and fourth rows, we can see that as the non-learning period (i.e., there is no learning when $N_t < N_L$) becomes longer, the agreement occurs sooner, because the length of the non-learning period indicates the cost of learning.

Figure 3: Distribution of the Time of Termination

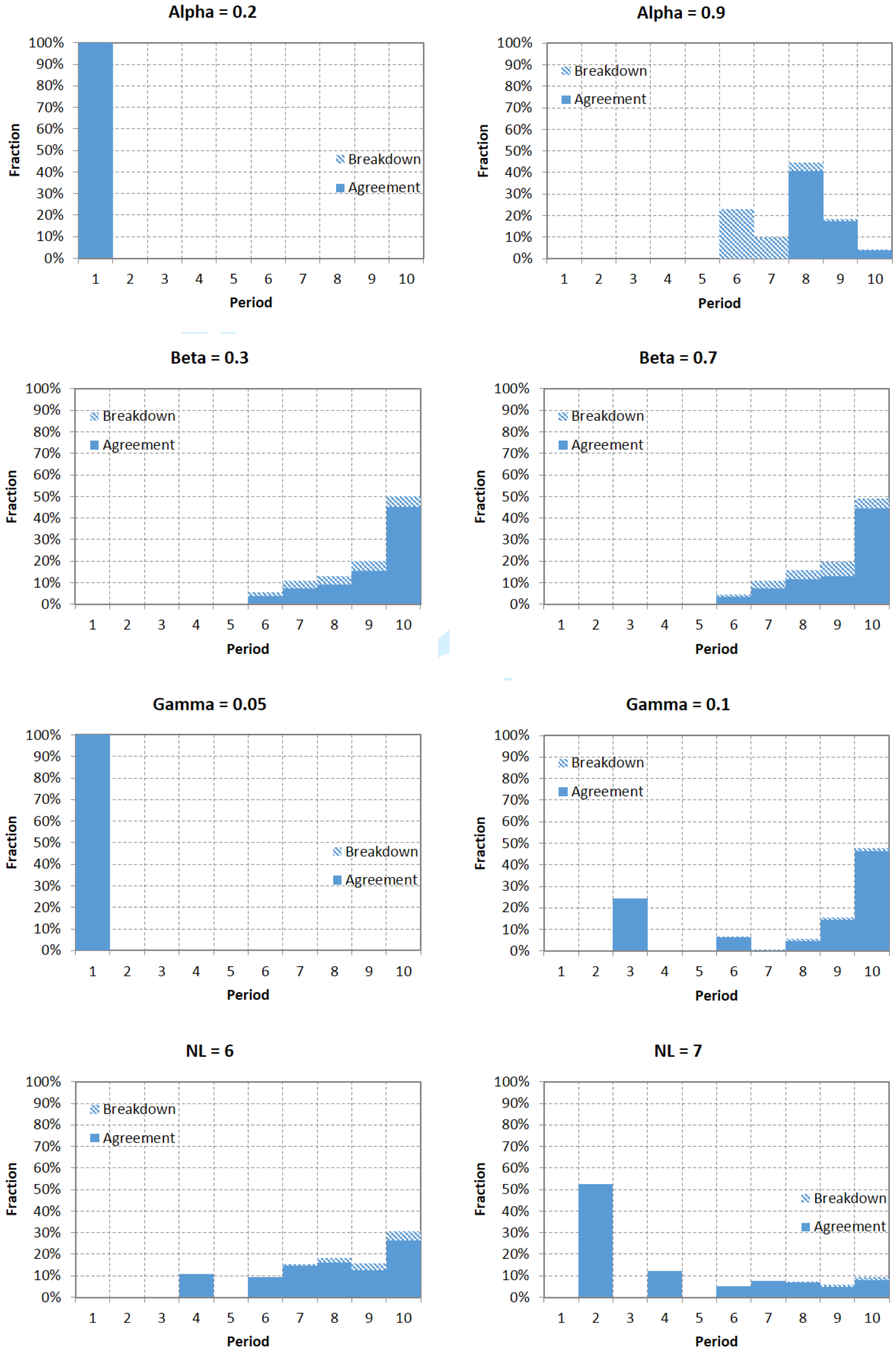
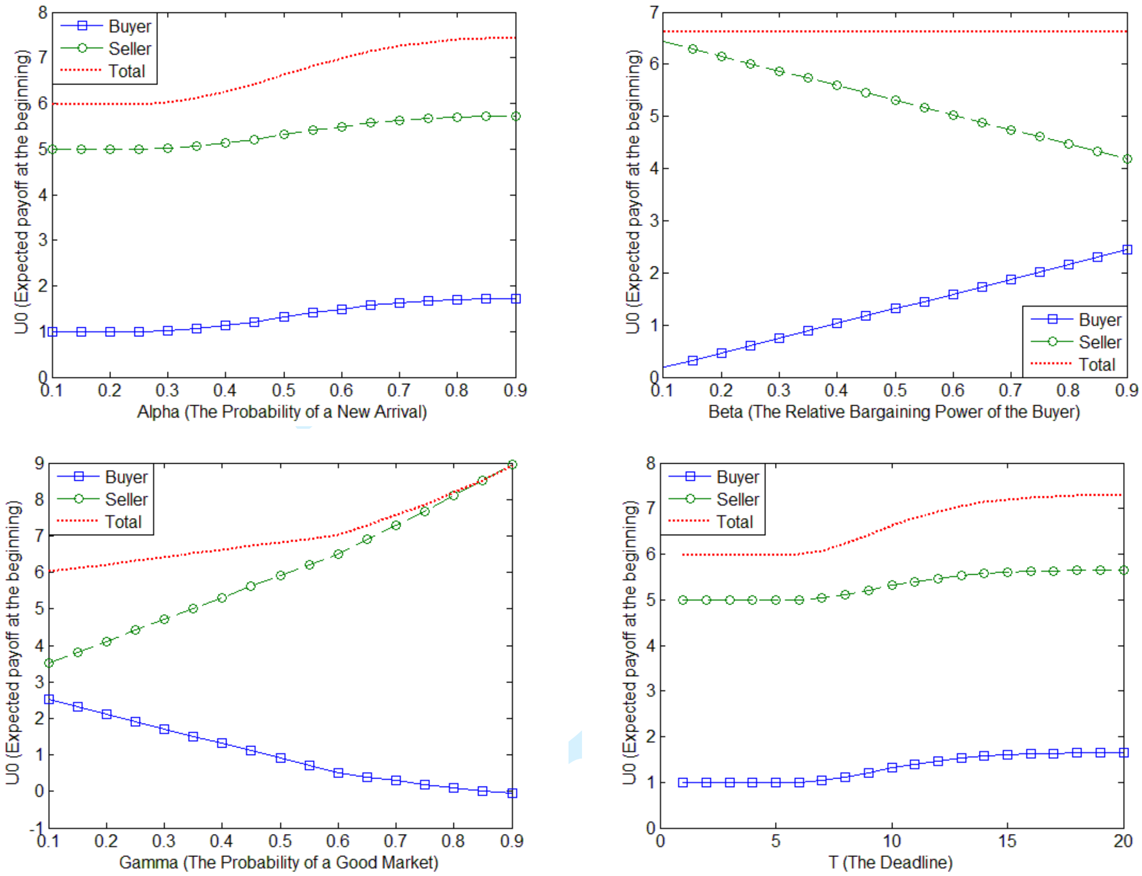


Figure 4: Impact of Different Parameters on $U_0^B$, $U_0^S$, and $U_0^B + U_0^S$




In the second study, we investigate the impact of four parameters and the results are presented in Figure 4. We can see that, as we change the parameters, the expected payoffs of the two players may change in different directions. In addition, the total expected payoff in general increases with the conditional arrival probability of buyers, the prior probability of a good market, and the length of the time horizon. Furthermore, there are two observations that are not straightforward.

First, learning in general benefits both seller $\mathcal{A}$ and buyer $\mathcal{B}$, which can be seen from the impacts of $\alpha$ and $T$. Recall that as $\alpha$ increases, learning becomes more effective and faster; as $T$ increases, the length of learning period increases. Through learning, seller $\mathcal{A}$ obtains the opportunity of selling the target capacity to buyers that would pay higher prices in the case of a good market. Although seller $\mathcal{A}$ has to make concessions to buyer $\mathcal{B}$ if they find out that it is not a good market, it turns out that the former effect dominates. From buyer $\mathcal{B}$'s perspective, a better price can be obtained if they find out that the seller is facing a low demand. Although the payoff is zero for buyer $\mathcal{B}$ in a good market, the expected payoff is still higher than that of without learning. (In a simple example wherein $Q = 1$, $\beta = 0.5$, and $c_* = 0$, the buyer's expected payoff is $v - (v + \pi_0\gamma)/2$ without learning and $(1-\gamma)v/2$ with learning. Clearly, the expected payoff with learning is higher if $\pi_0 > v$.) Based on this observation, we know that both the seller and buyer should prefer a longer time horizon over a shorter one. In addition, neither party needs to compensate each other for a longer horizon or extending the deadline. As a result, a committed deadline in such a setting is not credible.

The second important observation is that participation is possible even if $\gamma$ (i.e., the prior probability of a good market) is relatively high such that $\pi_0\gamma > v$ and the sufficient condition of participation is violated. Therefore, bargaining and learning "on the go" can take place for a wide range of scenarios, which means that our results can be widely applied.



## 6 Extensions and Discussions

In this section, we present four extensions of our base model to incorporate a number of realistic but complicating factors. We will see that the results will not be qualitatively different from what is offered by the base model. Hence, the robustness of the base model will be supported by the analyses of these extensions.

### 6.1 State-Dependent Value of Technology

Due to the *network effect* in a high technology market, it is likely that the value of a unit of capacity for the buyer is $v_H$ in a good market and is $v_L$ in an average market, where $v_H > v_L$. In such a setting, the expected product value in period $t$, given information $\{N_t, \theta_t\}$, is $v_t^e = \theta_t v_H + (1-\theta_t)v_L = v_L + (v_H - v_L)\theta_t$. Therefore, an agreement can be reached in period $t$ if and only if $U_t^S + U_t^B \le v_t^e Q$, or equivalently, $U_t^S + U_t^B - (v_H - v_L)\theta_t Q \le v_L Q$. Based on this criterion, we can define the following equivalent bargaining game.

Consider a bargaining game wherein the value of a unit of the capacity for buyer $\mathcal{B}$ is fixed at $v_L$ and the seller's opportunity loss for a unit of the target capacity in a good market is $\pi_* = \pi_0 - (v_H - v_L)$. All of the other settings are the same as those in the base model. We can prove that, in terms of the time when an agreement can be achieved, this bargaining game is completely equivalent to bargaining with network-based product value. Consequently, all the results in the base model can apply.

**Proposition 10.** *$U_t^S + U_t^B \leq v_t^e Q$ given $\{\pi_0, v_t^e\}$ is equivalent to $\tilde{U}_t^S + \tilde{U}_t^B \leq v_L Q$ given $\{\pi_*, v_L\}$ and $U_t^S + U_t^B = \tilde{U}_t^S + \tilde{U}_t^B + (v_H - v_L)\,\theta_t Q$ for every possible $t$.*

Similarly, the value of technology for the buyer could be market-condition-dependent due to the *competition* among the buyers. It is sometimes reasonable to expect that the more adopters for a technology, the more intense the competition and thus the lower the profit margin. Hence, for the focal buyer, the per-unit value could be $v_H$ in a good market and is $v_L$ in an average market, where $v_H < v_L$. Despite this difference, all the above arguments as well as the results can be carried over.

## 6.2 The Leader-Follower Effect

It is possible that in the high-tech industry, the adoption decision of a market leader could influence those of other firms in the same market segment. For example, in the microprocessor market for smartphones, buyers such as Apple, Qualcomm, and Nvidia can choose between the process technologies offered by Samsung and TSMC, and their adoption decisions are mainly driven by Apple (Lipsky 2016).

Here we study the situation wherein the state of demand depends on whether an agreement is reached between $\mathcal{A}$ and $\mathcal{B}$. In particular, if the market condition is initially good, the agreement will have no effect; however, if the market is initially average, the agreement between $\mathcal{A}$ and $\mathcal{B}$ in any period can turn the market into a good one with probability $\phi$. Let $\gamma$ denote the original probability of a good market and $\theta_t$ the probability of a good market in period $t$ without an agreement. After an agreement is reached in period $t$, the probability of a good market becomes $\theta_t + (1-\theta_t)\,\phi$. Accordingly, the value of an agreement between $\mathcal{A}$ and $\mathcal{B}$ is twofold. First, the value of $Q$ units of the capacity for the buyer is $vQ$. Second, the agreement can increase the probability of a good market and thus the probability of selling the extra capacity of $K - Q - (N_L - 1)$ units is raised from $\theta_t$ to $\theta_t + (1-\theta_t)\,\phi$ in period $t$. Let $\pi_e$ denote the value of the extra capacity for the seller in a good market when it is sold to other buyers. Hence, the total value of the agreement is $vQ + (1-\theta_t)\,\phi\pi_e$, and an agreement can be reached in period $t$ if and only if $U_t^S + U_t^B \leq vQ + (1-\theta_t)\,\phi\pi_e$, or equivalently, $U_t^S + U_t^B + \frac{\pi_e\phi}{Q}\theta_t Q \leq \left(v + \frac{\pi_e\phi}{Q}\right)Q$. Based on this criterion, we can define the following equivalent bargaining game in a way similar to Section 6.1.

Consider a bargaining game wherein the value of a unit of the capacity for buyer $\mathcal{B}$ is fixed at $v_{lfe} = v + \frac{\pi_e \phi}{Q}$ and the seller's opportunity loss for a unit of the target capacity in a good market is $\pi_{lfe} = \pi_0 + \frac{\pi_e \phi}{Q}$. All of the other settings are the same as those used in the base model. Using the same logic as in Proposition 10, we can show that, in terms of the time when an agreement can be achieved, this bargaining game is completely equivalent to the bargaining game with the leader-follower effect. The proof is omitted. All of the results in the base model can apply.

### 6.3 Adoption by Customer Groups

In practice, potential customers can usually be classified into several types in terms of the likelihood of adoption. Although the base model is reasonable if the seller does not know the type of a buyer *a priori*, when the type information is known for all of the buyers, a reasonable assumption for capturing market uncertainty in our model is that two types of buyers exist: strategic partners and market followers. It is certain that strategic partners will adopt the technology. Market followers will all adopt the technology if they think it is promising, which is true with probability $\gamma$. Given this assumption, firms can be sure that the market condition is good if one of the market followers decides to adopt the technology. To incorporate such a situation, we can just assume that $N_L$ buyers have arrived by period 0 (or equivalently, $N_L = 1$), and the learning about the market condition starts immediately in period 1. Hence, the same results as in the base model can apply.

### 6.4 The Option of Quitting

Proposition 7 gives us a sufficient condition under which the two parties will participate in the negotiation. Note that when the firms fail to reach an agreement in a period, it is equivalent that they participate in a new negotiation starting from the next period with the prior information as the current information. Therefore, Proposition 7 also gives a sufficient condition under which the firms will not choose to quit the negotiation in period $t$ even if quitting is allowed, except that the "prior information" $\gamma$ should be replaced by $\theta_t$. In particular, if $vQ \geq \pi_0 \theta_t Q + c_*$ and side payments are allowed, firms will not quit in period $t$. Note that $\theta_t \leq \gamma$ as long as $N_t \leq N_L$. Hence, if $\pi_0\gamma < v < \pi_0$ and $vQ \geq \pi_0\gamma Q + c_*$, firms will never quit unless agreement becomes impossible.

### 6.5 State-Dependent Arrivals

In the base model, we assume that the probability of a new adopter arriving in each period (given that $N_t \leq N$) is constant regardless of the market condition. Given this assumption, learning occurs at a critical point (i.e., when $N_t = N_L$), where the firms either find the demand to be high for sure or update the belief $\theta_t$ downwards. An alternative assumption is that the probability of a new arrival is different under different market conditions. In particular, the probability is $\alpha_L$ in an average market and $\alpha_H$ in a good market, wherein $\alpha_L < \alpha_H$. Given this assumption, learning starts from the very beginning. As time passes, the belief $\theta_t$ could be updated upwards or downwards. It is reasonable to expect that there exist a pair of critical values, $\overline{\theta}_t^*$ and $\underline{\theta}_t^*$, such that the bargaining breaks down when $\theta_t \geq \overline{\theta}_t^*$, an agreement is reached when $\theta_t \leq \underline{\theta}_t^*$, and the agreement is delayed when $\overline{\theta}_t^* < \theta_t < \underline{\theta}_t^*$. Hence, the insights of such a model regarding agreement delay will be the same as what are offered by the base model. In fact, the insights we obtained from the base model are independent of the learning mechanism, but the base model offers great tractability.

## 7 Concluding Remarks

In this paper, we study the negotiation process between a high-technology component supplier and an OEM buyer. We focus on a setting wherein the buyer decides to adopt the technology offered by the supplier for the next generation of product and has determined the production plan of the final product as well as the purchase quantity of the focal component. Therefore, the buyer's only task is to negotiate with the supplier for the price before a fixed deadline. Observations in the semiconductor industry suggest that when the manufacturing capacity is fixed and demand is uncertain, firms can delay the price agreement until close to the deadline even if they have symmetric information. To find the rationale of delay as well as the managerial insights in such a setting, we build a dynamic bargaining model with random price proposers, fixed bargaining and delay costs, uncertain outside options, symmetric information, and a deadline. Using the model, we discover that delay of agreements is driven by the incentive to learn about the supplier's opportunity cost of selling, which is jointly determined by the demand facing the supplier and the level of capacity. When the demand is high (low), the opportunity cost of selling to the buyer is high (low). With better information, the supplier can sell the manufacturing capacity to buyers who are expected to pay more. On the other hand, the buyer can also benefit from learning because the supplier must make consessions if they find that the demand is likely to be weak. Hence, contrary to most existing theories, delay can benefit both the supplier and buyer and the joint expected payoff always weakly increases as the deadline is extended. This logic holds even if we allow the value of the capacity to depend on the market condition or extend the model in a number of other ways.

We also point out that extending the deadline or a long negotiation window is not always a common interest for the buyer and supplier. Although extending the deadline can improve the joint payoff, close deadlines are preferred by the buyer when the buyer has a sufficiently low bargaining power or when the supplier with a strong bargaining power is very likely to have excessive capacities. Therefore, when the buyer is too weak in terms of bargaining power, the supplier should use side payments to subsidize the buyer and set the deadline as far in the future as possible so that the capacity can be better allocated. Surprisingly, when the initial belief for a good market is too low, the supplier should also consider subsidizing the buyer with side payments as long as the supplier's bargaining power is sufficiently high. If side payments cannot be used and firms are able to commit to an arbitrary deadline prior to the negotiation, we should expect the negotiation to terminate quickly when these conditions are satisfied.

In addition, our model suggests that the tendency of delay decreases as time passes and increases with the expected value of the supplier's outside option, the number of buyers that have decided to adopt the technology, and the bargaining time horizon. Based on these results, our model predicts that agreements are frequently achieved either at the beginning of negotiations or close to the deadlines. This is consistent with the "deadline effect" as documented in the literature (e.g., Roth et al. 1988, Fershtman and Seidmann 1993, and Damiano et al. 2012). However, our model offers a new explanation; that is, given that the incentive to learn is high enough at the outset, the delay tendency will be reduced below the threshold for an agreement only after a long-enough period of time.

One way to test the theory in this paper is to test the correlation between the chance of delay and the length of the negotiation window. Most existing theories should predict no correlation or a negative correlation because delay should not increase the joint payoff. However, our theory predicts a positive correlation because longer negotiation windows allow better learning and a higher joint payoff. Future research can consider testing the importance of learning in technology adoption along this direction.

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# Supplementary to "Demand Learning and Agreement Delay in Technology Adoption"

### Proof of Proposition 1

There are two special cases. First, if $N_t > N_L$, there is no uncertainty. Thus, either an agreement is reached or the bargaining breaks down. Second, in period $T$, an agreement must be reached or the bargaining breaks down. Let's then consider $N_t \le N_L$ for period $t < T$. In period $T-1$, we have $U^B_{T-1} + U^S_{T-1} \le Q \cdot \max\{\pi_0, v\} - c_S - c_B$. If $vQ + c_S + c_B \ge \pi_0 Q$, then we have $U^B_{T-1} + U^S_{T-1} \le \max\{vQ + c_S + c_B, vQ\} - c_S - c_B = vQ$. Suppose now $U^B_t + U^S_t \le vQ$. For period $t-1$, we have $U^B_{t-1} + U^S_{t-1} = \mathbf{E}\left[\max\left\{U^B_t + U^S_t, vQ\right\} | N_t, \theta_t\right] - c_S - c_B \le vQ - c_S - c_B < vQ$. $\square$

### Proof of Proposition 2

From Table-2, we know that $U^B_T + U^S_T$ increases with $\pi_0$. Because $\delta_t = U^B_t + U^S_t + c_S + c_B - vQ$, we know that $\delta_T$ increases with $\pi_0$. Now suppose that $\delta_{t+1}$ increases with $\pi_0$. According to (6), $\delta_t = \mathbf{E}\left[\max\left\{0, \delta_{t+1} - c_S - c_B\right\}\right]$, which is an increasing function of $\delta_{t+1}$ and thus $\pi_0$. $\square$

### Proof of Proposition 3

First consider that $N_t = N_L$. We have $\delta_{T-1} = Q \cdot \max\left\{\pi_0 \theta_{T-1} - v, \alpha\theta_{T-1}(\pi_0 - v)\right\}$ and it is increasing in $\theta_{T-1}$. Suppose that $\delta_t(N_L, \theta_t)$ is increasing in $\theta_t$ for a $t$. Using (6), we have

$$\delta_{t-1}(N_L, \theta_{t-1}) = \theta_{t-1}\alpha(\pi_0 - v)Q + (1 - \theta_{t-1}\alpha)\max\left\{\delta_t\left(N_L, \frac{(1-\alpha)\theta_{t-1}}{1-\alpha\theta_{t-1}}\right) - c_S - c_B, 0\right\}.$$

For any $\theta' > \theta''$, we have $\delta_t\left(N_L, \frac{(1-\alpha)\theta'}{1-\alpha\theta'}\right) \ge \delta_t\left(N_L, \frac{(1-\alpha)\theta''}{1-\alpha\theta''}\right)$ and thus

$$\begin{aligned}
&\delta_{t-1}(N_L, \theta') - \delta_{t-1}(N_L, \theta'') \\
&\quad \ge (\theta' - \theta'')\alpha(\pi_0 - v)Q + (\theta'' - \theta')\alpha\max\left\{\delta_t\left(N_L, \frac{(1-\alpha)\theta''}{1-\alpha\theta''}\right) - c_S - c_B, 0\right\} \\
&\quad \ge (\theta' - \theta'')\alpha(\pi_0 Q - vQ - \delta_t + c_S + c_B) \\
&\quad = (\theta' - \theta'')\alpha\left(\pi_0 Q - U^B_t - U^S_t\right) \ge 0.
\end{aligned}$$

Hence, $\delta_t(N_t, \theta_t)$ is increasing in $\theta_t$ for any $t$ given $N_t = N_L$. Next, consider that $N_t < N_L$, which suggests that $\theta_t \equiv \gamma$. We have $\delta_{T-1}(N_{T-1}, \gamma) = Q \cdot \max\{0, \pi_0\gamma - v\}$ and it is increasing in $\gamma$ for any $N_{T-1} < N_L$. Now suppose that $\delta_t(N_t, \gamma)$ is increasing in $\gamma$ for any $N_t < N_L$. Using (6), we get

$$\delta_{t-1}(N_{t-1}, \gamma) = (1-\alpha)\max\{0, \delta_t(N_{t-1}, \gamma) - c_S - c_B\} + \alpha \max\{0, \delta_t(N_{t-1}+1, \gamma) - c_S - c_B\}.$$

Clearly, $\delta_{t-1}(N_{t-1}, \gamma)$ is increasing in $\gamma$ given that $\delta_t(N_t, \gamma)$ is increasing in $\gamma$ for any $N_t \leq N_L$. The proof is complete. □

**Proof of Proposition 4**

We know that $\theta_t \equiv \gamma$ for $N_t < N_L$. In period $T-1$, $\delta_{T-1}(N_{T-1}-1, \gamma) = \delta_{T-1}(N_{T-1}, \gamma) = Q \cdot \max\{0, \pi_0\gamma - v\}$. Now suppose $\delta_t(N_t, \gamma) \geq \delta_t(N_t - 1, \gamma)$ in period $t$. Then in period $t-1$,

$$\begin{aligned}\delta_{t-1}(N_{t-1}-1, \gamma) &= (1-\alpha)\max\{0, \delta_t(N_{t-1}-1, \gamma) - c_S - c_B\} + \alpha\max\{0, \delta_t(N_{t-1}, \gamma) - c_S - c_B\} \\ &\leq (1-\alpha)\max\{0, \delta_t(N_{t-1}, \gamma) - c_S - c_B\} + \alpha\max\{0, \delta_t(N_{t-1}+1, \gamma) - c_S - c_B\} \\ &= \delta_{t-1}(N_{t-1}, \gamma).\end{aligned}$$

Hence, the inequality applies to every $t < T$. The proof is complete. □

**Proof of Proposition 5**

First, we know from Table 2 that $\delta_{T-1}(N_{T-1}, \theta_{T-1})$ is independent of $c_*$ for any $N_{T-1}$ and $\theta_{T-1}$. In other words, $\delta_{T-1}$ is weakly decreasing in $c_*$. Then according to the definition in (6), $\delta_t(c_*) = \mathbf{E}[\max\{0, \delta_{t+1}(c_*) - c_*\}]$. Hence, if $\delta_{t+1}$ is (weakly) decreasing in $c_*$, then $\delta_t$ must be (at least weakly) decreasing in $c_*$. □

**Proof of Proposition 6**

If the firms choose to agree on a price immediately, they can achieve at least a total payoff of $vQ - c_*$; i.e., $U_0^S + U_0^B \geq vQ - c_*$. Hence, if $vQ \geq \pi_0\gamma Q + c_*$, we have $U_0^S + U_0^B \geq (\pi_0\gamma Q + c_*) - c_* = \pi_0\gamma Q$. □

**Proof of Proposition 7**

For the ease of notation, we write $u_0(n, N_L, N_H, \gamma)$ as $u_0^n$. First, according to Table 2, we have

$u_0^1 = Q \cdot \max\{\pi_0\gamma, v\} - c_* = vQ - c_*$, $u_0^2 = vQ - c_* + \max\{0, Q\alpha\gamma(\pi_0 - v) - c_*\}$ if $N_L = 1$, and $u_0^2 = vQ - c_*$ if $N_L > 1$. Therefore, we must have $u_0^2 \geq u_0^1$ for $\forall N_L, N_H, \gamma$. Second, suppose that $u_0^n \geq u_0^{n-1}$ for a particular $n \geq 2$ and $\forall N_L, N_H, \gamma$. In the third step, we can show that $u_0^{n+1} \geq u_0^n$ using (9). This is because $u_0(n, N_L, N_H, \gamma) \geq u_0(n-1, N_L, N_H, \gamma)$ and $u_0(n, N_L - 1, N_H - 1, \gamma) \geq u_0(n-1, N_L - 1, N_H - 1, \gamma)$ according to the assumption made in the second step. The proof is complete. □

**Proof of Proposition 8**

We first check $T = 2$. In this case, $U_2^B = 0$ and $U_2^S = \theta_2\pi_0 Q \geq 0$. According to Table 1, we know that given $T = 2$

$$U_1^B + U_1^S = \begin{cases} Q \cdot \max\{\pi_0\gamma, v\} - c_* & N_1 < N_L \\ Q \cdot \max\{\pi_0\gamma, v + \alpha\gamma(\pi_0 - v)\} - c_* & N_1 = N_L \end{cases}$$

and thus

$$\begin{aligned} U_0^B(2) =& \beta \max\left\{U_1^B, vQ - U_1^S\right\} + (1-\beta)U_1^B - c_B \\ =& \begin{cases} \beta \max\{U_1^B, U_1^B + c_*\} + (1-\beta)U_1^B - c_B & N_1 < N_L \\ \beta \max\{U_1^B, U_1^B + c_* - \alpha\gamma Q(\pi_0 - v)\} + (1-\beta)U_1^B - c_B & N_1 = N_L \end{cases} \\ \leq& U_1^B + \beta c_* - c_B \end{aligned}$$

Using (2) and knowing that $\theta_2 \geq \frac{(1-\alpha)\gamma}{1-\alpha\gamma}$ and $\Pr\left\{\theta_2 = \frac{(1-\alpha)\gamma}{1-\alpha\gamma}\right\} < 1$, we have

$$\begin{aligned} U_1^B =& \mathbf{E}\left[\beta Q \max\{0, v - \theta_2\pi_0\} + (1-\beta) \cdot 0\right] - c_B \\ <& \beta Q\left(v - \pi_0 \cdot \frac{(1-\alpha)\gamma}{1-\alpha\gamma}\right) - c_B \\ =& U_0^B(1) + \beta Q\pi_0 \cdot \frac{\alpha\gamma(1-\gamma)}{1-\alpha\gamma}. \end{aligned}$$

Hence, $U_0^B(2) < U_0^B(1) + \beta Q\pi_0 \cdot \frac{\alpha\gamma(1-\gamma)}{1-\alpha\gamma} + \beta c_* - c_B$. Therefore, $\beta Q\pi_0 \cdot \frac{\alpha\gamma(1-\gamma)}{1-\alpha\gamma} + \beta c_* - c_B \leq 0$ or $Q\pi_0 \cdot \frac{\alpha\gamma(1-\gamma)}{1-\alpha\gamma} \leq (c_B - \beta c_*)/\beta$ is a sufficient condition under which $U_0^B(2) < U_0^B(1)$. We know that $\frac{\alpha(1-\gamma)}{1-\alpha\gamma} \leq 1$, so $Q\pi_0\gamma \leq (c_B - \beta c_*)/\beta$ is a sufficient condition under which $U_0^B(2) < U_0^B(1)$.

Next, let's suppose that for $T = m$ and $\pi_0\gamma < v < \pi_0$ we have $U_0^B(m) < U_0^B(m-1)$ if $Q\pi_0\gamma \leq (c_B - \beta c_*)/\beta$. We then consider the case of $T = m+1$. Using Proposition 8, we know that $U_1^B(m+1) + U_1^S(m+1) \geq U_1^B(m) + U_1^S(m)$. Hence,

$$
\begin{aligned}
U_0^B(m+1) =& \beta \max\left\{U_1^B(m+1) + U_1^S(m+1), vQ\right\} - \beta U_1^S(m+1) + (1-\beta)U_1^B(m+1) - c_B \\
=& \beta\left[vQ - U_1^B(m+1) - U_1^S(m+1)\right]^+ + U_1^B(m+1) - c_B \\
\leq& \beta\left[vQ - U_1^B(m) - U_1^S(m)\right]^+ + U_1^B(m+1) - c_B \\
=& \beta\left[vQ - U_1^B(m) - U_1^S(m)\right]^+ + U_1^B(m) - U_1^B(m) + U_1^B(m+1) - c_B \\
=& U_0^B(m) - U_1^B(m) + U_1^B(m+1).
\end{aligned}
$$

Notice that $U_1^B(m+1) = \mathbf{E}\left[\tilde{U}_0^B(m)\right]$, where $\tilde{U}_0^B(m)$ denotes the buyer's expected payoff in a hypothetical negotiation where $\tilde{\gamma} = \theta_2$ and $\tilde{N}_1 = N_2$ with $\theta_2$ and $N_2$ being the period-2 information in the focal negotiation. We know that we either have $\theta_2 = 1$ or $\theta_2 \leq \gamma$. In the former case, it is clear that $\tilde{U}_0^B(m) = 0$ regardless of the value of $m$. In the latter case, we have $Q\pi_0\theta_2 \leq (c_B - \beta c_*)/\beta$ and thus $\tilde{U}_0^B(m) < \tilde{U}_0^B(m-1)$. Therefore, if $Q\pi_0\gamma \leq (c_B - \beta c_*)/\beta$, we have $U_1^B(m+1) = \mathbf{E}\left[\tilde{U}_0^B(m)\right] < \mathbf{E}\left[\tilde{U}_0^B(m-1)\right] = U_1^B(m)$. Consequently, we have $U_0^B(m+1) < U_0^B(m)$ if $Q\pi_0\gamma \leq (c_B - \beta c_*)/\beta$.□

**Proof of Proposition 9**

We know that $\delta_t(N_t, \theta_t) = U_t^B(N_t, \theta_t) + U_t^S(N_t, \theta_t) + c_* - vQ$ and that $c_*$ and $vQ$ are independent of $T$. In addition, for any $T - t > 1$ and $N_t < N_L$, we have

$$
\begin{aligned}
U_t^B(N_t, \theta_t) + U_t^S(N_t, \theta_t) =& \mathbf{E}\left[\max\left\{U_{t+1}^B + U_{t+1}^S, vQ\right\} - c_* | N_t, \theta_t\right] \\
=& \mathbf{E}\left[u_0\left(T - t - 1, N_L - N_{t+1} + 1, N_H - N_{t+1} + 1, \theta_{t+1}\right) | N_t, \theta_t\right],
\end{aligned}
$$

wherein $u_0$ is the expected total payoff in an equivalent game that is parameterized by $T' = T - t - 1$, $N_L' = N_L - N_{t+1} + 1$, $N_H' = N_H - N_{t+1} + 1$, and $\gamma' = \theta_{t+1}$. The proof is then completed by Proposition 8. □

**Proof of Proposition 10**

In period $T$, we know $U_T^S + U_T^B = \pi_0 \theta_T Q$ and thus $U_T^S + U_T^B \leq v_T^e Q$ is equivalent to $\pi_0 \theta_T Q \leq [v_L + (v_H - v_L)\,\theta_T]\,Q$, which is simply $\tilde{U}_T^S + \tilde{U}_T^B = \pi_* \theta_T Q \leq v_L Q$. Clearly, $U_T^S + U_T^B = \tilde{U}_T^S + \tilde{U}_T^B + (v_H - v_L)\,\theta_T Q$. Now suppose that the two bargaining games are equivalent for any period $t \geq t'$ and $U_{t'}^S + U_{t'}^B = \tilde{U}_{t'}^S + \tilde{U}_{t'}^B + (v_H - v_L)\,\theta_{t'} Q$. We then consider period $t' - 1$. With network-based product value, we have

$$
\begin{aligned}
U_{t'-1}^S + U_{t'-1}^B =& \mathbf{E}[\max\left\{U_{t'}^B + U_{t'}^S, v_{t'}^e Q\right\}] - c_* \\
=& \mathbf{E}[\max\left\{\tilde{U}_{t'}^B + \tilde{U}_{t'}^S + (v_H - v_L)\,\theta_{t'} Q, v_{t'}^e Q\right\}] - c_* \\
=& \mathbf{E}[\max\left\{\tilde{U}_{t'}^B + \tilde{U}_{t'}^S, v_L Q\right\}] - c_* + (v_H - v_L)\,\theta_{t'-1} Q.
\end{aligned}
$$

Therefore, $U_{t'-1}^S + U_{t'-1}^B \leq v_{t'-1}^e Q$ is equivalent to $\mathbf{E}[\max\{\tilde{U}_{t'}^B + \tilde{U}_{t'}^S, v_L Q\}] - c_* = \tilde{U}_{t'-1}^B + \tilde{U}_{t'-1}^S \leq v_{t'-1}^e Q - (v_H - v_L)\,\theta_{t'-1} Q = v_L Q$. □