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Supply Chain Performance Under Market Valuation: An Operational Approach to Restore Efficiency

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Based on a supply chain framework, we study the stocking decision of a downstream buyer who receives private demand information and has the incentive to influence her capital market valuation. We first characterize a market equilibrium under a general, single buyback contract. We show that the buyer's stocking decision can be distorted in equilibrium. Such a downstream stocking distortion hurts the buyer firm's own performance, and it also influences the performances of the supplier and the supply chain. We further reveal scenarios where full supply chain efficiency cannot be reached under any single buyback contract. Then, focusing on contract design, we characterize conditions under which a menu of buyback contracts can prevent downstream stocking distortion and restore full efficiency in the supply chain. Our study demonstrates that in a supply chain context, a firm's incentive to undertake real economic activities to influence capital market valuation can potentially be resolved through operational means.

Key words: supply chain; newsvendor; capital market valuation
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1. Introduction

Firms, when making their decisions, might consider not only their long-term profitability but also their short-term valuation in the capital market. If the market is able to correctly assess a firm's performance, the short-term focus on market value would be aligned with the long-term goals. Nevertheless, given their information advantage, firms might undertake real economic activities to purposely influence their market valuation. For instance, Bebchuk and Stole (1993) demonstrate that firms may overinvest in projects to influence their market value. In this paper, we study a firm's inventory stocking decision in the presence of a short-term interest in market value. Although the stocking decision does not directly reveal a firm's value, it conveys information about its expectations regarding potential sales. Investors might thus react to those stocking decisions that can have significant effects on a firm's performance.[1] Given that firms might anticipate a market response, it is interesting to investigate whether a firm, when it has a short-term interest in market value, might purposely distort its stocking level. We study this problem based on the newsvendor and supply chain framework. In our model, a downstream buyer who receives private information of her potential demand (either

[1] For instance, when it was revealed on May 26, 2010, that Gome, China's second-biggest electronics retailer, signed a distribution contract with LG that targeted $1.4 billion (9.3 billion RMB) of sales of LG products through Gome's retail stores in 2010 (a 90% increase from 2009), Gome's stock price rose 13.7% in Hong Kong trading (the benchmark Hang Seng Index rose 1.1%), the most in 10 months. Ashley Cheung, an analyst at BOCI Research Ltd. in Hong Kong, commented on the news: "With this contract, Gome is going to see a material positive impact on its revenue" (Longid 2010). In contrast, when it was revealed on December 18, 2009, that Zales, the second-largest U.S. jewelry retailer at that time, refused to accept tens of millions of dollars of inventory at the end of November 2009, its stock price plunged 12.7%. Both the Dow Jones and S&P 500 indices closed up that day. Cancellation of orders was generally permitted for Zales' contracts with the suppliers; however, "the cancellation of orders at a busy time of year is an ominous sign for Zales' sales prospects," Milton Pedraza, Chief Executive of Luxury Institute, said of the cancellation. "Anyone who thinks Christmas will be dramatically up is fooling themselves. It [cancellation] means they are in trouble, that they're not expecting sales to be as good as expected" (Wahba 2009).

optimistic or pessimistic) decides on the stocking level of a product supplied by an upstream supplier. The buyer cares not only about the firm's long-term profitability but also about the firm's market value in the short term.

We first study a scenario where the buyer orders according to a single contract offered by the supplier. The contract contains a wholesale price and may also include a per-unit buyback price and a lump-sum transfer payment. A capital market that consists of homogeneous, rational investors values the buyer firm. Although the market valuation will be accurate after the sales are observed, a discrepancy in the valuation can arise in the shorter term when the market observes neither the sales nor the demand signal but only the stocking level. The buyer might distort her stocking decision to influence the market belief of her potential demand. We characterize a separating market equilibrium in which overstocking can arise under certain conditions. We show that a stocking distortion, if it occurs, hurts the buyer firm's true performance; it can also influence the supplier's profit as well as the total supply chain surplus, which, for a given contract, may either increase or decrease in the magnitude of the buyer's short-term interest in market value. Furthermore, we find situations where the maximum supply chain surplus that could be achieved under the classical supply chain framework (i.e., in the absence of the buyer's short-term interest in market value) becomes no longer achievable in our model.

In the second part of the paper, we seek ways to prevent such a system-wise inefficient stocking distortion. To do this, we focus on the design of trade contracts between the supplier and the buyer. We characterize conditions under which a menu of buyback contracts can successfully prevent downstream stocking distortion in equilibrium. A typical menu would contain one contract that has a premium wholesale price but a generous buyback term and another contract that has a discounted wholesale price but a stringent buyback term. The buyer prefers the first contract if the true demand outlook is pessimistic and the second contract otherwise, even if she takes her market valuation into account. Providing alternative contracting choices serves as an operational means to overcome the buyer's incentive to influence the market valuation. Our findings extend to the setting with a continuous demand signal. In such an environment, the menu of buyback contracts can be alternatively implemented using a specific single contract that has a quantity discount scheme and a buyback schedule.

Prior literature has explored operations distortions under capital market interaction. In particular, our study has similar motivation and modeling approach as the study by Bebchuk and Stole (1993). They study a firm's investment decision in a project with an interest in the market value. They show that in a separating equilibrium the firm that has private information about the investment productivity may choose to overinvest in the project to signal to the capital market about the potential of the future cash flows. However, our study differs from theirs in that we investigate the impact of a downstream firm's interest in market value on the performance of a supply chain. More importantly, we reveal that stocking distortions might be prevented by implementing appropriately designed supply chain contract schemes. This finding indicates that a firm's incentive to use real economic activities to influence the capital market valuation can potentially be resolved not just at the regulatory level (e.g., through accounting policies) but through operational means.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature. Section 3 describes the model. Section 4 analyzes the game with a single buyback contract, which reveals the potential distortion of the buyer's stocking decision. Section 5 explores the design of a menu of buyback contracts to restore supply chain efficiency. We discuss the results of an extension with a continuous demand signal in §6 and conclude in §7.

2. Literature

Our work relates to the supply chain literature. Based on the newsvendor model, the supply chain literature has studied various supply contracts, including wholesale price contracts (Lariviere and Porteus 2001), buyback contracts (Pasternack 1985, Emmons and Gilbert 1998), and revenue-sharing contracts (Cachon and Lariviere 2005). Some research has also been conducted on contract design in settings with asymmetric demand information (Cachon and Lariviere 2001, Özer and Wei 2006, Taylor and Xiao 2009), asymmetric cost information (Ha 2001, Zhang 2010), asymmetric inventory information (Zhang et al. 2010), and strategic consumers (Su and Zhang 2008). However, the element that we explore—the interest in market value and its interplay with asymmetric demand information—have been little investigated. We enrich the above literature by revealing the possibility of stocking distortion in a setting like ours and providing a mitigating mechanism based on supply contract design.

The capital market interaction is not new in the earnings management and signaling literature. Stein (1989) reveals that a firm that cares about the market value might inflate the current earnings by pulling future cash flows forward. Based on a two-period inventory model, Lai et al. (2011) demonstrate that after obtaining true sales a firm may apply different magnitudes of channel stuffing (i.e., pushing excess inventory to the downstream channel) to inflate the first-period reported sales as well as the prospect of the second-period demand. Firms might also use investment to influence the capital market valuation. Bebchuk and Stole (1993) show that high productivity firms might overinvest in long-term projects to signal their productivity to the capital market. In certain environments, firms with different quality investment opportunities also might invest in the same amount, which results in a pooling outcome, as revealed in Kedia and Philippon (2009) and Schmidt et al. (2012). This literature, however, has not investigated approaches that can be used to mitigate such inefficient distortions. Several accounting works do discuss that aspect, but they focus on accounting policies. For instance, Dye and Sridhar (2004) and Liang and Wen (2007) examine the magnitude of investment distortions under different accounting regimes and discuss the advantages and disadvantages of different accounting policies. Our work extends to a supply chain setting and reveals the significant role that a supplier can play in restoring system efficiency.

Finally, our work relates to several recent empirical research studies in operations management. Chen et al. (2005) and Hendricks and Singhal (2009) reveal that excess inventory (e.g., inventory writedowns) often negatively affects stock returns. Some of our results are qualitatively aligned with their empirical observations. In our study, when the sales are realized, for the same initial stocking level, high leftovers suggest a low firm value. Lai (2006) discusses that, anticipating the market response, firms may have incentive to maintain less inventory to signal their competencies as measured by fill rate to inventory ratios. Lai uses aggregated inventory data from financial reports across firms and industries. Our study shares a similar motivation but has a more specific focus. We study the stocking decision of an individual firm for a specific selling event, where the stocking level implies the prospect of the demand and the investors need to value the firm before any sales are realized.

3. Model

3.1. Problem Description

We consider a buyer (she) who procures a product from a supplier (he) for a selling event. The selling price is fixed at p per unit, and the unit production cost for the supplier is c. The stocking decision and the production need to be carried out before the demand is realized. There is no replenishment opportunity afterward; thus, any excess demand is lost. In the case of overage, the leftover inventory has zero value. This setting is common knowledge.

Before deciding at what level to stock, the buyer is able to observe a signal of the demand. Ex ante, the signal is uncertain, denoted by i, which is high (H) with probability $\lambda \in (0,1)$ and low (L) with probability $1-\lambda$. The demand conditional on i is a nonnegative random variable X_i with a strictly increasing distribution $F_i(\cdot)$ (density $f_i(\cdot)$) over $\mathbb{R}^+$. A high-value signal implies a stochastically larger demand, with $F_H(x) < F_L(x)$ for all $x > 0$. Let $\bar{F}_i(\cdot) \equiv 1 - F_i(\cdot)$. We assume that the prior distribution of the signal and the conditional distributions of the demand are all common knowledge, but only the buyer observes the realization of the signal, and she is not able to credibly communicate this information to external parties.

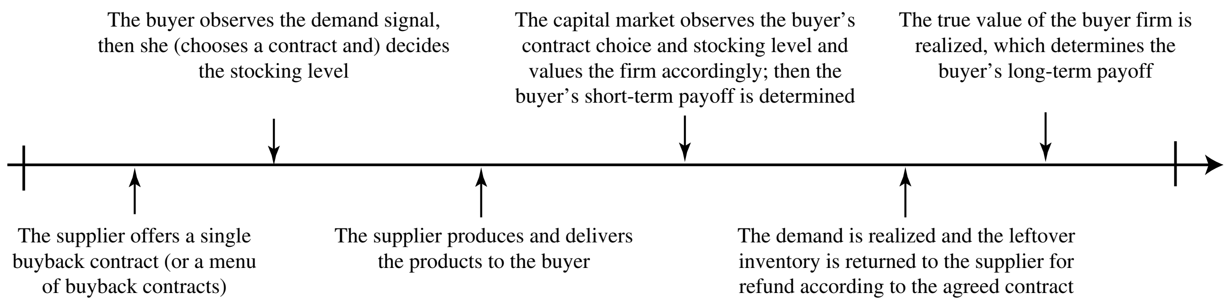
The trade between the buyer and the supplier is carried out through a general form of buyback contract. We use (w, b, t) to denote a single contract in which w is the per-unit wholesale price, b is the per-unit buyback price, and t is the transfer payment. If b and t are zero, the contract reduces to a wholesale price contract. Given a single contract, the buyer procures q units from the supplier. The trade can also be carried out through a menu of two buyback contracts, denoted as $\{(w_H, b_H, t_H), (w_L, b_L, t_L)\}$, with the subscripts corresponding to the possible values of the signal. Given a menu of two contracts, the buyer chooses one contract (w_i, b_i, t_i) and procures q units from the supplier. We impose no constraint on the choice of q. That is, the buyer can select any $q \in \mathbb{R}^+$ that maximizes her own payoff. The contract, once taken, is legally binding and is not renegotiable. We assume the contract information is accessible to the capital market.[2]

Deviating from the classical supply chain framework, we include a capital market that values the buyer.[3] The capital market is competitive and consists of homogeneous, rational, and risk-neutral investors. Their valuation of the buyer firm is the expectation of the buyer's ending-period profit conditional on the

[2] Although it is a simplification in our model, firms in practice may voluntarily disclose information of their supply contracts (the firm, Gome, mentioned in Footnote 1, discussed the contract with analysts after it was signed). Firms may also use rules such as, "on a need-to-know basis," in releasing information to external parties by request. In some scenarios, regulators might demand that suppliers make the information of their wholesale contracts public to the market (as discussed in Albaek et al. 1997, a Danish authority gathered and regularly published the statistics on transactions prices of individual firms in the ready-mix concrete industry; as discussed in Arya and Mittendorf 2011, strong efforts in the United States have pushed for disclosure of medical equipment and pharmaceutical costs incurred at the wholesale level). More about this assumption is discussed in §7.

[3] To simplify the model, we limit our study to the setting where the buyer cares about her market value but the supplier does not. We discuss the rationale and limitation of this assumption in §7.

Figure 1 **Timeline of the Model**



information they can access. As the demand signal is private to the buyer, a discrepancy of the valuation may arise in the short term when the sales have not been realized. We use j to denote the market belief of the signal to formulate the short-term market value. The buyer cares not only about the true profit the firm will make but also about the market value in the short term. To model the buyer's incentive scheme, we apply a simple objective function (which has been similarly applied in the literature; see, e.g., Stein 1989, Liang and Wen 2007): the buyer places a weight $\beta \in (0, 1)$ on the short-term market value and a weight $1-\beta$ on the long-term true profit in her consideration. We consider no time discount. The buyer's incentive scheme (captured by β) is common knowledge. Such an objective function can be motivated, for instance, if the buyer firm's executive managers receive market-based incentives (e.g., shares, options) or if, as discussed in Stein (1989) and Liang and Wen (2007), the buyer bears some liquidation pressure and needs to sell a fraction of her shares to the capital market. Finally, we consider no accounting manipulation. That is, all the information accessible to the market is precise.

3.2. Timeline

Figure 1 details the timeline of the model. First, the supplier offers a single contract or a menu of contracts to the buyer. The buyer privately observes the demand signal and chooses a contract and the corresponding stocking level. The supplier produces and delivers the products to meet the buyer's order, and the buyer pays the wholesale and transfer prices. Then, the capital market observes the buyer's contract choice and stocking level and assesses the expected profit the buyer can make, which forms the short-term market value. The buyer realizes a short-term payoff equal to the market value multiplied by the weight β. After that, the demand is realized and then the leftover inventory is returned and the payments between the buyer and the supplier are made according to the chosen contract. Finally, the buyer firm's true value is realized, which equals the true profit, and the buyer realizes another payoff equal to the profit multiplied by the weight $1-\beta$.

3.3. Information Structure

Similar to the settings adopted in the signaling and the supply contract design literatures (see, e.g., Stein 1989, Bebchuk and Stole 1993, Cachon and Lariviere 2001), we assume a single source of information asymmetry in our model. Such a stylized modeling approach lends tractability to the analysis and also captures the major qualitative insights. In particular, the realization of the demand signal, which we assume is private to the buyer, represents information that is most difficult for external parties to obtain. Furthermore, compared to the selling price, the production cost, and the details of a contract (for which invoices and other legal proofs could exist), a signal of the potential demand is also difficult to communicate credibly (as cheap talks could arise). Finally, to simplify the model, we assume the same information setting for the supplier and the investors.[4]

3.4. Benchmark

Notice that without the interaction with the capital market, the problem we have described follows the classical selling to newsvendor problem. An appropriately designed single contract would be sufficient to maximize the total supply chain surplus. That is, when $(w-b)/(p-b) = c/p$, the buyer would stock $q_i^o \equiv \bar{F}_i^{-1}(c/p)$, which maximizes the total supply chain surplus for each signal $i \in \{H, L\}$—a classic result in the supply chain literature (see, e.g., Pasternack 1985). Nevertheless, when the buyer cares about her capital market valuation, her decision can deviate from these quantities. Hence, we use the classical selling to newsvendor problem as our benchmark and call $q^o_{i\in\{H,L\}}$ the first-best stocking level. We summarize the notation that is used throughout the following analysis in Table 1.

[4] It would be more realistic to assume that the supplier has more information about the buyer firm's demand outlook than the investors. For instance, the supplier might receive a noisy signal about the buyer firm's information and then update his belief of the demand outlook to high (low) with some probability $\lambda'(1-\lambda')$. However, note that the separating equilibrium as well as the menu of contracts we characterize does not depend on the probability of the demand outlook. Such a change of the model would not qualitatively change the main findings.

Table 1 **Table of Notation**

$\lambda(1-\lambda)$	Probability that the demand signal is high (low)
$\beta(1-\beta)$	Weight on the buyer's short-term (long-term) objective
p	Selling price
c	Production cost
(w, b, t)	Contract with wholesale, buyback, and transfer prices
$F_H(\bar{F}_H)$, $F_L(\bar{F}_L)$	Cumulative (complementary) demand distribution with high, low signal
$\bar{F}_{HL}(\bar{F}_{LH})$	$\bar{F}_{HL} = \beta\bar{F}_L + (1-\beta)\bar{F}_H$ $(\bar{F}_{LH} = \beta\bar{F}_H + (1-\beta)\bar{F}_L)$
$G_H(q)(G_L(q))$	Buyer payoff function if the market holds correct belief for high (low) signal
$G_{HL}(q)(G_{LH}(q))$	Buyer payoff function if the market holds incorrect belief for high (low) signal
$q_H^o(q_L^o)$	First-best stocking level for high (low) signal under coordination
$q_H^*(q_L^*)$, $q_{HL}^*(q_{LH}^*)$	Maximizers of $G_H(q)(G_L(q))$, $G_{HL}(q)$ $(G_{LH}(q))$
$\underline{q}(\bar{q})$	Threshold stocking level with $G_{LH}(\underline{q}) = G_L(q_L^*)(G_H(\bar{q}) = G_{HL}(q_{HL}^*))$
$\hat{q}$	Separating stocking level for high signal $(\hat{q} = \max\{\underline{q}, q_H^*\})$
$\hat{\beta}$	Threshold β above which stocking distortion arises in equilibrium
β'	Threshold β above which stocking distortion may benefit the supplier
β''	Threshold β above which stocking distortion may benefit the supply chain
$\hat{\beta}^o$	Threshold β above which coordination is not achievable by single contract
$q_{LH}^o(q_{HL}^o)$	Intermediate variables for characterizing menu of contracts $q_{LH}^o \equiv \bar{F}_{LH}^{-1}(c/p)$ $(q_{HL}^o \equiv \bar{F}_{HL}^{-1}(c/p))$
$g_{ij}(q)$	Intermediate functions for characterizing menu of contracts $g_{ij}(q) \equiv \int_0^q \bar{F}_{ij}(x)\,dx - (c/p)q, \forall i, j \in \{H, L\}$
K	Condition parameter for characterizing menu of contracts

4. Analysis with a Single Contract

In this section, we analyze the model with a single contract offer (w, b, t). We first derive the downstream market equilibrium and analyze the impact of the buyer's short-term interest in market value on her payoff in §4.1; then we analyze the supplier's profitability and the supply chain efficiency in §§4.2 and 4.3, respectively.

4.1. Downstream Market Equilibrium

Given a contract offer (w, b, t), for each signal $i \in \{H, L\}$, the expected profit of the buyer firm with a stocking level q follows:

$$\begin{aligned}\pi^B(q; i) &= p\mathbb{E}[\min(q, X_i)] + b\mathbb{E}[\max(q - X_i, 0)] - wq - t \\ &= (p-b)\int_0^q \bar{F}_i(x)\,\mathrm{d}x - (w-b)q - t. \qquad (1)\end{aligned}$$

However, the buyer's payoff depends partially on the firm's real profit and partially on the firm's short-term market value. In the following, we formulate the buyer firm's market value.

Because the signal is private to the buyer, the market needs to hold a belief to infer the signal. We focus on pure-strategy separating equilibrium in the following analysis[5] and formulate the market belief as

$$j(q) = \begin{cases} H & \text{if } q \in \mathbb{Q}_H, \\ L & \text{otherwise,} \end{cases}$$

where $\mathbb{Q}_H$ is a subset of $\mathbb{R}^+$. That is, if the observed stocking level $q \in \mathbb{Q}_H$, then the market believes that the realization of the signal is high; otherwise, the market believes that the signal is low. Given this belief, the buyer firm's market value follows:

$$P(q) = (p-b)\int_0^q \bar{F}_{j(q)}(x)\,\mathrm{d}x - (w-b)q - t. \qquad (2)$$

Hence, to maximize her own payoff, the buyer, for each signal $i \in \{H, L\}$, solves

$$\max_{q\in\mathbb{R}^+} \beta P(q) + (1-\beta)\pi^B(q; i), \qquad (3)$$

where the weight β represents the buyer's interest in her market value. Before carrying out the equilibrium analysis, we first analyze the buyer's objective function. We use the following definition:

$$\bar{F}_{ij}(x) \equiv \beta\bar{F}_j(x) + (1-\beta)\bar{F}_i(x), \quad \forall i, j \in \{H, L\},$$

where the subscript i (j) indicates the true (market believed) signal value; in addition, we use

$$G_{ij}(q) \equiv (p-b)\int_0^q \bar{F}_{ij}(x)\,\mathrm{d}x - (w-b)q - t, \quad \forall i, j \in \{H, L\},$$

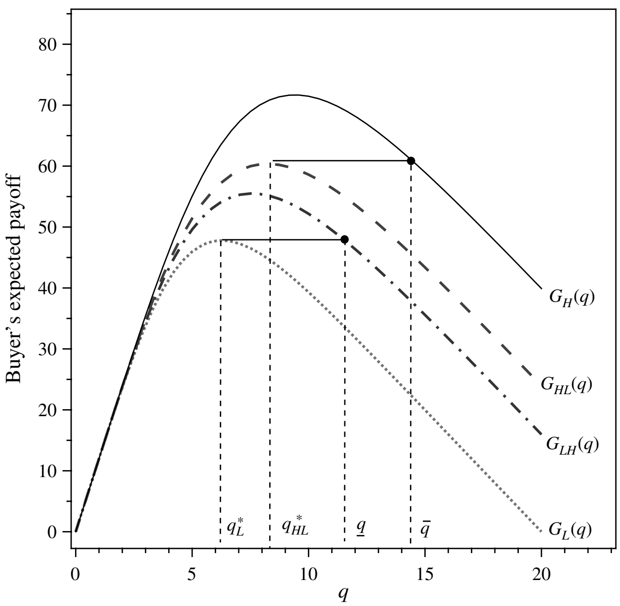
which is the buyer's expected payoff if, given q, the market believes the value of the signal is j while the true signal value is i.

Lemma 1. *$G_{ij}(q)$ is concave in q for any $i, j \in \{H, L\}$.*

Lemma 1 establishes the concavity result of the possible payoff functions of the buyer (see Figure 2 for an illustration). Therefore, a unique maximizer of the buyer's problem exists in any scenario. Define $q_{ij}^* \equiv \bar{F}_{ij}^{-1}((w-b)/(p-b))$, which maximizes $G_{ij}(q)$. To simplify the notation, we reduce the subscript ij of $G_{ij}(\cdot)$ and q_{ij}^* to i whenever $i = j$. We can verify $q_H^* > q_{HL}^* > q_L^*$ and $q_H^* > q_{LH}^* > q_L^*$.

[5] We have described a typical signaling game that can have multiple pooling and separating equilibria. Stocking distortion occurs also in pooling equilibrium because the buyer stocks the same quantity for either demand outlook. We focus only on separating equilibrium in the paper because any pooling equilibrium in our model cannot survive the intuitive criterion refinement (Cho and Kreps 1987), as discussed in the online supplement to this paper (Lai et al. 2012). However, note that we have not considered any constraint on the stocking level. Specific constraints may exist in practice, for which pooling equilibrium might survive the intuitive criterion. Pooling equilibrium might also survive the intuitive criterion if there are more than two states for the demand signal.

Figure 2 **Demonstration of the Buyer's Possible Payoff Functions and the Thresholds $\underline{q}$ and $\bar{q}$**



Note. The parameters are $\beta = 0.4$, $p = 20$, $c = 5$, $w = 8$, $b = 4$, $t = 0$, and $\lambda = 0.5$, and the demand follows the gamma distribution with density $f_i(x) = ((x/\kappa_i)^{\theta_i - 1} e^{-x/\kappa_i})/(\kappa_i \Gamma(\theta_i))$ for $i \in \{H, L\}$ with $(\kappa_H, \theta_H) = (1.5, 5)$ and $(\kappa_L, \theta_L) = (1, 5)$ such that $F_H(x) < F_L(x)$, $\forall\, x > 0$.

Now we can proceed with the equilibrium analysis. Let $q(i)$ denote the buyer's optimal stocking level that solves (3) for each signal $i \in \{H, L\}$. In equilibrium, the market belief shall be consistent with the buyer's strategy on every equilibrium path. Formally,

Definition 1. Given a single contract offer (w, b, t), a separating market equilibrium is reached if the buyer's optimal stocking decision and the market belief satisfy $j(q(i)) = i$ so that $P(q(i)) = \pi^B(q(i); i)$ for each signal $i \in \{H, L\}$.

We derive Lemma 2, which will be useful for the equilibrium characterization.

Lemma 2. *There exists a unique $\underline{q} > q_{LH}^*$ that satisfies $G_{LH}(\underline{q}) = G_L(q_L^*)$ and a unique $\bar{q} > q_H^*$ that satisfies $G_H(\bar{q}) = G_{HL}(q_{HL}^*)$; $\underline{q} < \bar{q}$.*

We depict $\underline{q}$ and $\bar{q}$ in Figure 2 that equate $G_{LH}(q)$ to $G_L(q_L^*)$ and $G_H(q)$ to $G_{HL}(q_{HL}^*)$, respectively. In the following, we explain the implications of Lemma 2 by assuming some given market belief ($\mathbb{Q}_H$) that is known to the buyer.

After stocking a quantity q, the worst outcome for the buyer with a high signal is to be valued by the market as if she has a low signal, which leads to an expected payoff $G_{HL}(q)$. Maximizing $G_{HL}(q)$ would result in a payoff $G_{HL}(q_{HL}^*)$ that the buyer observing a high signal can at least secure. With the understanding of this reservation payoff, $\bar{q}$, as defined in Lemma 2, represents the largest quantity the buyer with a high signal is willing to stock to achieve a correct market recognition. This result implies that, for the buyer's strategy to be consistent with the given market belief, there must be some quantity in $\mathbb{Q}_H$ that is no larger than $\bar{q}$. By a similar reason, $G_L(q_L^*)$ serves as the reservation payoff for the buyer when she has a low signal. As defined in Lemma 2, $\underline{q}$ represents the largest quantity the buyer with a low signal is willing to stock to be considered as having a high signal. Therefore, the strategy of the buyer with a low signal is consistent with the market belief if $\mathbb{Q}_H$ contains quantities all above $\underline{q}$.

The result that $\underline{q} < \bar{q}$ guarantees the existence of a market belief under which the buyer's strategy with either signal is consistent with the market belief, thereby resulting in a separating equilibrium. In fact, multiple equilibria exist in our model. We focus on the one presented in Proposition 1 that uniquely survives the intuitive criterion (Cho and Kreps 1987). The intuitive criterion is generally used to test whether an equilibrium of a signaling game is stable. For instance, in our context, pooling equilibrium can exist under some market belief in which the buyer with either signal installs the same stocking level. However, the intuitive criterion can challenge such an equilibrium by testing whether an alternative stocking level exists that the buyer with a high (low) signal will strictly prefer (not prefer) to the equilibrium stocking level, assuming deviating to that alternative stocking level she is always considered by the market as having a high signal. If such a stocking level exists (i.e., the buyer with a high signal wants to deviate from the equilibrium while the buyer with a low signal does not want to deviate), then intuitively, observing such a deviation, the market should believe that the buyer does have a high signal, so the given equilibrium would not be stable. The insights obtained from an instable equilibrium may lose their generality.

Proposition 1. *Given any single contract offer (w, b, t), a unique separating market equilibrium exists that survives the intuitive criterion in which the stocking level follows*

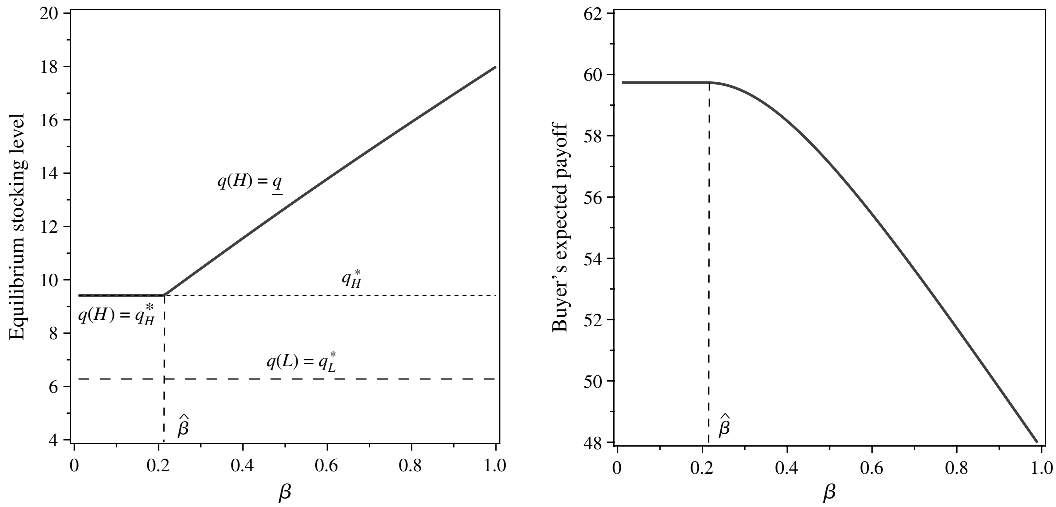
$$q(i) = \begin{cases} \hat{q} & \text{if } i = H, \\ q_L^* & \text{if } i = L, \end{cases} \tag{4}$$

with $\hat{q} = \max\{\underline{q}, q_H^*\}$, and the market belief can be specified as[6]

$$j(q) = \begin{cases} H & \text{if } q = \hat{q}, \\ L & \text{otherwise}. \end{cases} \tag{5}$$

[6] The market belief on the off-equilibrium path could be specified in other ways as long as the stocking strategy on the off-equilibrium path is dominated by the equilibrium strategy for the buyer. For instance, instead of the singleton $\mathbb{Q}_H = \{\hat{q}\}$, we can alternatively specify $\mathbb{Q}_H = \{q \in \mathbb{R}^+ \colon q \geq \hat{q}\}$. The equilibrium will not change.

Figure 3 Demonstration of the Equilibrium Stocking Level and the Buyer's Expected Payoff Π^B as Functions of β



Note. The parameters are $p = 20$, $c = 5$, $w = 8$, $b = 4$, $t = 0$, and $\lambda = 0.5$, and the demand follows the gamma distribution with density $f_i(x) = ((x/\kappa_i)^{\theta_i - 1} e^{-x/\kappa_i})/(\kappa_i \Gamma(\theta_i))$ for $i \in \{H, L\}$, where $(\kappa_H, \theta_H) = (1.5, 5)$ and $(\kappa_L, \theta_L) = (1, 5)$.

In this equilibrium, the buyer stocks $\hat{q}$ with a high signal and q_L^* with a low signal, consistent with the market belief. Notice that if the signal is low, stocking distortion does not occur. In contrast, if the signal is high, overstocking occurs when $q_H^* < \underline{q}$. Proposition 2 establishes a further result of the buyer's equilibrium stocking decision.

Proposition 2. *Given any single contract offer (w, b, t), a threshold $\hat{\beta} = (G_L(q_L^*) - G_L(q_H^*))/(G_H(q_H^*) - G_L(q_H^*))$ exists such that $q(H) = q_H^*$, which is fixed when $\beta \leq \hat{\beta}$, and $q(H) = \underline{q}$, which increases in β when $\beta > \hat{\beta}$.*

In the presence of a short-term interest in market value, the buyer observing a low demand signal may find it advantageous to mimic the order quantity associated with a high demand signal to gain from market valuation. It may thus become necessary for the buyer when truly observing a high demand signal to inflate her order to an extent (i.e., $\underline{q}$) such that it would not be profitable for her to mimic when observing a low signal, thereby credibly signaling her demand outlook. Such overstocking will not arise only when β is small ($\beta \leq \hat{\beta}$). In such circumstances, the buyer with a low signal will never attempt to mimic the order quantity under a high signal, even without quantity inflation, because the potential gain from market valuation does not outweigh the cost associated with the profit loss from a suboptimal quantity. The left plot of Figure 3 illustrates the buyer's equilibrium stocking levels. We see that when $\beta \leq \hat{\beta}$, $q(H) = q_H^*$, which is fixed, and when $\beta > \hat{\beta}$, $q(H) = \underline{q}$, which is larger than q_H^* and increases in β. (It is intuitive that the larger β is, the more the buyer with a high signal would need to inflate her order to credibly signal her demand information.) Overstocking, if it occurs, apparently will hurt the buyer firm's true performance, given that the quantity deviates from the truly optimal. This is concluded in Corollary 1 and depicted in the right plot of Figure 3.

Corollary 1. *The buyer's expected payoff follows $\Pi^B = \lambda G_H(q_H^*) + (1-\lambda) G_L(q_L^*)$, which is fixed when $\beta \leq \hat{\beta}$ and follows $\Pi^B = \lambda G_H(\underline{q}) + (1-\lambda) G_L(q_L^*)$, which decreases in β when $\beta > \hat{\beta}$.*

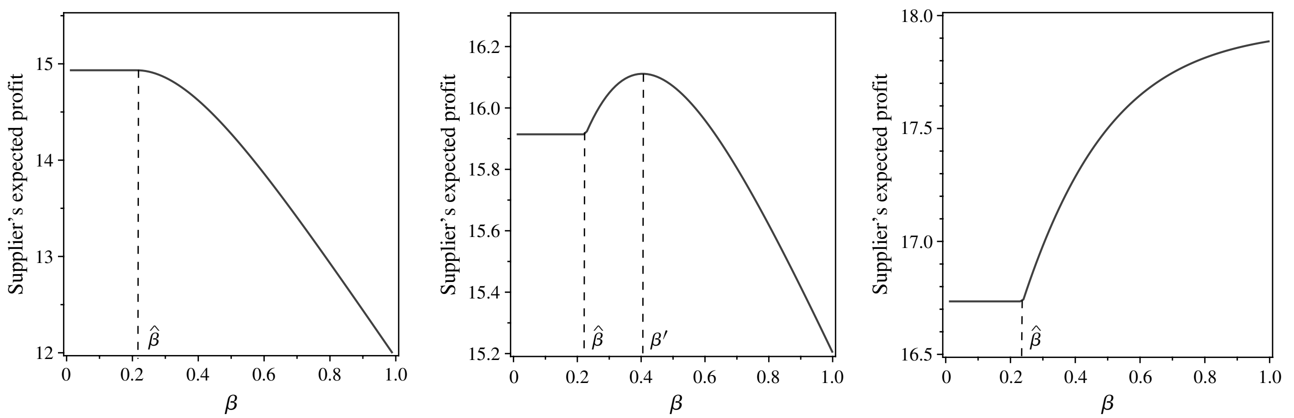
Thus far, we have derived the results of the game between the buyer and the investors that value the buyer. In the following subsection, we analyze how this downstream market game influences the performance of the supplier and the supply chain.

4.2. Supplier Profit

We have discussed that stocking distortion could occur in equilibrium, which hurts the buyer firm's true performance. However, whether such a stocking distortion is detrimental or beneficial for the supplier is not straightforward. If the buyer overstocks, on one hand, the supplier would seem to benefit, because more revenues could be collected; on the other hand, when a buyback term is provided, more returns could occur, which is costly for the supplier. In the following, we investigate this impact for a given contract offer (w, b, t).[7]

[7] In principle, if the supplier has the full bargaining power in the supply chain, he can optimize the contract offer, anticipating how the downstream market equilibrium is formed. The buyer's incentive to overstock may lead to a lower optimal buyback price. We do not provide the detailed analysis here for two reasons: First, a supplier may not have full bargaining power, and thus the insights we reveal with a general contract would be useful. Second, such an optimization would become superfluous when, as we reveal in §5,

Figure 4 Demonstration of the Supplier's Expected Profit Π^S as a Function of β



Notes. The common parameters are $p = 20$, $c = 5$, $w = 8$, $t = 0$, and $\lambda = 0.5$, and the demand follows the gamma distribution with density $f_i(x) = ((x/\kappa_i)^{\theta_i - 1} e^{-x/\kappa_i})/(\kappa_i \Gamma(\theta_i))$ for $i \in \{H, L\}$, where $(\kappa_H, \theta_H) = (1.5, 5)$ and $(\kappa_L, \theta_L) = (1, 5)$. In the left plot, $b = 4$; in the middle plot, $b = 3.5$; and in the right plot, $b = 3$.

From the results of Propositions 1 and 2, the supplier's expected profit follows:

$$\Pi^S = \begin{cases} \lambda\Big[(w-c-b)q_H^* + b\displaystyle\int_0^{q_H^*} \bar{F}_H(x)\,\mathrm{d}x\Big] + (1-\lambda) \\ \quad \cdot \Big[(w-c-b)q_L^* + b\displaystyle\int_0^{q_L^*} \bar{F}_L(x)\,\mathrm{d}x\Big] + t \quad \text{if } \beta \le \hat{\beta}, \\ \lambda\Big[(w-c-b)\underline{q} + b\displaystyle\int_0^{\underline{q}} \bar{F}_H(x)\,\mathrm{d}x\Big] + (1-\lambda) \\ \quad \cdot \Big[(w-c-b)q_L^* + b\displaystyle\int_0^{q_L^*} \bar{F}_L(x)\,\mathrm{d}x\Big] + t \quad \text{if } \beta > \hat{\beta}. \end{cases} \tag{6}$$

Based on (6), we derive the following proposition:

Proposition 3. *When $\beta \le \hat{\beta}$, the supplier's expected profit Π^S is independent of β; when $\beta > \hat{\beta}$, the following properties hold*:

(i) *If $b \ge ((w-c)/(p-c))p$, then Π^S strictly decreases in β.*

(ii) *If $b < ((w-c)/(p-c))p$, then a threshold $\beta' \in [\hat{\beta}, 1]$ exists such that Π^S increases in β when $\hat{\beta} < \beta < \beta'$ and decreases in β when $\beta > \beta'$.*

In Proposition 3, when $\beta < \hat{\beta}$, the supplier's profit does not change in β because stocking distortion does not occur in this region (see the straight lines in Figure 4).

In addition, stocking distortion, when it occurs $(\beta > \hat{\beta})$, could either hurt or benefit the supplier, depending on the contract terms. When $b \ge ((w-c)/(p-c))p$, which can be rewritten as $((p-w)/(p-b)) \cdot b \ge w - c$, stocking distortion always hurts the supplier (see the left plot in Figure 4). In particular, $(p-w)/(p-b)$, which equals $F_H(q_H^*)$, represents the probability that a unit product will be returned to the supplier when the buyer stocks q_H^*, and $((p-w)/(p-b))b$ captures the marginal refund cost. Hence, if $((p-w)/(p-b))b \ge w-c$, then the marginal refund cost $(F_H(q)b)$ will always outweigh the marginal revenue $(w-c)$ when the buyer stocks any q beyond q_H^* (given that $F_H(q)$ increases in q), which is costly for the supplier.

In contrast, if $b < ((w-c)/(p-c))p$, some amount of overstocking might benefit the supplier in that it mitigates double marginalization. A threshold β' can be determined such that the downstream overstocking will benefit (hurt) the supplier when $\beta < (>)\beta'$ (see the middle plot in Figure 4). Note that the value of β' can possibly reach one if the double marginalization effect is strong (see the right plot in Figure 4). Therefore, for a given contract offer, the downstream stocking distortion is beneficial for the supplier if it mitigates double marginalization in scenarios where β is intermediate, and it is detrimental if the downstream stocking level is distorted to a large extent when β is large.

We further note that if p becomes larger relative to c, then the term $((w-c)/(p-c))p$ becomes smaller and the region where the downstream stocking distortion is detrimental for the supplier becomes wider. In other words, for high-margin products (e.g., jewelry or other luxury products), the buyer's short-term interest in market value is more likely to be detrimental for the supplier.

4.3. Supply Chain Efficiency

The previous two subsections have shown that, for a given single contract offer, the buyer's short-term interest in market value hurts the firm's performance, whereas it can be either detrimental or beneficial for the supplier. Because the market value always coincides with the buyer firm's true expected profit

menus of buyback contracts exist under which full supply chain efficiency can be restored and the supplier can be better off compared with any single contract.

in equilibrium, the total supply chain surplus is, in essence, the "pie" that the supplier and the buyer are sharing through the trade contract, even though the buyer realizes a part of that value from the investors. Thus, examining the effect of the buyer's short-term interest in market value on supply chain efficiency is useful.

Summing up the two parties' expected profits leads to the total supply chain surplus:

$$\Pi^{SC} = \begin{cases} \lambda\left[p\int_0^{q_H^*}\bar{F}_H(x)\,dx - cq_H^*\right] \\ \quad +(1-\lambda)\left[p\int_0^{q_L^*}\bar{F}_L(x)\,dx - cq_L^*\right] & \text{if } \beta \le \hat{\beta}, \\ \lambda\left[p\int_0^{\underline{q}}\bar{F}_H(x)\,dx - c\underline{q}\right] \\ \quad +(1-\lambda)\left[p\int_0^{q_L^*}\bar{F}_L(x)\,dx - cq_L^*\right] & \text{if } \beta > \hat{\beta}. \end{cases} \tag{7}$$

The following proposition details the impact of the buyer's short-term interest in market value on the performance of the supply chain.

Proposition 4. *When $\beta \le \hat{\beta}$, the expected supply chain surplus Π^{SC} is independent of β; when $\beta > \hat{\beta}$, the following properties hold*:

(i) *If $b \ge ((w-c)/(p-c))p$, then Π^{SC} strictly decreases in β.*

(ii) *If $b < ((w-c)/(p-c))p$, then a threshold $\beta'' \in [\hat{\beta}, 1]$ exists such that Π^{SC} increases in β when $\hat{\beta} < \beta < \beta''$ and decreases in β when $\beta > \beta''$.*

We see that the supply chain surplus is not affected when $\beta \le \hat{\beta}$, and it may decrease or increase in β when $\beta > \hat{\beta}$, depending on the contract terms. In particular, when $b \ge ((w-c)/(p-c))p$, the downstream stocking distortion deteriorates the supply chain efficiency (see the left plot in Figure 5). To explain the intuition, we rewrite the condition $b \ge ((w-c)/(p-c))p$ to $c \ge ((w-b)/(p-b))p$ $(= \bar{F}_H(q_H^*)p)$. Hence, stocking beyond q_H^* is costly because the marginal cost c exceeds the marginal revenue $\bar{F}_H(q)p$. In contrast, when $b < ((w-c)/(p-c))p$, downstream overstocking could benefit the supply chain if β is less than a threshold β''; it is detrimental otherwise (see the middle plot in Figure 5). β'' may reach one for some given contract if the double marginalization effect is strong (see the right plot in Figure 5).

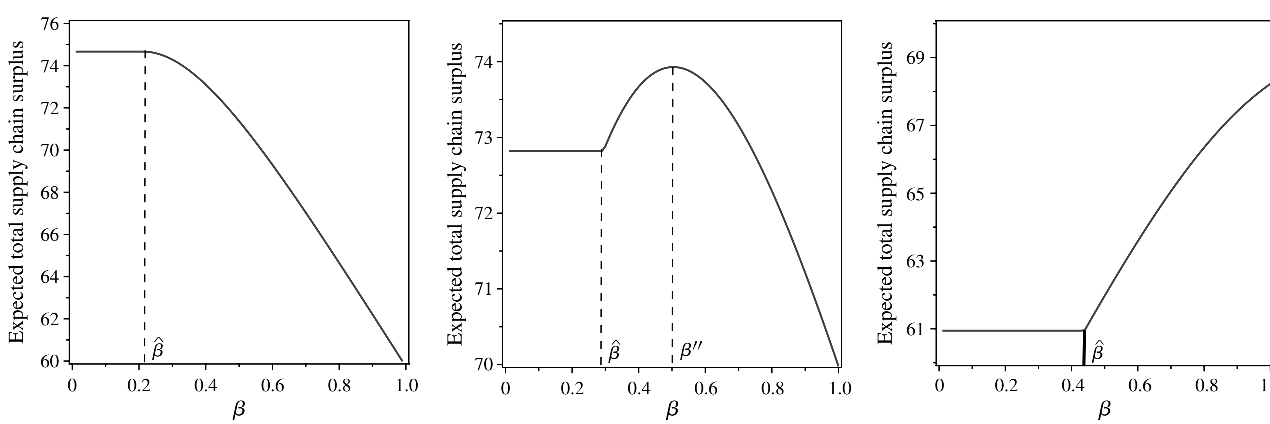
We note that when $b = ((w-c)/(p-c))p$ (or identically, $(w-b)/(p-b) = c/p$), the supply chain would be coordinated in the benchmark. Therefore, the intuition we have just explained suggests that, for a given contract offer, if the buyer's short-term interest in market value leads the stocking level closer to the level that would coordinate the supply chain in the benchmark, then such an interest improves the performance of the supply chain; otherwise, it hurts the supply chain.

More importantly, Proposition 4(i) shows that when $b = ((w-c)/(p-c))p$ (i.e., $(w-b)/(p-b) = c/p$, the necessary condition for coordination), the supply chain surplus decreases in β when $\beta > \hat{\beta}$; this result implies that supply chain coordination is not achieved. In fact, we can define $\hat{\beta}^o = (G_L(q_L^o) - G_L(q_H^o))/(G_H(q_H^o) - G_L(q_H^o))$, which depends only on the system parameters, and obtain the following proposition:

Proposition 5. *When $\beta > \hat{\beta}^o$, supply chain coordination cannot be achieved by any single contract offer in the form of (w, b, t).*

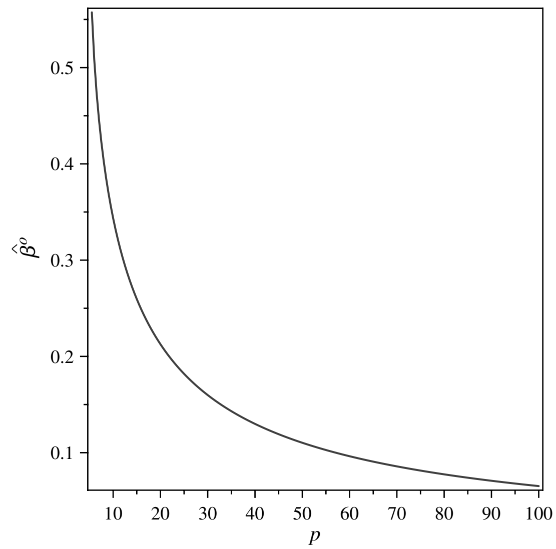
As shown in Figure 6, $\hat{\beta}^o$ decreases as p (or equivalently, the margin $p-c$) increases. Hence, the larger the margin is, the more likely the supply chain efficiency will be affected. Although similar operations

Figure 5 Demonstration of the Expected Total Supply Chain Surplus Π^{SC} as a Function of β



Notes. The common parameters are $p = 20$, $c = 5$, $t = 0$, and $\lambda = 0.5$, and the demand follows the gamma distribution with density $f_i(x) = ((x/\kappa_i)^{\theta_i - 1}e^{-x/\kappa_i})/(\kappa_i\Gamma(\theta_i))$ for $i \in \{H, L\}$, where $(\kappa_H, \theta_H) = (1.5, 5)$ and $(\kappa_L, \theta_L) = (1, 5)$. In the left plot, $w = 8$ and $b = 4$; in the middle plot, $w = 8$ and $b = 0$; and in the right plot, $w = 14$ and $b = 0$.

Figure 6 Demonstration of $\hat{\beta}^o$ as p Increases



Note. The parameters are $c = 5$ and $\lambda = 0.5$, and the demand follows the gamma distribution with density $f_i(x) = ((x/\kappa_i)^{\theta_i - 1} e^{-x/\kappa_i})/(\kappa_i \Gamma(\theta_i))$ for $i \in \{H, L\}$, where $(\kappa_H, \theta_H) = (1.5, 5)$ and $(\kappa_L, \theta_L) = (1, 5)$.

distortions have been revealed in the literature in either separating or pooling equilibrium (see, e.g., Bebchuk and Stole 1993, Schmidt et al. 2012), little discussion appears in the literature about how to restore system efficiency. Notice that in our model, improving supply chain efficiency is in both the buyer's and the supplier's interest because the buyer's market value always coincides with her true profit in equilibrium. Maximizing the total supply chain surplus thus maximizes the "pie" that the two parties can divide through their trade. Naturally, one approach to improve system efficiency would be to reduce β, for instance, structuring executive compensation to include fewer market-based incentives; regulation policies might also help. In the following section, we investigate whether operational approaches exist that can improve system efficiency.

5. Design of Menus of Buyback Contracts

In this section, we explore menus of buyback contracts that can restore full supply chain efficiency. Notice that the contract design in our study differs from those in the traditional adverse selection context because our problem involves a third party, the capital market; as a result, we need to establish a downstream market equilibrium. This equilibrium must be a separating equilibrium because full efficiency would not be achieved otherwise.

Let (w_i, b_i, t_i) denote the menu of contracts corresponding to the signal $i \in \{H, L\}$. We use $\tau \in \{H, L\}$ to denote the buyer's contract choice. The market infers the signal from the buyer's decisions by a belief denoted by

$$j(\tau, q) = \begin{cases} H & \text{if } q \in \mathbb{Q}_H^{\tau}, \\ L & \text{otherwise,} \end{cases}$$

where $\mathbb{Q}_H^{\tau \in \{H,L\}}$ is the set of stocking levels corresponding to the contract τ, for which the market believes the signal to be high. Recall from §3 that $q_i^o = \bar{F}_i^{-1}(c/p)$ is the first-best stocking level. Under a menu of contracts, full efficiency can be achieved in the supply chain if and only if the first-best stocking level can be implemented and, at the same time, the market is able to correctly infer the signal from the buyer's decisions. Formally, we define the following concept.

Definition 2. A market equilibrium with a menu of two buyback contracts is system-wise efficient if the buyer's decisions follow $(\tau, q)(i) = (i, q_i^o)$ and the market belief satisfies $j((\tau, q)(i)) = i$ for each signal $i \in \{H, L\}$.

Notice from Definition 2 that in a system-wise efficient market equilibrium, the set $\mathbb{Q}_H^H$ must contain q_H^o so that a high signal can be correctly inferred if the buyer with a high signal chooses the H contract and stocks q_H^o; in contrast, $\mathbb{Q}_H^L$ must not contain q_L^o, so that a low signal can be correctly inferred if the buyer with a low signal selects the L contract and stocks q_L^o. Given the structure of the game, any design of the contracts needs to be associated with the characterization of a market belief (i.e., $\mathbb{Q}_H^{\tau \in \{H,L\}}$). To directly solve this contract design problem could be challenging. However, the result of the following lemma will greatly reduce its complexity.

Lemma 3. *Given any menu of two buyback contracts, if a system-wise efficient market equilibrium is achieved with a market belief* $(\mathbb{Q}_H^H, \mathbb{Q}_H^L)$, *then the equilibrium can also be achieved with the market belief* $(\{q_H^o\}, \varnothing)$.

Lemma 3 indicates that if a system-wise efficient market equilibrium of our problem exists, then it must be achievable under a restrictive market belief in which the set $\mathbb{Q}_H^H$ is a singleton that contains just q_H^o and $\mathbb{Q}_H^L$ is an empty set. Under this market belief, if the buyer chooses the H contract, then she must stock q_H^o to be recognized as having a high signal; if the buyer chooses the L contract, then she is automatically considered to have a low signal. This result is powerful but also very intuitive, as we explain next.

Suppose there is a general belief $(\mathbb{Q}_H^H, \mathbb{Q}_H^L)$ with which a system-wise efficient market equilibrium is achieved. Then, choosing the $H(L)$ contract and stocking q_H^o (q_L^o) is the buyer's best strategy, given a high (low) signal. Now, suppose we keep $\mathbb{Q}_H^L$ fixed but shrink the set $\mathbb{Q}_H^H$ to the singleton containing only q_H^o. Such a modification obviously does not change the buyer's payoff with a high signal from choosing the H contract and stocking q_H^o; however, the modification will reduce the payoff for the buyer if she stocks other quantities, because, for any deviation from q_H^o, she would be considered to have a low signal. Thus, the buyer's best strategy if she has a high signal remains the same. It is also clear that the buyer with a low signal will not pretend to have a high signal because succeeding from mimicking becomes more difficult (the buyer now would have to stock q_H^o to succeed; before, she could select an ideal quantity from the original set $\mathbb{Q}_H^H$). The result and intuition of shrinking $\mathbb{Q}_H^L$ to the empty set ($\varnothing$) are similar.

Lemma 3 asserts that any system-wise efficient market equilibrium, if it exists, can always be achieved with the market belief $(\{q_H^o\}, \varnothing)$; thus, we can design the mechanism directly using this market belief, which greatly shrinks the searching space.

Notice that for the buyer to stock the first-best quantity for each signal $i \in \{H, L\}$, the contract terms must satisfy

$$\frac{w_H - b_H}{p - b_H} = \frac{w_L - b_L}{p - b_L} = \frac{c}{p}.$$

With this condition, we can determine the wholesale price w_i once the buyback price b_i is given, and vice versa. Further, let

$$g_{ij}(q) \equiv \int_0^q \bar{F}_{ij}(x)\,\mathrm{d}x - \frac{c}{p}q, \quad \forall\, i, j \in \{H, L\},$$

where the subscript ij is reduced to i when $i = j$, and $q_{ij}^o \equiv \bar{F}_{ij}^{-1}(c/p)$ for $i \neq j$. Proposition 6 establishes conditions under which a menu of buyback contracts can restore full efficiency.

Proposition 6. *With the market belief $(\{q_H^o\}, \varnothing)$, a system-wise efficient market equilibrium can be achieved if the menu of buyback contracts (w_i, b_i, t_i) satisfies $(w_i - b_i)/(p - b_i) = (c/p)$ for each $i \in \{H, L\}$, $b_L \geq (1/K)b_H + p(K-1)/K$, and $t_H - t_L \in [\underline{\Delta}_t, \bar{\Delta}_t]$, where*

$$K = \max\left\{\frac{g_{HL}(q_{HL}^o) - g_L(q_L^o)}{g_H(q_H^o) - g_{LH}(q_H^o)}, \frac{g_{HL}(q_{HL}^o) - g_L(q_L^o)}{g_H(q_H^o) - g_L(q_L^o)}\right\};$$

$$\underline{\Delta}_t = (p - b_H)\max\{g_{LH}(q_H^o), g_L(q_L^o)\} - (p - b_L)g_L(q_L^o);$$

$$\bar{\Delta}_t = (p - b_H)g_H(q_H^o) - (p - b_L)g_{HL}(q_{HL}^o).$$

In equilibrium, the buyer observing the high (low) signal shall prefer the H (L) contract and stock the associated first-best quantity, even if she takes the market value into account. A key condition for achieving this result is the buyback prices chosen for the contracts. In general, the buyer favors a generous return term when the demand outlook is pessimistic. Thus, the buyback price (b_L) of the L contract shall be attractive enough for the buyer with a low signal to choose this contract. Specifically, b_L shall be no less than a particular threshold level ($(1/K)b_H + p((K-1)/K)$) that is contingent on b_H. When this condition is satisfied, a pair of transfer payments can always be chosen (with their difference bounded by the two thresholds $\underline{\Delta}_t$ and $\bar{\Delta}_t$, depending on the buyback prices) that provides sufficient incentives for the buyer having each signal to take the truth-telling contract and stock the first-best quantity under the coordination condition.

The result of Proposition 6 indicates that in a supply chain context, the supplier might be able to "correct" the downstream stocking distortion by offering alternative contract choices. The buyer credibly reveals her information through her choice of contract, in contrast to the overstocking that would otherwise be necessary under a single contract offer.

A remaining issue in implementing the mechanism described is to determine how the surplus can be divided between the parties in the supply chain. Notice that the mechanism could be difficult to implement if the resulting payoff is not satisfactory for one party (e.g., compared with the payoff she or he can obtain under an existing single contract offer). This issue is addressed in the following.

Proposition 7. *With the market belief $(\{q_H^o\}, \varnothing)$, there exists a menu of buyback contracts*

$$b_H = 0,\ w_H = c \quad \textit{and}$$

$$t_H = p g_H(q_H^o) - \varepsilon[g_H(q_H^o) - g_L(q_L^o)] - T,$$

$$b_L = p - \varepsilon,\ w_L = p - \varepsilon\left(1 - \frac{c}{p}\right) \quad \textit{and}$$

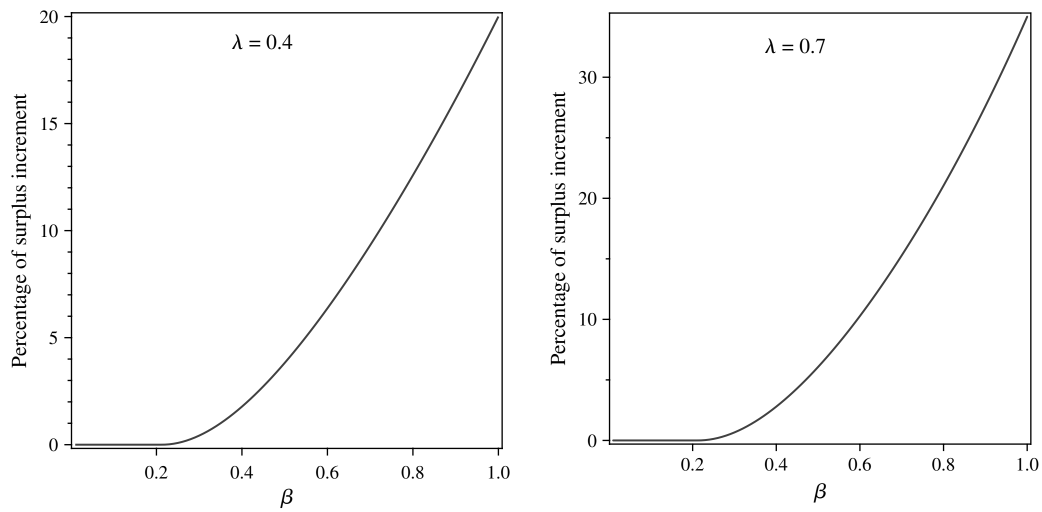
$$t_L = \varepsilon g_L(q_L^o) - T,$$

with any constant $\varepsilon \leq p/K$ and T, under which a system-wise efficient market equilibrium can be reached. The supplier's profit goes to the total supply chain surplus as ε and T go to zero.

Proposition 7 provides a special menu of buyback contracts that can achieve a system-wise efficient market equilibrium. In particular, under this menu, the supplier is able to obtain almost all of the supply chain surplus as ε and T go to zero. Because T is a constant appearing in both t_H and t_L, any specific allocation of the supply chain surplus can always be achieved by adjusting T. As a result, Proposition 7 demonstrates that both parties feasibly can be made better off compared to a single contract scenario (given that the total supply chain surplus is enlarged). That is, pareto improvement can be achieved. Note that Proposition 7 gives just one example. One can design menus of contracts with other wholesale, buyback, and transfer prices for the specific need of implementation, as long as the conditions in Proposition 6 are satisfied.

Thus far, we have shown that offering an appropriately designed menu of buyback contracts can

Figure 7 **Demonstration of the Gain of Supply Chain Surplus by Using the Mechanism**



Notes. We calculate the total supply chain surplus Π^{SC}_{SNG} when a single traditional coordinating buyback contract ($w = 11$, $b = 8$, $t = 0$) is used; we then calculate the total supply chain surplus Π^{SC}_{MN} of the case where the proposed mechanism is implemented (that is, the truly coordinated supply chain surplus) and compute $(\Pi^{SC}_{MN} - \Pi^{SC}_{SNG})/(\Pi^{SC}_{SNG}) \times 100\%$. The other parameters are $p = 20$ and $c = 5$, and the demand follows the gamma distribution with density $f_i(x) = (x/\kappa_i)^{\theta_i-1} e^{-(x/\kappa_i)})/(\kappa_i \Gamma(\theta_i))$ for $i \in \{H, L\}$ with $(\kappa_H, \theta_H) = (1.5, 5)$ and $(\kappa_L, \theta_L) = (1, 5)$ such that $F_H(x) < F_L(x)$, $\forall\, x > 0$.

resolve the downstream stocking distortion. It might be interesting to assess the benefit from using such a mechanism. For that purpose, we define a specific benchmark where, instead of a menu, a *single* traditional coordinating buyback contract is used (that satisfies $(w-b)/(p-b) = c/p$; the supply chain obviously would not be coordinated, as the downstream buyer will overstock). We derive the total supply chain surplus of this case, denoted by Π^{SC}_{SNG}. We also derive the total supply chain surplus of the case where the proposed mechanism is implemented, that is, the supply chain surplus when it is truly coordinated, denoted by Π^{SC}_{MN}. Figure 7 provides an example of the benefit from using this mechanism (the percentage of surplus increment).[8] It is straightforward that the benefit of this mechanism increases in the magnitude (β) of the buyer's interest in market value and the probability (λ) that the demand signal is high (the buyer will distort the stocking level only if she receives a high signal). The benefit also increases as the (stochastic) difference of the demands under the two signals increases, because the buyer will have a stronger incentive to distort the stocking level. Certainly, the benefit also increases in the profitability of the business.

Prior research has explored different purposes for using a menu of contracts, such as to share and improve demand forecasting (Cachon and Lariviere 2001, Özer and Wei 2006, Taylor and Xiao 2009) or to elicit cost and inventory information (Ha 2001, Zhang 2010, Zhang et al. 2010). Our study reveals that offering a menu of contracts might also be helpful to mitigate stocking distortion when the downstream party has private demand information and, at the same time, cares about her market value.

6. Robustness: The Continuous Signal Case

The model analyzed in the previous sections has a two-state demand signal—either high or low. It is useful to check whether the insights are robust for more complex settings. We conduct such an analysis with a continuous demand signal, as presented in Appendix B (where we again assume that a larger signal implies a stochastically larger demand).

Similar to what we have shown in §4, under a single contract, a fully separating equilibrium exists when the demand signal is continuous. In this equilibrium, the buyer firm always overstocks except when she receives the least signal. Moreover, the amount of overstocking increases monotonically in the signal, and thus the investors can perfectly infer the signal from the stocking level. The stocking distortion is systematically larger when the buyer firm's interest

[8] We do not present the menus of contracts or the parties' payoffs in the figure, as they can vary for different β and λ and there can be many choices for the contracts. We provide one example here: When $\beta = 0.5$ and $\lambda = 0.7$, under the single contract ($w = 11$, $b = 8$, $t = 0$), the buyer stocks 12.69 (6.27) units when the signal is high (low); the supplier's (buyer's) expected payoff is 30.41 (45.62). In contrast, if the following menu of contracts $\{(w_H, b_H, t_H), (w_L, b_L, t_L)\} = \{(8.75, 5, 15), (12.5, 10, -9)\}$ is used, then the buyer stocks the first-best quantity 9.41 (6.27) units when the signal is high (low); the supplier's (buyer's) expected payoff is 32.44 (48.20). (The buyer pays the supplier $wq + t$ up front; a negative t means a deduction of the total wholesale payment.)

in her market value increases. Such stocking distortions always hurt the buyer firm's true performance and reduce the maximum efficiency of the supply chain.

It is natural to question whether a menu of buyback contracts can be designed to resolve the downstream stocking distortion in an environment with a continuous demand signal. Our analysis in Appendix B shows that it is achievable by designing a menu of buyback contracts corresponding to the values of the signal. In particular, to reach a system-wise efficient market equilibrium, each buyback contract in the menu must first satisfy the classical supply chain coordination condition; second, both the return schedule and the wholesale price of the contracts in the menu must decrease in the value of the signal (intuitively, the buyer firm will favor a generous return term to a lesser degree but a low wholesale price to a greater degree when the demand outlook improves). With these conditions, a proper transfer payment scheme can be designed, depending on β, that ensures the buyer firm always takes the truth-telling contract. The design of the transfer payment can be flexible in the sense that any desired allocation of the supply chain surplus among the two parties can be achieved, and thus pareto improvement is feasible compared to the case of using a single contract. We further find that it is possible to transform the designed menu of buyback contracts to a specific single quantity discount contract with a return scheme under which the system-wise efficient market equilibrium is guaranteed. This result is practically meaningful because implementing a single contract can be much simpler than implementing a menu of contracts.

7. Conclusion

In this paper, we explore how a downstream buyer's short-term interest in her market value might influence the performances of the parties in the supply chain. First, we show that under a single buyback contract the buyer might purposely distort the stocking level in equilibrium. Such a stocking distortion hurts the buyer firm's profitability, and it either benefits or hurts the supplier, depending on the contract terms. We reveal scenarios where full supply chain efficiency cannot be achieved by any single buyback contract offer. These findings enrich the supply chain literature. An interest in the capital market valuation is not uncommon for firms in practice; however, it has been little explored in the supply chain literature. Second, aiming to prevent stocking distortion, we investigate providing a menu of buyback contracts in such a context. We derive conditions under which a menu of buyback contracts can restore full efficiency in the supply chain. This finding enriches the literature that explores real earnings management. We demonstrate that in a supply chain context, operational means can possibly be designed to resolve the distortions.

We conclude by discussing several assumptions in our study. First, we have assumed that the buyer cares about her market value but the supplier does not. In practice, both firms might be interested in their market values. Notice that if the information of the supplier's operations is complete, our results continue to hold, because the market can correctly assess the supplier's performance. However, if the supplier also possesses private information he may have an incentive to induce the buyer to order more (and potentially report a false return allowance) to gain from market valuation. The mechanism proposed in our study is effective in resolving the distortion caused by a downstream buyer but may not be effective for distortions triggered by an upstream supplier. Exploring operational approaches to mitigate the distortions caused by upstream suppliers is an interesting direction for future research.

Second, we have assumed that the contract information (in particular, the wholesale, buyback, and transfer prices) is accessible to the market. In other words, our model assumes that either the investors are familiar with the firms' operations and are able to gather specific supply chain information or disclosure about the supply contracts is made publicly to the capital market. Note that in some scenarios, regulators demand that suppliers publish information about their wholesale contracts to the market. Furthermore, firms in practice often adopt rules such as "a need-to-know basis" in communicating information such as supply contracts to external parties. Thus, investors (e.g., institutional investors and professional analysts) might be able to gather public information from the market and also request specific information from the firms. Our study suggests the bright side of such information disclosure about the supply contracts (instead of just having the stocking level revealed), which can reduce the capital market friction caused by firms' short-term interest in their market value. When competition is concerned, such information disclosure can be either costly or more beneficial for firms, because the information could either reduce the competition advantages or deter the competitors. A broad discussion on this matter is out of the scope of this research. Certainly, our study is limited from the perspective of this assumption. When the information of the supply contracts is incomplete or noisy, constructing some belief of the contracts would then be necessary for the investors to value the firm. The analysis will be significantly complex for such scenarios.

Third, we have assumed that the information of the buyer firm's interest in market value (i.e., β) is public. In other words, the supplier and the investors have the same information about β and that is precise. In practice, public firms often need to disclose the compensation packages offered to their top executives and their plans of selling shares; also, information of firms' capital structures is often accessible to both investors and other parties. Certainly, the information that the investors and the supplier have about the downstream buyer firm's true β could be different or imprecise. In such situations, the effectiveness of the mechanism can be affected.

Finally, our study focuses on a specific selling event and we apply a one-period model. Extending our study to more general inventory decision problems with a longer time horizon is interesting for future research.

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Appendix A. Proofs

Proof of Lemma 1. $G_L(q)$ and $G_H(q)$ follow the classical newsvendor objective function and are thus concave. Notice that $G_{LH}(q)$ and $G_{HL}(q)$ are linear combinations of $G_L(q)$ and $G_H(q)$. Therefore, they are also concave. □

Proof of Lemma 2. From the definitions of $G_{LH}(q)$, q^*_{LH}, and q^*_L, it is directly seen that $G_{LH}(q^*_{LH}) > G_{LH}(q^*_L) > G_L(q^*_L)$. Given that $G_{LH}(q)$ is concave, there exists a unique $\underline{q} > q^*_{LH}$ that satisfies $G_{LH}(\underline{q}) = G_L(q^*_L)$. By a similar argument, we can show that there exists a unique $\bar{q} > q^*_H$ that satisfies $G_H(\bar{q}) = G_{HL}(q^*_{HL})$.

In the following, we show $\underline{q} < \bar{q}$ by contradiction. Suppose $\underline{q} \geq \bar{q}$. Then, we have

$$\begin{aligned}
G_H(\bar{q}) - G_{LH}(\underline{q}) &= (p-b)\int_0^{\bar{q}} (1-\beta)[\bar{F}_H(x) - \bar{F}_L(x)]\,dx \\
&\quad + (w-b)(\underline{q} - \bar{q}) - (p-b)\int_{\bar{q}}^{\underline{q}} \bar{F}_{LH}(x)\,dx \\
&= (p-b)\int_0^{\bar{q}} (1-\beta)[\bar{F}_H(x) - \bar{F}_L(x)]\,dx \\
&\quad + (p-b)\int_{\bar{q}}^{\underline{q}} [\bar{F}_{LH}(q^*_{LH}) - \bar{F}_{LH}(x)]\,dx \\
&\geq (p-b)\int_0^{\bar{q}} (1-\beta)[\bar{F}_H(x) - \bar{F}_L(x)]\,dx.
\end{aligned}$$

The second equality holds because $q^*_{LH} = \bar{F}^{-1}_{LH}((w-b)/(p-b))$ and thus $\bar{F}_{LH}(q^*_{LH}) = (w-b)/(p-b)$. The last inequality holds because $\bar{q} > q^*_H > q^*_{LH}$ and thus $\bar{F}_{LH}(q^*_{LH}) > \bar{F}_{LH}(x)$ for any $x > \bar{q}$. Further, we can obtain

$$\begin{aligned}
G_{HL}(q^*_{HL}) - G_L(q^*_L) &= (p-b)\int_0^{q^*_{HL}} (1-\beta)[\bar{F}_H(x) - \bar{F}_L(x)]\,dx \\
&\quad + (p-b)\int_{q^*_L}^{q^*_{HL}} [\bar{F}_L(x) - \bar{F}_L(q^*_L)]\,dx \\
&\leq (p-b)\int_0^{q^*_{HL}} (1-\beta)[\bar{F}_H(x) - \bar{F}_L(x)]\,dx.
\end{aligned}$$

Notice that $\bar{q} > q^*_H > q^*_{HL}$. Consequently, the above two inequalities lead to $G_H(\bar{q}) - G_{LH}(\underline{q}) > G_{HL}(q^*_{HL}) - G_L(q^*_L)$, which contradicts the definitions that $G_H(\bar{q}) = G_{HL}(q^*_{HL})$ and $G_{LH}(\underline{q}) = G_L(q^*_L)$. Hence, we conclude that $\underline{q} < \bar{q}$. □

Proof of Proposition 1. From Lemma 2, it is clear that if the market holds a belief as

$$j(q) = \begin{cases} H & \text{if } q = \hat{q}, \\ L & \text{otherwise}, \end{cases}$$

where $\hat{q} = \max\{\underline{q}, q^*_H\}$, then the buyer's strategy follows

$$q(i) = \begin{cases} \hat{q} & \text{if } i = H, \\ q^*_L & \text{if } i = L. \end{cases}$$

That is, under this market belief, when observing a low signal, the buyer stocks q^*_L and has no incentive to stock $\hat{q}$ to mimic the high signal strategy; the buyer also has no incentive to deviate from $\hat{q}$ if she observes a high signal. The market belief is consistent with the buyer's strategies. Thus, a separating equilibrium holds. We show in the online supplement to this paper (Lai et al. 2012) that this is the unique equilibrium that survives the intuitive criterion in our model. □

Proof of Proposition 2. We first prove $\underline{q}$ increases in β. Define

$$\begin{aligned}
H(\underline{q}, \beta) &\equiv G_{LH}(\underline{q}) - G_L(q^*_L) \\
&= \left[(p-b)\int_0^{\underline{q}} \bar{F}_{LH}(x)\,dx - (w-b)\underline{q}\right] \\
&\quad - \left[(p-b)\int_0^{q^*_L} \bar{F}_L(x)\,dx - (w-b)q^*_L\right] = 0.
\end{aligned}$$

Recall that $\bar{F}_{LH}(q) = \beta\bar{F}_H(q) + (1-\beta)\bar{F}_L(q)$. We can easily verify that $\partial H(\underline{q}, \beta)/\partial\beta > 0$ as $G_{LH}(q)$ increases in β and $G_L(q^*_L)$ is independent of β. On the other hand, given $\underline{q} > q^*_{LH}$ by its definition, $G_{LH}(q)$ decreases in $\underline{q}$; thus, $\partial H(\underline{q}, \beta)/\partial\underline{q} < 0$. Consequently, $\partial\underline{q}/\partial\beta = -(\partial H(\underline{q}, \beta)/\partial\beta)/(\partial H(\underline{q}, \beta)/\partial\underline{q}) > 0$.

In the following we show that a unique threshold $\beta = \hat{\beta}$ exists at which $\underline{q} = q^*_H$. First, when $\beta = 0$, from the definition of $\underline{q}$ (i.e., $G_{LH}(\underline{q}) = G_L(q^*_L)$), we learn $\underline{q} = q^*_L < q^*_H$. Second, when $\beta = 1$, $q^*_{LH} = q^*_H$. The definition of $\underline{q}$ asserts $\underline{q} > q^*_{LH} = q^*_H$. Therefore, a unique threshold $\beta = \hat{\beta}$ exists at which $\underline{q} = q^*_H$.

To characterize $\hat{\beta}$, we know $\underline{q} = q^*_H$ at $\hat{\beta}$ and thus the condition $G_{LH}(\underline{q}) = G_L(q^*_L)$ that determines $\underline{q}$ is equivalent to $G_{LH}(q_H^*) = G_L(q_L^*)$, or identically, $G_{LH}(q_H^*) = \hat{\beta} G_H(q_H^*) + (1-\hat{\beta})G_L(q_H^*) = G_L(q_L^*)$. By rearranging the terms, we obtain $\hat{\beta} = (G_L(q_L^*) - G_L(q_H^*))/(G_H(q_H^*) - G_L(q_H^*))$. □

Proof of Corollary 1. When $\beta \le \hat{\beta}$, the buyer's stocking decision is fixed and thus her expected payoff is also fixed; when $\beta > \hat{\beta}$, $q(H) = \underline{q}$ increases in β, which implies that the buyer overstocks more units, and thus her expected payoff decreases. □

Proof of Proposition 3. To show proof for (i) and (ii), we take the derivative $d\Pi^S/d\beta = \lambda[w - c - bF_H(\underline{q})](d\underline{q}/d\beta)$. Recall from Proposition 2 that $d\underline{q}/d\beta > 0$. Thus, we only need to determine the sign of $w - c - bF_H(\underline{q})$.

(i) Note that $F_H(q_H^*) = (p-w)/(p-b)$. When $\beta > \hat{\beta}$, $\underline{q} > q_H^*$ and $F_H(\underline{q}) > F_H(q_H^*) = (p-w)/(p-b)$. Therefore, if $\bar{b} \ge ((p-b)/(p-w))(w-c)$, then we have $w - c - bF_H(\underline{q}) < w - c - ((p-b)/(p-w))(w-c)((p-w)/(p-b)) = 0$, which asserts $d\Pi^S/d\beta < 0$.

(ii) Given $\underline{q}$ increases in β, $\underline{q}$ reaches the largest, denoted as $\underline{q}^{\max}$, when $\beta = 1$. Note that when $\beta = 1$, $q_{LH}^* = q_H^*$. Therefore, by the definition of $\underline{q}$, $\underline{q}^{\max}$ is the solution of $G_H(q) = G_L(q_L^*)$ that satisfies $\underline{q}^{\max} > q_H^*$. Given that $F_H(\underline{q})$ reaches the largest at $\underline{q} = \underline{q}^{\max}$, if $w - c - bF_H(\underline{q}^{\max}) \ge 0$, then Π^S is increasing in β when $\beta \in [\hat{\beta}, 1]$. That is, $\beta' = 1$. Now, suppose $w - c - bF_H(\underline{q}^{\max}) < 0$. When $\beta > \hat{\beta}$, $F_H(\underline{q})$ reaches the least as $\beta \to \hat{\beta}$ (and $\underline{q} \to q_H^*$). At $\underline{q} = q_H^*$, we have $w - c - bF_H(q_H^*) = w - c - b((p-w)/(p-b)) > 0$. Therefore, there exists a $\beta' \in [\hat{\beta}, 1]$ and a corresponding $\underline{q} \in [q_H^*, \underline{q}^{\max}]$ at which $w - c - bF_H(\underline{q}) = 0$, and Π^S is increasing in β when $\hat{\beta} < \beta < \beta'$ and decreasing in β when $\beta > \beta'$. □

Proof of Proposition 4. To verify (i) and (ii), we take the derivative $d\Pi^{SC}/d\beta = \lambda[p\bar{F}_H(\underline{q}) - c](d\underline{q}/d\beta)$. Given $d\underline{q}/d\beta > 0$, we only need to determine the sign of $p\bar{F}_H(\underline{q}) - c$.

(i) Note that $\bar{F}_H(q_H^*) = (w-b)/(p-b)$. When $\beta > \hat{\beta}$, $\underline{q} > q_H^*$ and $\bar{F}_H(\underline{q}) < \bar{F}_H(q_H^*) = (w-b)/(p-b)$. Therefore, if $(w-b)/(p-b) \le c/p$, $p\bar{F}_H(\underline{q}) - c < p\bar{F}_H(q_H^*) - c \le 0$, and $d\Pi^{SC}/d\beta < 0$.

(ii) When $\beta > \hat{\beta}$, $\bar{F}_H(\underline{q})$ reaches the largest as $\beta \to \hat{\beta}$ (and thus $\underline{q} \to q_H^*$). If $(w-b)/(p-b) > c/p$, then at $\underline{q} = q_H^*$, we have $p\bar{F}_H(\underline{q}) - c = p((w-b)/(p-b)) - c > 0$, which implies that Π^{SC} is increasing at $\beta = \hat{\beta}$. Given $\underline{q}$ increases in β, $d\Pi^{SC}/d\beta$ decreases in β. The result of (ii) then follows directly. □

Proof of Proposition 5. To coordinate the supply chain, the contract must satisfy $(w-b)/(p-b) = c/p$. From Proposition 4(i), we notice that if $(w-b)/(p-b) = c/p$, then Π^{SC} is strictly decreasing in β when $\beta > \hat{\beta}$. Hence, the supply chain will not be coordinated by any single contract offer (w, b, t). The definition of $\hat{\beta}^o$ follows directly from that of $\hat{\beta}$ as $q_i^* = q_i^o$ when $(w-b)/(p-b) = c/p$. □

Proof of Lemma 3. If the system can achieve the first-best level with a market belief $(\mathbb{Q}_H^H, \mathbb{Q}_H^L)$, then these two sets must satisfy $q_H^o \in \mathbb{Q}_H^H$ and $q_L^o \notin \mathbb{Q}_H^L$ (otherwise, the buyer would need to distort the stocking levels for the market to correctly infer the signal). To achieve the maximum efficiency, we need $(w_H - b_H)/(p - b_H) = (w_L - b_L)/(p - b_L) = c/p$. Under such a menu of buyback contracts, when the signal is high, the buyer's decision follows

$$
\max_{(\tau, q)} \begin{cases}
\Pi^B(H,H;H) \\
\quad \equiv \max\limits_{q\in\mathbb{Q}_H^H} (p-b_H)\left[\int_0^q \bar{F}_H(x)\,dx - \dfrac{c}{p}q\right] - t_H \quad \text{if } \tau = H, \\
\Pi^B(H,L;H) \\
\quad \equiv \max\limits_{q\notin\mathbb{Q}_H^H} (p-b_H)\left[\int_0^q \bar{F}_{HL}(x)\,dx - \dfrac{c}{p}q\right] - t_H \quad \text{if } \tau = H, \\
\Pi^B(L,H;H) \\
\quad \equiv \max\limits_{q\in\mathbb{Q}_H^L} (p-b_L)\left[\int_0^q \bar{F}_H(x)\,dx - \dfrac{c}{p}q\right] - t_L \quad \text{if } \tau = L, \\
\Pi^B(L,L;H) \\
\quad \equiv \max\limits_{q\notin\mathbb{Q}_H^L} (p-b_L)\left[\int_0^q \bar{F}_{HL}(x)\,dx - \dfrac{c}{p}q\right] - t_L \quad \text{if } \tau = L;
\end{cases}
$$

when the signal is low, the buyer's decision follows

$$
\max_{(\tau, q)} \begin{cases}
\Pi^B(H,H;L) \\
\quad \equiv \max\limits_{q\in\mathbb{Q}_H^H} (p-b_H)\left[\int_0^q \bar{F}_{LH}(x)dx - \dfrac{c}{p}q\right] - t_H \quad \text{if } \tau = H, \\
\Pi^B(H,L;L) \\
\quad \equiv \max\limits_{q\notin\mathbb{Q}_H^H} (p-b_H)\left[\int_0^q \bar{F}_L(x)\,dx - \dfrac{c}{p}q\right] - t_H \quad \text{if } \tau = H, \\
\Pi^B(L,H;L) \\
\quad \equiv \max\limits_{q\in\mathbb{Q}_H^L} (p-b_L)\left[\int_0^q \bar{F}_{LH}(x)\,dx - \dfrac{c}{p}q\right] - t_L \quad \text{if } \tau = L, \\
\Pi^B(L,L;L) \\
\quad \equiv \max\limits_{q\notin\mathbb{Q}_H^L} (p-b_L)\left[\int_0^q \bar{F}_L(x)\,dx - \dfrac{c}{p}q\right] - t_L \quad \text{if } \tau = L.
\end{cases}
$$

If a system-wise efficient market equilibrium is reached with the market belief $(\mathbb{Q}_H^H, \mathbb{Q}_H^L)$, then the buyer takes the contract (w_H, b_H, t_H) and stocks q_H^o when the signal is high and she takes the contract (w_L, b_L, t_L) and stocks q_L^o when the signal is low, which implies the following (IC) and (IR) constraints:

$$
\begin{cases}
\Pi^B(L,L;L) \ge \max\{\Pi^B(H,H;L), \\
\qquad \Pi^B(H,L;L), \Pi^B(L,H;L)\} \quad \text{(IC1)}, \\
\Pi^B(H,H;H) \ge \max\{\Pi^B(H,L;H), \\
\qquad \Pi^B(L,H;H), \Pi^B(L,L;H)\} \quad \text{(IC2)}, \\
\Pi^B(L,L;L) \ge 0 \qquad \text{(IR1)}, \\
\Pi^B(H,H;H) \ge 0 \quad \text{(IR2)}.
\end{cases} \tag{A1}
$$

When the thresholds in the market belief $(\mathbb{Q}_H^H, \mathbb{Q}_H^L)$ are replaced by $(\{q_H^o\}, \varnothing)$, $\Pi^B(H,H;H)$ and $\Pi^B(L,L;L)$ will not change and it is not difficult to find out that the right-hand sides of the IC constraints will only become smaller because the market belief becomes stricter in terms of recognizing a high signal. Hence, the same separating equilibrium will be achieved. □

Proof of Proposition 6. We start the proof by analyzing the (IC) constraints. With the market belief $(\{q_H^o\}, \varnothing)$, the (IC1) constraint in (A1) can be captured by the following two inequalities:

$$\begin{aligned}(p-b_L)\left[\int_0^{q_L^o}\bar{F}_L(x)\,dx-\frac{c}{p}q_L^o\right]-t_L\\ \geq (p-b_H)\left[\beta\int_0^{q_H^o}\bar{F}_H(x)\,dx\right.\\ \left.+(1-\beta)\int_0^{q_H^o}\bar{F}_L(x)\,dx-\frac{c}{p}q_H^o\right]-t_H\end{aligned}\qquad (A2)$$

and

$$\begin{aligned}(p-b_L)\left[\int_0^{q_L^o}\bar{F}_L(x)\,dx-\frac{c}{p}q_L^o\right]-t_L\\ \geq (p-b_H)\left[\int_0^{q_L^o}\bar{F}_L(x)\,dx-\frac{c}{p}q_L^o\right]-t_H.\end{aligned}\qquad (A3)$$

The (IC2) constraint can be rewritten as

$$\begin{aligned}(p-b_H)\left[\int_0^{q_H^o}\bar{F}_H(x)\,dx-\frac{c}{p}q_H^o\right]-t_H\\ \geq (p-b_L)\left[\beta\int_0^{q_{HL}^o}\bar{F}_L(x)\,dx\right.\\ \left.+(1-\beta)\int_0^{q_{HL}^o}\bar{F}_H(x)\,dx-\frac{c}{p}q_{HL}^o\right]-t_L.\end{aligned}\qquad (A4)$$

From (A2)–(A4), we can obtain

$$t_H-t_L \geq (p-b_H)g_{LH}(q_H^o)-(p-b_L)g_L(q_L^o), \qquad (A5)$$

$$t_H-t_L \geq (p-b_H)g_L(q_L^o)-(p-b_L)g_L(q_L^o), \qquad (A6)$$

$$t_H-t_L \leq (p-b_H)g_H(q_H^o)-(p-b_L)g_{HL}(q_{HL}^o). \qquad (A7)$$

Therefore, the right-hand side of (A7) must be larger than or equal to the maximum of those of (A5) and (A6); hence, we obtain the condition $(p-b_H)/(p-b_L)\geq K$, where

$$K=\max\left\{\frac{g_{HL}(q_{HL}^o)-g_L(q_L^o)}{g_H(q_H^o)-g_{LH}(q_H^o)},\frac{g_{HL}(q_{HL}^o)-g_L(q_L^o)}{g_H(q_H^o)-g_L(q_L^o)}\right\}. \qquad (A8)$$

When $(p-b_H)/(p-b_L)\geq K$, a pair of t_H and t_L that satisfy the (IC) and (IR) constraints always exist. □

Proof of Proposition 7. When $b_H=0$ and $b_L=p-\varepsilon$ with $\varepsilon<p/K$, the condition for efficiency, $(p-b_H)/(p-b_L)\geq K$, is satisfied. By the condition $(w_H-b_H)/(p-b_H)=(w_L-b_L)/(p-b_L)=c/p$, we can obtain $w_H=c$ and $w_L=p-\varepsilon(1-c/p)$. We can easily verify that the given t_H and t_L satisfy $t_H-t_L\in[\underline{\Delta}_t,\bar{\Delta}_t]$, and the supplier will obtain almost all of the supply chain surplus as ε and T go to zero. □

Appendix B. Extension with Continuous Demand Signal

Assume that the signal i is distributed on $[i_L, i_H]$ by a density function $\varphi(i)$. The demand conditional on the signal follows a strictly increasing distribution function $F(x,i)$ (density $f(x,i)$) over $\mathbb{R}^+$ that satisfies $\partial F(x,i)/\partial i<0$. It is immediate that the first-best stocking quantity is $q^o(i)=\bar{F}^{-1}(c/p,i)$.

Analysis with a Single Contract

We focus on pure-strategy separating equilibrium. We use $q(i)$ to denote the buyer's optimal stocking level and $j(q)$ to denote the investors' belief. The formulations of the problem remain the same as in (1), (2), and (3), except that $\bar{F}_i(x)$ and $\bar{F}_{j(q)}(x)$ are replaced by $\bar{F}(x,i)$ and $\bar{F}(x,j(q))$. A separating market equilibrium is reached if $j(q(i))=i$ and $P(q(i))=\pi^B(q(i);i)$ for any signal $i\in[i_L,i_H]$. Note that we focus only on separating equilibrium for the purpose of our study because it provides the most relevant benchmark to show that inefficiency can arise under a single contract and the effectiveness of offering a menu of contracts. Other equilibria might exist. Also the intuitive criterion may not be capable when the signal becomes continuous.

Proposition 8. *Given any (w,b,t), a fully separating equilibrium exists where $q(i)$ follows*

$$[(p-b)\bar{F}(q(i),i)-(w-b)]q'(i)+\beta(p-b)\int_0^{q(i)}\frac{\partial\bar{F}(x,i)}{\partial i}\,\mathrm{d}x=0, \qquad (B1)$$

with $q(i_L)=\bar{F}^{-1}((w-b)/(p-b),i_L)$, and $j(q)$ can be characterized by $q^{-1}(\cdot)$ for $q(i_L)\leq q\leq q(i_H)$. The off-equilibrium belief can be specified as $j(q)=i_L$ for $q<q(i_L)$ and $j(q)=i_H$ for $q>q(i_H)$.

Proof of Proposition 8. We denote the buyer's objective function as

$$\begin{aligned}G(q,i)&=\beta\left[(p-b)\int_0^q\bar{F}(x,j(q))\,\mathrm{d}x-(w-b)q-t\right]\\&\quad+(1-\beta)\left[(p-b)\int_0^q\bar{F}(x,i)\,\mathrm{d}x-(w-b)q-t\right].\end{aligned}\qquad (B2)$$

The optimal stocking level $q(i)$ shall satisfy $\partial G(q,i)/\partial q=0$ and $\partial^2 G(q,i)/\partial q^2\leq 0$, where $\partial G(q,i)/\partial q=0$ follows

$$\beta\left[(p-b)\left[\bar{F}(q,j(q))+\int_0^q\frac{\partial\bar{F}(x,j(q))}{\partial i}\frac{\mathrm{d}j(q)}{\mathrm{d}q}\mathrm{d}x\right]-(w-b)\right]$$
$$+(1-\beta)[(p-b)\bar{F}(q,i)-(w-b)]=0.$$

To verify $\partial^2 G(q,i)/\partial q^2\leq 0$ when $\partial G(q,i)/\partial q=0$ holds, we derive from the latter: $\partial^2 G(q,i)/(\partial q\partial i)+(\partial^2 G(q,i)/\partial q^2)(\mathrm{d}q/\mathrm{d}i)\equiv 0$. Given $\partial F(q,i)/\partial i<0$, it can be easily verified from (B2) that $\partial^2 G(q,i)/(\partial q\partial i)>0$. Therefore, $\partial^2 G(q,i)/\partial q^2<0$ if and only if $(\mathrm{d}q)/(\mathrm{d}i)>0$. To have a fully separating equilibrium, the stocking level must increase in the signal value. Hence, $\partial^2 G(q,i)/\partial q^2<0$ can be assured if a separating equilibrium exists, which we validate below.

In equilibrium, the market belief must be consistent with the true signal for any given q that the buyer firm optimally stocks. In other words, $j(q)=i$ must hold in equilibrium. We thus impose this equilibrium condition over the buyer firm's first-order condition

$$\beta\left[(p-b)\left[\bar{F}(q,i)+\int_0^q\frac{\partial\bar{F}(x,i)}{\partial i}\frac{\mathrm{d}i}{\mathrm{d}q}\mathrm{d}x\right]-(w-b)\right]$$
$$+(1-\beta)[(p-b)\bar{F}(q,i)-(w-b)]=0.$$

Rearranging the terms, we obtain

$$[(p-b)\bar{F}(q,i)-(w-b)]\frac{\mathrm{d}q}{\mathrm{d}i}+\beta(p-b)\int_0^q\frac{\partial\bar{F}(x,i)}{\partial i}\,\mathrm{d}x=0, \qquad (B3)$$

which serves as the equilibrium condition of the buyer's stocking level. Finally, as the signal can be perfectly inferred in a separating equilibrium, the best strategy for the buyer receiving a signal i_L is to stock $q(i_L)=\bar{F}^{-1}((w-b)/(p-b), i_L)$. Given that the buyer has no incentive to pretend to have a lower signal, stocking $q(i_L)=\bar{F}^{-1}((w-b)/(p-b), i_L)$ can credibly reveal her signal to the market. Consequently, $q(i_L)=\bar{F}^{-1}((w-b)/(p-b), i_L)$ serves as the initial condition to (B3). Given this initial condition, we can easily verify that $\mathrm{d}q/\mathrm{d}i>0$, and thus the first-order approach we use to characterize the equilibrium is validated. A similar proof procedure is applied in Bebchuk and Stole (1993). □

In this equilibrium, $q(i)$ is strictly increasing, so the investors can perfectly infer the buyer's signal from the equilibrium stocking level. We further derive Corollary 2.

Corollary 2. *When $\beta>0$, $q(i)>\bar{F}^{-1}((w-b)/(p-b), i)$ for any $i>i_L$, and $q(i)$ increases in β.*

Proof of Corollary 2. Rearranging (B3) we obtain $\bar{F}(q,i)=(w-b)/(p-b)-\beta\int_0^q(\partial\bar{F}(x,i)/\partial i)\mathrm{d}x(\mathrm{d}i/\mathrm{d}q)$. Given both $\partial\bar{F}(x,i)/\partial i>0$ and $\mathrm{d}i/\mathrm{d}q>0$, the solution $q(i)$ must be larger than $\bar{F}^{-1}((w-b)/(p-b), i)$. Furthermore, when β increases, $\bar{F}(q,i)=(w-b)/(p-b)-\beta\int_0^q(\partial\bar{F}(x,i)/\partial i)\,\mathrm{d}x(\mathrm{d}i/\mathrm{d}q)$ decreases and thus the solution $q(i)$ will increase. □

It becomes apparent that only if β goes to zero would the buyer's stocking level coincide with the first-best level under the coordination condition $(w-b)/(p-b)=c/p$. In the following, we design menus of buyback contracts to restore the supply chain efficiency.

Design of Menus of Buyback Contracts

A menu of buyback contracts can be specified as a continuum of $(w(i), b(i), t(i))$. The buyer, observing signal i, chooses one contract, denoted by τ, and decides on the stocking level, q. The investors then infer the buyer's signal from her decisions, with a belief denoted by $j(\tau, q)$. We apply the equilibrium concept in Definition 2 with the extension to a continuous signal. A system-wise efficient market equilibrium is reached if the buyer's decision follows $(\tau, q)(i)=(i, q^o(i))$ and the market belief satisfies $j((\tau,q)(i))=i$ for any signal $i\in[i_L, i_H]$. Notice that this equilibrium concept only specifies the market belief on the equilibrium path. The market belief is not specified for any input (τ, q) with $q\neq q^o(\tau)$. We impose the following specific off-equilibrium belief, which does not eliminate any equilibrium solution to the original problem.

Lemma 4. *Given any menu of buyback contracts $(w(i), b(i), t(i))$, if a system-wise efficient market equilibrium is achieved with a market belief $j(\tau, q)$, then the equilibrium can also be achieved with the market belief*:

$$\bar{j}(\tau,q)=\begin{cases}\tau & \text{if } q=q^o(\tau),\\ i_L & \text{otherwise.}\end{cases}$$

Proof of Lemma 4. If a system-wise efficient market equilibrium holds with a given market belief $j(\tau, q)$, this market belief must take the chosen contract as the signal value; also, the buyer with signal i always chooses the truth-telling contract $\tau=i$ and stocks the first-best quantity $q^o(i)$. Notice that the market belief $\bar{j}(\tau, q)$ will also take the chosen contract as the signal value if the stocking level matches the first-best quantity and assume the signal is the least otherwise. As a result, $\tau=i$ and $q^o(i)$ will continue to be the buyer's best strategy under $\bar{j}(\tau, q)$. □

Proposition 9. *With the market belief $\bar{j}(\tau, q)$, a system-wise efficient market equilibrium can be achieved if the menu of buyback contracts $(w(i), b(i), t(i))$ satisfies $(w(i)-b(i))/(p-b(i))=c/p$, $b'(i)<0$, and $t(i)=(p-b(i))\int_0^{q^o(i)}\bar{F}(x,i)\,\mathrm{d}x-(w(i)-b(i))q^o(i)-(1-\beta)\int_{i_L}^{i}[(p-b(y))\int_0^{q^o(y)}(\partial/\partial y)\bar{F}(x,y)\,\mathrm{d}x]\,\mathrm{d}y-T$ for any constant T. The supplier's expected profit goes to the total supply chain surplus when the function $b(\cdot)$ that specifies the return schedule converges to p and the constant T goes to zero.*

Proof of Proposition 9. The buyer's objective function follows

$$\begin{aligned}&G(\tau, q; i)\\&\quad=(p-b(\tau))\left[\beta\int_0^q\bar{F}(x, j(\tau,q))\,\mathrm{d}x+(1-\beta)\int_0^q\bar{F}(x,i)\,\mathrm{d}x\right]\\&\qquad-(w(\tau)-b(\tau))q-t(\tau).\end{aligned}$$

First, to ensure the first-best stocking level, we must have $(w(i)-b(i))/(p-b(i))=c/p$ for any $i\in[i_L, i_H]$.

Second, we need to ensure that the buyer always selects the truth-telling contract; i.e., $\tau=i$. Notice that with the coordination condition, as long as the buyer firm selects the truth-telling contract, she will stock the first-best quantity. Thus, we can focus on a reduced objective function

$$\begin{aligned}&\bar{G}(\tau, i)\\&\quad\equiv G(\tau, q^o(\tau); i)\\&\quad=(p-b(\tau))\left[\beta\int_0^{q^o(\tau)}\bar{F}(x,\tau)\,\mathrm{d}x+(1-\beta)\int_0^{q^o(\tau)}\bar{F}(x,i)\,\mathrm{d}x\right]\\&\qquad-(w(\tau)-b(\tau))q^o(\tau)-t(\tau).\end{aligned}$$

When $\tau=i$, we have

$$\begin{aligned}\bar{G}(i,i)&=(p-b(i))\int_0^{q^o(i)}\bar{F}(x,i)\,\mathrm{d}x\\&\quad-(w(i)-b(i))q^o(\tau)-t(i).\end{aligned}\tag{B4}$$

For the buyer to select the truth-telling contract, the first-order condition of the buyer's objective function, $(\partial\bar{G}(\tau,i))/(\partial\tau)\mid_{\tau=i}=0$, must hold, with which we have

$$\begin{aligned}\frac{\mathrm{d}\bar{G}(i,i)}{\mathrm{d}i}&=\left[\frac{\partial\bar{G}(\tau,i)}{\partial i}+\frac{\partial\bar{G}(\tau,i)}{\partial\tau}\frac{\partial\tau}{\partial i}\right]\Bigg|_{\tau=i}\\&=\frac{\partial\bar{G}(\tau,i)}{\partial i}\bigg|_{\tau=i}=(1-\beta)(p-b(i))\int_0^{q^o(i)}\frac{\partial}{\partial i}\bar{F}(x,i)\,\mathrm{d}x.\end{aligned}$$

Integrating the above equation yields

$$\begin{aligned}&\bar{G}(i,i)\\&\quad=T+(1-\beta)\int_{i_L}^{i}\left[(p-b(y))\int_0^{q^o(y)}\frac{\partial}{\partial y}\bar{F}(x,y)\,\mathrm{d}x\right]\mathrm{d}y,\end{aligned}\tag{B5}$$

where T is a constant. (This procedure is classical for mechanism design problems.)

Therefore, if the first-order condition holds, then, comparing (B4) with (B5), we have

$$t(i) = (p-b(i))\int_0^{q^o(i)} \bar{F}(x,i)\,\mathrm{d}x - (w(i)-b(i))q^o(i) - (1-\beta) \cdot \int_{i_L}^{i}\left[(p-b(y))\int_0^{q^o(y)} \frac{\partial}{\partial y}\bar{F}(x,y)\,\mathrm{d}x\right]\mathrm{d}y - T,$$

which serves as a necessary condition for the buyer to select the truth-telling contract.

Now we derive the sufficient condition under which the first-order condition of the buyer's objective function holds. Substituting $t(i)$ into the original $\bar{G}(\tau, i)$ function, we obtain

$$\bar{G}(\tau,i) = (1-\beta)(p-b(\tau))\left[\int_0^{q^o(\tau)}\bar{F}(x,i)\,\mathrm{d}x - \int_0^{q^o(\tau)}\bar{F}(x,\tau)\,\mathrm{d}x\right] + (1-\beta)\int_{i_L}^{\tau}\left[(p-b(y))\int_0^{q^o(y)}\frac{\partial}{\partial y}\bar{F}(x,y)\,\mathrm{d}x\right]\mathrm{d}y + T;$$

$$\frac{\partial \bar{G}(\tau,i)}{\partial \tau} = -(1-\beta)b'(\tau)\left[\int_0^{q^o(\tau)}\bar{F}(x,i)\,\mathrm{d}x - \int_0^{q^o(\tau)}\bar{F}(x,\tau)\,\mathrm{d}x\right] + (1-\beta)(p-b(\tau))\left[\bar{F}(q^o(\tau),i) - \bar{F}(q^o(\tau),\tau)\right]\frac{\mathrm{d}q^o(\tau)}{\mathrm{d}\tau}.$$

Given $q^o(\tau) = \bar{F}^{-1}(c/p, \tau)$, we know that $\mathrm{d}q^o(\tau)/(\mathrm{d}\tau) > 0$; by assumption, $\partial\bar{F}(x,i)/\partial i > 0$. Therefore, we will have $\partial\bar{G}(\tau,i)/\partial\tau|_{\tau=i} = 0$ and $(\partial\bar{G}(\tau,i))/(\partial\tau) > (<) 0$ when $\tau < (>) i$ if $b'(\tau) < 0$ (it is implicitly assumed that $b(i) < p$; $b(i)$ shall not be a constant because $w(i)$ would otherwise be a constant, too, given $(w(i)-b(i))/(p-b(i)) = c/p$). Hence, $b'(i) < 0$ serves as a sufficient condition for the buyer to take the truth-telling contract.

Given a menu of contracts $(w(i), b(i), t(i))$, we can formulate the supplier's expected profit as

$$\Pi^S = \int_{i_L}^{i_H}\varphi(i)\left[t(i) + (w(i)-c-b(i))q^o(i) + b(i)\int_0^{q^o(i)}\bar{F}(x,i)\,\mathrm{d}x\right]\mathrm{d}i$$
$$= \int_{i_L}^{i_H}\varphi(i)\left\{p\int_0^{q^o(i)}\bar{F}(x,i)\,\mathrm{d}x - cq^o(i) - (1-\beta) \cdot \int_{i_L}^{i}\left[(p-b(y))\int_0^{q^o(y)}\frac{\partial}{\partial y}\bar{F}(x,y)\,\mathrm{d}x\right]\mathrm{d}y - T\right\}\mathrm{d}i.$$

Notice that only the return term and the fixed payment T influence the supplier's expected profit. It is obvious that if $b(i)$ converges to p and T goes to zero, then Π^S goes to the maximum supply chain surplus $(\int_{i_L}^{i_H}\varphi(i)[p\int_0^{q^o(i)}\bar{F}(x,i)\,\mathrm{d}x - cq^o(i)]\,\mathrm{d}i)$. ☐

Proposition 9 shows that menus of buyback contracts exist that can restore full supply chain efficiency. In particular, the return schedule decreases in the value of the signal, which implies that the wholesale price also decreases in the value of the signal, by the condition $(w(i)-b(i))/(p-b(i)) = c/p$. A proper transfer payment scheme $t(i)$ can be designed that ensures the buyer always takes the truth-telling contract. Furthermore, notice that $t(i)$ contains a constant T that provides the flexibility to divide the supply chain surplus among the two parties. Given menus of contracts exist by which the supplier can obtain almost all of the supply chain surplus, we can thus adjust T in those contracts to achieve any specific allocation of the surplus. Hence, pareto improvement is achievable.

Finally, notice that the total initial payment from the buyer to the supplier is $M(i) = t(i) + w(i)q^o(i)$, which satisfies the following lemma.

Lemma 5. *$\mathrm{d}M/(\mathrm{d}q^o) > 0$ and $\mathrm{d}^2M/\mathrm{d}(q^o)^2 < 0$ if $b(i)$ satisfies the following condition:*

$$\beta(p-b(i))\int_0^{q^o(i)}\frac{\partial}{\partial i}\bar{F}(x,i)\,\mathrm{d}x + b'(i)\int_0^{q^o(i)}F(x,i)\,\mathrm{d}x = 0. \quad \text{(B6)}$$

Proof of Lemma 5. $M(i) = t(i) + w(i)q^o(i)$ satisfies

$$M(i) = (p-b(i))\int_0^{q^o(i)}\bar{F}(x,i)\,\mathrm{d}x + b(i)q^o(i) - (1-\beta) \cdot \int_{i_L}^{i}\left[(p-b(y))\int_0^{q^o(y)}\frac{\partial}{\partial y}\bar{F}(x,y)\,\mathrm{d}x\right]\mathrm{d}y - T,$$

$$\frac{\mathrm{d}M}{\mathrm{d}i} = -b'(i)\int_0^{q^o(i)}\bar{F}(x,i)\mathrm{d}x + b'(i)q^o(i) - (1-\beta)(p-b(i)) \cdot \int_0^{q^o(i)}\frac{\partial}{\partial i}\bar{F}(x,i)\,\mathrm{d}x + (p-b(i))\int_0^{q^o(i)}\frac{\partial}{\partial i}\bar{F}(x,i)\,\mathrm{d}x + (p-b(i))\bar{F}(q^o(i),i)\frac{\mathrm{d}q^o}{\mathrm{d}i} + b(i)\frac{\mathrm{d}q^o}{\mathrm{d}i}$$
$$= \beta(p-b(i))\int_0^{q^o(i)}\frac{\partial}{\partial i}\bar{F}(x,i)\mathrm{d}x + b'(i)\int_0^{q^o(i)}F(x,i)\,\mathrm{d}x + (p-b(i))\frac{p-c}{p}\frac{\mathrm{d}q^o}{\mathrm{d}i} + b(i)\frac{\mathrm{d}q^o}{\mathrm{d}i}.$$

Therefore, if the sum of the first two terms equals zero, we will have $\mathrm{d}M/\mathrm{d}q^o = (\mathrm{d}M/\mathrm{d}i)/(\mathrm{d}q^o/\mathrm{d}i) = (p-c) + (c/p)\cdot b(i) > 0$ and $(\mathrm{d}^2M)/(\mathrm{d}(q^o)^2) = (c/p)b'(i)(\mathrm{d}i/\mathrm{d}q^o) < 0$ (given $b'(i) < 0$ and $(\mathrm{d}q^o/\mathrm{d}i) > 0$). ☐

With (B6), $M(i)$ increases in $q^o(i)$ at a decreasing rate, which satisfies the property of a quantity discount contract. (B6) implies that $b'(i) < 0$, and thus it is aligned with the condition specified in Proposition 9; also, $b(i)$ can be expressed as a monotonically decreasing function of $q^o(i)$. Hence, we assert that a system-wise efficient market equilibrium can be achieved by a single contract that consists of a proper pair of quantity discount scheme and return schedule $(q, M(q), b(q))$.

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