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# Managing Opportunistic Supplier Product Adulteration: Deferred Payments, Inspection, and Combined Mechanisms

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Recent cases of product adulteration by foreign suppliers have compelled many manufacturers to rethink approaches to deterring suppliers from cutting corners, especially when manufacturers cannot fully monitor and control the suppliers' actions. In this paper, we study three mechanisms for dealing with product adulteration problems: (a) the deferred payment mechanism—the buyer pays the supplier after the deferred payment period only if no adulteration has been discovered by the customers; (b) the inspection mechanism—the buyer pays the supplier immediately, contingent on product passing the inspection; and (c) the combined mechanism—a combination of the deferred payment and inspection mechanisms. We show that the inspection mechanism cannot completely deter the suppliers from product adulteration, whereas the deferred payment mechanism can. Surprisingly, the combined mechanism is redundant: either the inspection or the deferred payment mechanisms perform just as well. Finally, we identify four factors that determine the dominance of deferred payment mechanism over the inspection mechanism: (a) the inspection cost relative to inspection accuracy, (b) the buyer's liability for adulterated products, (c) the difference in financing rates for the buyer and the supplier relative to the defects discovery rate by customers, and (d) the difference in production costs for adulterated and unadulterated product. We find that the deferred payment mechanism is preferable to inspection if the threats of adulteration (either incentive to adulterate or the consequences) are low.

*Key words*: operations strategy; incentives and contracting; operations and finance interface; supply risk management; trade credit
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## 1. Introduction

Product adulteration became a common cause of recent product recalls, including Baxter's recall of Heparin (Fairclough 2008), Mattel's recall of toys (Story and Barboza 2007), and the recalls of pet food and milk products (Roth et al. 2008). To improve product safety, many U.S. manufacturers have implemented or refined quality management programs applied over different stages of the production process, including (1) supplier process certification prior to placing orders; (2) product inspection after receiving it from the supplier; and (3) postsales programs such as deferred payments, product liability, and warranties. All these programs have their advantages and disadvantages. In this paper, we will focus on three mechanisms: deferred payments, inspection, and the combined deferred payments and inspection, because we believe that these mechanisms are more likely to be effective in controlling incentives of foreign suppliers to adulterate products (this view is supported by a recent *Wall Street Journal* article by Vandenbosch and Sapp 2010).

Specifically, even though many foreign suppliers are ISO 9000 certified, this does not guarantee that they follow the formalized businesses processes at all times (see Babich and Tang 2011 for details). A case in point is that Mattel's supplier was a certified supplier. Product inspection is a more direct way to detect product quality problems. After recalls, Mattel has implemented an intensive inspection mechanism with its contract manufacturers (Tang 2008). But inspections have two major drawbacks: they are costly and they might not detect adulteration. For example, consider adulterated milk products produced by Chinese suppliers in 2008. Knowing that the standard testing methods fail to distinguish between nitrogen in melamine and nitrogen that naturally occurs in amino acids, these suppliers managed to falsify their products by adding melamine to conceal the dilution of milk with water. Still, given the prevalence of product inspection research and practice, in this paper we shall use inspection as the benchmark to evaluate the performance of other mechanisms for controlling suppliers' incentives.

Because adulteration will be discovered by customers eventually, we emphasize the postsales mechanisms: deferred payment and combined deferred payment and inspection. Under the deferred payment, the buyer pays an upfront amount to the supplier to initiate the production, withholds the contingent payment, and releases this contingent payment only if no adulteration is discovered by the customers over a prespecified duration. A combined mechanism "combines" product inspection with deferred payment.

We focus on the deferred payment mechanism out of all postsales programs for two reasons. First, deferred payments can be implemented in the form of trade credit. Trade credit is the largest source of external short-term financing for firms both in the United States (Petersen and Rajan 1994) and internationally (Rajan and Zingales 1995). Second, other postsales programs, such as product liability and warranties, are difficult to implement with foreign suppliers. Product liability is rarely enforceable with foreign suppliers because of different legal systems and inconsistent law enforcement practices in different countries. Similarly, to get the supplier to pay on a warranty claim, the buyer has to prove that a warranty event occurred and that the fault for this event lies with the supplier. Furthermore, the supplier has to be financially sound at the time of the warranty event to make the warranty payment.

### 1.1. Overview of the Analysis and Results

In §2 we discuss our contribution relative to the literature. In §3 we present a stylized model that captures the essence of the supplier's decision to adulterate a product and the consequences of adulteration to the supplier and the buyer. Next, in §4 we discuss the deferred payment mechanism. Although the deferred payment mechanism provides incentives to the supplier to produce an unadulterated product, the supplier has to finance its operations while the payments are deferred. If the supplier's financing cost is greater than that of the buyer then the total financing costs of the supply chain is increased. The additional cost of financing is eventually passed on from the supplier to the buyer through inflated wholesale prices due to the supplier's participation constraints. We study properties of the optimal deferment contract and determine the conditions under which this mechanism is a practical choice.

In §5 we study the inspection mechanism. Similar to the deferred payment mechanism, the inspection mechanism provides incentives for the supplier to produce unadulterated products. However, the buyer incurs the inspection cost. Given the inspection contract parameters, we analyze the inspection subgame in which the supplier chooses to produce adulterated product or not and the buyer decides to inspect or not. For the optimal inspection contract, it is optimal for the buyer to adopt a mixed strategy so that a random inspection of a unit or a partial inspection of a batch of products is performed.

In §6 we extend our analysis to the combined inspection and deferred payment mechanism: the buyer pays an upfront payment to initiate the production, makes the first payment contingent on the inspection outcome, and makes the second payment contingent on whether customers discover defects during the deferred payment period. The combined mechanism can be viewed as contingent installment payments (Lee and Png 1990) and it contains costs and benefits from both simpler mechanisms. A priori, one expects a more general mechanism to be superior, but we prove that, interestingly, the combined mechanism is redundant because either the inspection or the deferred payment mechanisms can generate the same profit for the buyer.

In §7, by comparing the deferred payment and inspection mechanisms, we identify four key factors that determine the dominance of one mechanism over the other: (a) the inspection cost relative to the inspection accuracy; (b) the buyer's liability for adulterated products; (c) the difference in financing rates between the buyer and the supplier relative to the rate at which customers discover defects; and (d) the difference between production costs of unadulterated and adulterated products, reflecting the supplier's incentive to cheat. We show that the deferred payment mechanism dominates when the inspection cost relative to the inspection accuracy is high, when the buyer's liability is low, or when the gap between the unadulterated and adulterated production costs is low. However, the inspection mechanism dominates when the financing cost gap relative to the rate at which customers discover defects is high. We conclude with §8.

## 2. Literature Review

Our work intersects with the following research areas: supply risk, supplier quality control, and trade credit. For a general review of supply risk problems and solutions, see Tang (2006). For a discussion on decentralized supply risk management, see Aydın et al. (2012) and Yang et al. (2009, 2012). For a review of supplier quality control, see Powell (1995).

Even though the deferred payment mechanism for deterring product adulteration has not been examined before, an example of this mechanism is the financial trade credit contract. Theoretical models that explain trade credit's popularity and the corresponding empirical findings are reviewed in Petersen and

Rajan (1997) and, more recently, in Giannetti et al. (2011). For recent research on trade credit in operations management literature, see Gupta and Wang (2009), Babich et al. (2012), Zhou and Groenevelt (2008), Kouvelis and Zhao (2009), Yang and Birge (2009), and Brunet and Babich (2007, 2009). We build on the ideas articulated in Smith (1987), Long et al. (1993), and Lee and Stowe (1993) that trade credit allows the buyers to learn about suppliers' product quality and to withhold contingent payments in case the suppliers produced defective products. By analyzing a sample data that contains all industrial firms from 1984 to 1987, Long et al. (1993) provide empirical evidence to show that the trade credit period (i.e., the deferred payment period) increases when defects take more time to discover. As it turns out, our analytical results for the deferred payment model are consistent with this empirical finding. Lee and Stowe (1993) propose a signalling model where the quality of the product is known to the supplier but not the buyer and find a separating equilibrium, in which trade credit terms reflect product quality. More recently, Klapper et al. (2010) argued that trade credit reduces the buyers' risk because the buyers have more time to investigate product quality before deciding whether or not to make the contingent payments.

Our work differs from this literature in two ways. First, we consider the case when the supplier's adulteration decision is *endogenous*. Second, we allow the buyer (a large manufacturer) to set the deferred payment contract terms. Thus, when analyzing the deferred contingent payment mechanism, we solve a moral hazard problem rather than a signalling problem.

The inspection games have been studied extensively in economics, operations management, and accounting. For example, Reyniers and Tapiero (1995a, b) present models in which the supplier selects its effort in controlling product quality and the buyer determines whether or not to inspect. The buyer's contract has two components: (a) the supplier's penalty for producing a defective part; and (b) the supplier's liability for an undetected defective unit when the buyer chooses not to inspect. By analyzing a noncooperative game, they determine the buyer's optimal penalty structure. Recently, Baiman et al. (2000) study a model in which the supplier decides on the quality level and the buyer decides on the accuracy of the inspection. They determine the equilibrium for the quality level and the buyer's inspection accuracy level. Rather than dealing with the inspection accuracy, Starbird (2001) presents a model in which the buyer can select the inspection level (in terms of the size of the sample to inspect) and examines how the buyer's inspection level affects the supplier's quality level when the underlying contracts involve certain rewards and penalties associated with the supplier's quality. More recently, Chao et al. (2009) examine a situation in which the supplier and the buyer can exert their own efforts that will result in a higher quality product. They consider two types of cost sharing contracts under which each party is liable to cover certain portions of the cost associated with the root causes of product failures. By analyzing the optimal contract of each type, they show that the menu of contracts can decrease the buyer's cost and increase product quality when the supplier quality is not revealed to the buyer. Balachandran and Radhakrishnan (2005) consider a similar problem; however, they focus on the use of inspection information to achieve first best quality improvement efforts exerted by the buyer and the supplier.

In contrast to the inspection literature, our paper has a different intent: We are interested in examining the extent to which various mechanisms (including inspection) deter suppliers from product adulteration. Second, we treat inspection as the benchmark used to evaluate the performance of the deferred payment and the combined mechanisms. Third, after analyzing all three mechanisms, we derive the conditions under which one mechanism dominates the others. Fourth, our inspection model is developed in a different context: (a) our focus is on product adulteration rather than accidental variations in product quality; and (b) our model reflects the fact that in practice foreign supplier's product liability is effectively unenforceable.

## 3. Model

Consider a decentralized supply chain comprising a buyer and a certified supplier. The buyer buys a single unit from the supplier. One can view this setting as applicable to project management where the buyer is the project manager and the supplier is the contractor. Alternatively, one can think of a batch process environment, where adulteration affects the entire batch and it is discovered for the entire batch simultaneously. The same approach can be used to analyze the case when the buyer purchases multiple units from the supplier; however, with the additional decisions on the number of units, choices of inspection sizes, and other features, analysis becomes tedious. The buyer is facing a moral hazard problem with respect to the supplier's action. The supplier's action is either $a = n$, i.e., produce an unadulterated (nondefective) product at a cost $c_n$, or $a = d$, i.e., produce an adulterated (defective) product at a cost $c_d$. In the sequel, we will use the terms *adulterated* (*unadulterated*) and *defective* (*nondefective*) interchangeably. Because the production cost for the adulterated product is lower, $c_n > c_d$, and because the supplier's action is not observable by the buyer, the supplier has an incentive to adulterate.

If the buyer decides to sell the product to the customer, the buyer receives revenue with present value $r$ at time 0. If the product turns out to be adulterated, the defect will eventually be discovered by customers at time $\tau$. By definition, the product is adulterated if its functional characteristics are altered and customers thus perceive the product as not functioning as intended. The noise in the customer's adulteration perception does not change our results. For tractability, we assume that $\tau$ follows an exponential distribution with rate parameter $\lambda$. We can obtain similar structural results when $\tau$ follows a general distribution, where $f(\cdot)$ is the probability density function and $F(\cdot)$ is the cumulative distribution function of this distribution, provided $f(\cdot)/F(\cdot)$ is decreasing. When defects are discovered at time $\tau$, the buyer pays liability $\rho_B$ (if $\rho_B$ is random, we assume that it is independent from $\tau$). It is convenient to define the probability that the customer will not discover the defect by time $T$ as $\eta(T)$, where $\eta(T) \overset{\text{def}}{=} \Pr[\tau > T] = e^{-\lambda T}$. For ease of exposition, we suppress the explicit dependence of $\eta$ on $T$, unless it is necessary. For simplicity, we assume that the supplier's liability is zero to capture the fact that the supplier's product liability is rarely enforceable in practice especially when dealing with foreign suppliers. By letting $\alpha_B > 0$ be the buyer's continuously compounded financing rate, the expected present value of the buyer's product liability for selling an adulterated product equals

$$v_B \overset{\text{def}}{=} E[\rho_B e^{-\alpha_B \tau}] = E[\rho_B] \frac{\lambda}{\alpha_B + \lambda}. \tag{1}$$

To ensure that selling adulterated product is unprofitable for the buyer, we assume that $v_B > r$.

In the following three sections, we study three contingent payment mechanisms for deterring product adulteration.

## 4. Deferred Payment Mechanism

In this section, we introduce and analyze the deferred payment mechanism. Our analysis is based on a Stackelberg game in which the buyer is the leader who specifies the deferred payment contract and the supplier is the follower who decides on her product quality action. We will derive the optimal deferred payment contract and discuss its practicality.

### 4.1. Deferred Payment Mechanism Model

The deferred payment contract has three parts: $(Y, q, T)$, where $Y \geq 0$ is the upfront payment and $q \geq 0$ is the payment made at time $T \geq 0$, contingent on customers not discovering product defects.

While waiting for the payment from the buyer, the supplier must finance its operations. Let $\alpha_S > 0$ be the supplier's continuously compounded financing rate. The buyer and the supplier may have different financing rates. We shall focus our analysis for the case when the following holds.

**Table 1** **The Supplier's and Buyer's Expected Discounted Profits for Any Deferred Payment Contract**

| | Supplier | Buyer |
|---|---|---|
| $a = n$ (nondefective) | $Y + q_S - c_n$ | $r - Y - q_B$ |
| $a = d$ (defective) | $Y + q_S\eta - c_d$ | $r - v_B - Y - q_B\eta$ |

Assumption 1. *The supplier's financing rate is higher than the buyer's*: $\alpha_S \geq \alpha_B > 0$.

Although our model can be easily extended to the case when Assumption 1 is violated, so that $\alpha_S < \alpha_B$, Assumption 1 is more likely to hold when the buyer is a larger firm with higher credit rating than the supplier. For example, Klapper et al. (2010, p. 9) observe that in their data set "most suppliers are much smaller than their buyers, and are unlikely to have access to cheaper financing."

If the supplier produces an unadulterated product, the supplier pays $c_n$ for production at time 0, receives $Y$ at time 0, and receives $q$ at time $T$. Define $q_S \overset{\text{def}}{=} qe^{-\alpha_S T}$ to be the present value of the contingent payment for the supplier. The present value of the supplier's profit is $Y + q_S - c_n$. The corresponding present value of the buyer's profit is $r - Y - q_B$, where $q_B \overset{\text{def}}{=} qe^{-\alpha_B T}$. Recall that $\eta(T) = \Pr[\tau > T]$ is the probability that customers will not detect adulteration prior to time $T$. Therefore, when the supplier produces a defective product, the supplier pays $c_d$ for production at time 0, receives $Y$ at time 0, and receives $q$ at time $T$ with probability $\eta$. Thus, the expected present value of the supplier's profit is $Y + q_S\eta - c_d$. The corresponding expected present value of the buyer is $r - v_B - Y - q_B\eta$. These profits are summarized in Table 1.

If the supplier produces an adulterated product, then the buyer's profit, $r - v_B - Y - q_B\eta$, is guaranteed to be negative because (as we discussed earlier) $r < v_B$, $Y \geq 0$, and $q \geq 0$. Thus, the buyer will try to induce the supplier to produce an unadulterated product with a contract that keeps $r - Y - q_B$ positive.

### 4.2. The Buyer's Problem Under the Deferred Payment Mechanism

Given a deferred payment contract $(Y, q, T)$, let $\pi_S^a(Y, q, T)$ be the supplier's expected profit and $\pi_B^a(Y, q, T)$ be the buyer's expected profit for any supplier's action $a$, where $a \in \{n, d\}$. As we just discussed, the buyer will always prefer selling the nondefective product for any deferred payment contract $(Y, q, T)$. To entice the supplier to produce unadulterated product in a rational manner, the deferred payment contract $(Y, q, T)$ must satisfy: (a) the supplier's *incentive compatibility* constraint $\pi_S^n(Y, q, T) \geq \pi_S^d(Y, q, T)$; and (b) the supplier's *individual rationality* constraint $\pi_S^n(Y, q, T) \geq 0$. By considering the payoffs presented in Table 1, these two constraints can be rewritten as $q_S(1-\eta) \geq c_n - c_d$ and $Y + q_S - c_n \geq 0$. Because the above constraints will deter the supplier from adulterating (i.e., it will take action $a = n$), the buyer will obtain an expected profit $\pi_B^n(Y, q, T)$. Hence, the buyer's problem is

$$\max_{Y\geq 0,\, q\geq 0,\, T\geq 0} \quad r - Y - q_B \tag{2a}$$

$$\text{s.t.} \quad q_S(1-\eta) \geq c_n - c_d, \tag{2b}$$

$$Y + q_S \geq c_n. \tag{2c}$$

### 4.3. Optimal Deferred Payment Contract

To solve problem (2) we transform decision variables from $(Y, q, T)$ to $(Y, q_S, T)$, where $q_S = qe^{-\alpha_S T}$. Thus, the buyer's problem (2) becomes

$$\max_{Y\geq 0,\, q_S\geq 0,\, T\geq 0} \quad r - Y - q_S e^{(\alpha_S - \alpha_B)T} \tag{3a}$$

$$\text{s.t.} \quad q_S(1-\eta) \geq c_n - c_d, \tag{3b}$$

$$Y + q_S \geq c_n. \tag{3c}$$

The solution to problem (3) is presented in the following proposition. In the following discussion, it is convenient to define the ratio of financing rates gap over the defect discover rate $a \overset{\text{def}}{=} (\alpha_S - \alpha_B)/\lambda$.

Proposition 1. *The following is the solution of the buyer's problem* (3).

1. *If $c_d/c_n \geq a/(1+a)$, then the optimal deferred payment contract $(Y^*, q_S^*, T^*)$ satisfies $Y^* = 0$, $q_S^* = c_n$, and $e^{-\lambda T^*} = c_d/c_n$. The corresponding buyer's profit is $r - c_n(c_d/c_n)^{-a}$. The supplier's profit is zero.*
2. *If $c_d/c_n < a/(1+a)$, then the optimal deferred payment contract $(Y^*, q_S^*, T^*)$ satisfies $Y^* = 0$, $q_S^* = (c_n - c_d)(1+a) \geq c_n$, and $e^{-\lambda T^*} = a/(1+a)$. The corresponding buyer's profit is $r - (c_n - c_d)(1+a)(a/(1+a))^{-a}$. The supplier's profit is $(c_n - c_d)(1+a) - c_n$.*

The proofs of all lemmas and propositions are presented in the online appendix (available at http://msom.journal.informs.org/). Proposition 1 reveals that the buyer will always offer an "effective" deferred payment $q_S^* \geq c_n$ that deters the supplier from adulteration entirely. In fact, regardless which part of Proposition 1 holds, the incentive compatibility constraint $q_S(1-\eta) \geq c_n - c_d$ and the upfront payment constraint $Y \geq 0$ are binding under the optimal contract. However, the individual rationality constraint $Y + q_S - c_n \geq 0$ is binding in part 1 and not binding in part 2 of Proposition 1.

A priori, it is not obvious that $Y^* = 0$ must be optimal. The buyer would like to maximize its profit subject to the nonnegative constraints, as well as two constraints on the supplier's profit: incentive compatibility (2b) and individual rationality (2c). It is not clear which of the constraints should be binding. The supplier is being put at a disadvantage by the deferred payment contract, and the buyer needs to compensate the supplier, to induce supplier's participation in the mechanism. Thus, the buyer might have to pay something upfront ($Y^* > 0$) to ensure this participation.

The results stated in Proposition 1 are robust even when we extend our model to capture the buyer's bankruptcy feature (where bankruptcy arrives according to the Poisson process at the exogenously given rate). It can be shown that the buyer's optimal contract continues to follow the same structure (two parts, depending on the supplier's incentive to adulterate, $c_d/c_n$). However, the optimal $T^*$ is smaller for two reasons: the supplier is concerned with not receiving the payment (this translates into a smaller region for part 1 of Proposition 1), and the buyer is concerned with not earning future revenue (lowering the value $T^*$ in part 2). We can also extend the analysis of problem (3) to allow for externally imposed (e.g., by the industry) constraint on the duration of the deferred payment contract, i.e., $T \leq \hat{T}$ (see Babich and Tang 2011).

### 4.4. Properties of the Optimal Deferred Payment Contract

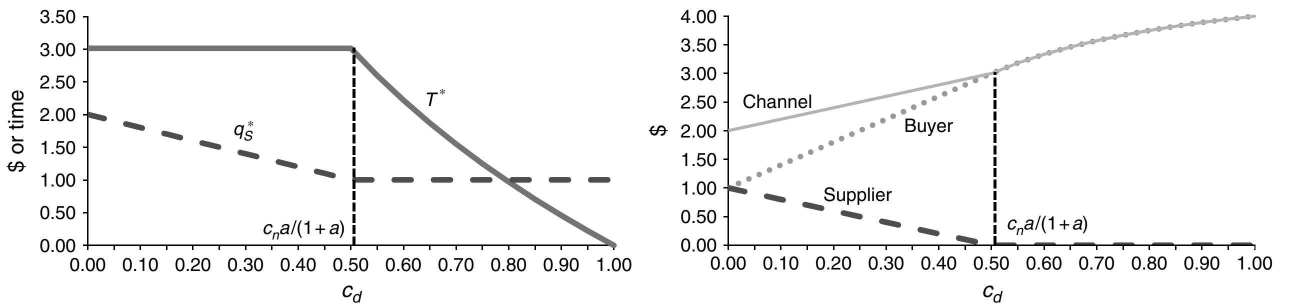
We now examine the comparative statics of different quantities presented in Proposition 1. For ease of exposition, we shall describe our results graphically even though we proved all comparative statics analytically. We begin with Figure 1 and the cost of producing an adulterated product $c_d$.

First, consider the case when the supplier's incentive to adulterate the product is not very high, so that $c_d/c_n \geq a/(1+a)$, where $a = (\alpha_S - \alpha_B)/\lambda$. In this case, part 1 of Proposition 1 reveals that the "effective" deferred contingent payment $q_S$ is fixed ($q_S^* = c_n$) and the buyer can deter adulteration by extending the optimal duration $T^*$ as $c_d$ decreases. Figure 1 also illustrates that the supplier makes zero profit and the buyer's profit is fairly close to that of the centralized system ($r - c_n = 4$).

Second, consider the case when the supplier's incentive to adulterate the product is very high so that $c_d/c_n < a/(1+a)$. In this case, part 2 of Proposition 1 indicates that to prevent adulteration, the optimal payment $q_S^* > c_n$ increases as $c_d$ decreases, and the optimal duration $T^*$ remains fixed. The supplier's profit is positive and the system overall deviates significantly from the centralized system's profit.

According to Proposition 1, the optimal deferred payment duration, $T^*$, is capped by the value in part 2. This facilitates the use of the deferred payment contract in practice. For part 2, the cost gap

**Figure 1** **Deferred Payment Optimal Contract, Comparative Statics with Respect to $c_d$**




*Notes.* Left panel: Optimal $T^*$ and $q_S^*$. Right panel: Optimal buyer's, supplier's, and channel profits. Parameter values: $c_n = 1$, $r = 5$, $\alpha_S = 0.2$, $\alpha_B = 0.1$, $\lambda = 0.1$, $a = (\alpha_S - \alpha_B)/\lambda$. Centralized system profit is $r - c_n = 4$.

$(c_n - c_d)$ is significant and the optimal duration is $T^* = (1/\lambda)\ln(1 + \lambda/(\alpha_S - \alpha_B))$. Thus, the optimal duration equals the average time it takes to discover defects, $1/\lambda$, adjusted by the coefficient $\ln(1 + \lambda/(\alpha_S - \alpha_B))$ for financing costs. Therefore, $T^* > 1/\lambda$ if and only if $\lambda/(\alpha_S - \alpha_B) > e - 1$. For part 1 the cost gap $(c_n - c_d)$ is small and the optimal duration is $T^* = (1/\lambda)\ln(c_n/c_d)$. Thus, the optimal duration equals the average time for the customer to discover defects adjusted by the coefficient $\ln(c_n/c_d)$. The cost ratio $c_n/c_d$ has to be greater than $e \approx 2.72$ for the optimal deferred payment duration to exceed the average time of defect discovery.

Proposition 1 suggests that $T^*$ is decreasing in the rate of defect discovery, $\lambda$, which has been confirmed empirically by Long et al. (1993). Therefore, our analytical result complements the empirical result obtained by Long et al. (1993).

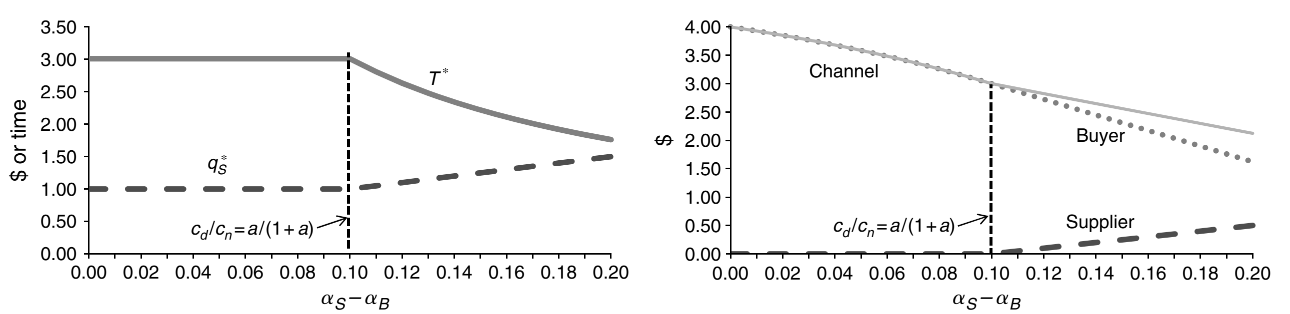
To see that the model predictions are reasonable in practice, consider the case when average time to discover defects $1/\lambda = \frac{1}{4}$ years $= 3$ months, the supplier's financing rate $\alpha_S = 20\%$ per year, and the buyer's financing rate $\alpha_B = 7\%$ per year. Babich and Tang (2011) show that as long as $c_d/c_n > 71.65\%$, a 30-day trade credit contract gives sufficient incentives for the supplier not to adulterate the product.

Interestingly, the inefficiencies of the deferred payment mechanism are due to two factors: cost gap $(c_n - c_d)$, which creates incentives for the suppliers to cheat; and financing rate gap $(\alpha_S - \alpha_B)$, which makes it expensive for the system to use deferred payments to control the supplier's incentives to cheat. As shown in Figure 1, for fixed financing gap $(\alpha_S - \alpha_B)$ the smaller the cost gap $(c_n - c_d)$ the closer the channel profit to the centralized system profit, $r - c_n$. However, the smaller the financing gap $(\alpha_S - \alpha_B)$ the closer the channel profit to the profit of the centralized system. In particular, for small $\alpha_S - \alpha_B$, part 1 of Proposition 1 applies and the channel profit is $r - c_n(c_d/c_n)^{-(\alpha_S - \alpha_B)/\lambda}$, which converges to the centralized system profit $r - c_n$, as $\alpha_S - \alpha_B \to 0$. Figure 2 illustrates this observation.

## 5. Inspection Mechanism

To use the inspection mechanism as a benchmark, we first determine the supplier's action and the buyer's inspection decision in equilibrium for any given inspection contract. Then we find the optimal contract. We show that the optimal inspection contract cannot completely deter the supplier from product adulteration, and it cannot completely eliminate the need for the buyer to conduct inspection.

**Figure 2** **Deferred Payment Optimal Contract, Comparative Statics with Respect to $\alpha_S - \alpha_B$**




*Notes.* Left panel: Optimal $T^*$ and $q_S^*$. Right panel: Optimal buyer's, supplier's, and channel profits. Parameter values: $c_n = 1$, $c_d = 0.5$ $r = 5$, $\lambda = 0.1$, $a = (\alpha_S - \alpha_B)/\lambda$. The centralized system profit is $r - c_n = 4$.

**Table 2** The Supplier's (Top Expression) and Buyer's (Bottom Expression) Expected Discounted Profits for Any Combination of Pure Strategies Selected by the Players Under the Inspection Contract $(X, p)$

| | $i=0$ (do not inspect) | $i=1$ (inspect) |
|---|---|---|
| $a=n$ (nondefective) | $(X+p-c_n, r-X-p)$ | $(X+p-c_n,\ r-X-p-I)$ |
| $a=d$ (defective) | $(X+p-c_d,$ $r-v_B-X-p)$ | $(X+p(1-\mu)-c_d,$ $(r-p-v_B)(1-\mu)-X-I)$ |

### 5.1. Inspection Mechanism Model

Under the inspection mechanism, the buyer offers a two-part inspection contract $(X, p)$, where $X \geq 0$ is the upfront payment and $p \geq 0$ is the payment, contingent on whether a defect is detected by the inspection at time 0. Given any two-part inspection contract $(X, p)$, the supplier and the buyer engage in an inspection subgame, where the pure strategies of the supplier are to produce nondefective $(a = n)$ or defective $(a = d)$ product and the pure strategies of the buyer are to inspect $(i = 1)$ or not to inspect $(i = 0)$ the product. The cost of inspection to the buyer is $I > 0$.

If the supplier delivered an unadulterated product, then the inspection will not discover any defects. That is, Pr[inspection report = nondefective $\mid a = n$] $= 1$. However, if the supplier delivered an adulterated product, then the inspection sends a correct signal with probability $\mu > 0$ so that Pr[inspection report = defective $\mid a = d$] $= \mu$. Hence, $\mu$ measures the "accuracy" of the inspection. If the inspection indicates that the product is defective, then the buyer rejects the product without paying the contingent payment $p$. However, if no defect is discovered during inspection (or due to no inspection), then the buyer presumes the product is nondefective, accepts the product, pays the contingent payment $p$ to the supplier, and sells the product to a customer. Recall that the expected present values of liabilities for the adulterated product is $v_B$ and for the revenue is $r$. Table 2 presents the strategic form of the inspection subgame. The top expression in each cell is the expected discounted profit of the supplier and the bottom expression is the expected discounted profit of the buyer. For example, if the supplier chooses to produce an adulterated (defective) product by setting $a = d$ and the buyer chooses not to inspect by selecting $i = 0$, then the supplier's discounted profit is equal to $X + p - c_d$ and the buyer's discounted profit is equal to $r - v_B - X - p$.

To simplify our exposition and to eliminate trivial cases (in which the buyer does not participate in the inspection game), we make two mild assumptions.

Assumption 2. *The inspection is sufficiently accurate: When inspection is conducted, the supplier's expected penalty for getting caught is higher than the supplier's expected gain from cutting corners. Because the defect is detected by the buyer with probability $\mu$, this assumption implies that $\mu c_d > (1-\mu)(c_n - c_d)$ or equivalently, $\mu$ is sufficiently high so that $\mu > (c_n - c_d)/c_n$.*

When Assumption 2 is violated so that $\mu \leq (c_n - c_d)/c_n$, regardless of the buyer's inspection decision, the supplier will always choose to produce adulterated products. As we assumed earlier, the buyer does not find it profitable to sell products that are adulterated for certain. Therefore, the buyer would not participate in this inspection game.

Assumption 3. *The inspection is cost effective: When inspection is conducted, the inspection cost, $I$, is less than the expected loss from selling an adulterated product $\mu(v_B - r)$, i.e., $I/\mu < v_B - r$.*

When Assumption 3 is violated, so that $I/\mu > v_B - r$, it costs the buyer more to conduct the inspection than the expected loss from selling an adulterated product. Therefore, the buyer will never inspect and the supplier will always produce adulterated product. Again, the buyer would not participate in this inspection game.

### 5.2. Analysis of the Inspection Game

For any given contract $(X, p)$, we now analyze a noncooperative game, which we shall call the inspection game. The solution of the inspection game is presented in Lemma 1. In preparation, let us define the supplier's "adulteration" probability as $x \stackrel{\text{def}}{=} \Pr[a = d]$, and the buyer's "inspection" probability as $y \stackrel{\text{def}}{=} \Pr[i = 1]$.

Lemma 1. *For any given inspection contract $(X, p) \geq 0$, the equilibrium of the inspection game can be described as follows:*

1. *If $p < (c_n - c_d)/\mu$, then the pure strategy $(x^* = 1, y^* = 1)$ is a unique equilibrium. The corresponding equilibrium profits are $\pi_S(X, p) = X + p(1-\mu) - c_d$ and $\pi_B(X, p) = -X - I - (v_B - r + p)(1-\mu)$.*
2. *If $p > (c_n - c_d)/\mu$, then the inspection game has a unique mixed strategy equilibrium: $x^* = I/(\mu(p - r + v_B))$ and $y^* = (c_n - c_d)/(p\mu)$, where $x^* \in (0, 1)$ and $y^* \in (0, 1)$. The supplier's and the buyer's profits are $\pi_S(X, p) = X + p - c_n$ and $\pi_B(X, p) = -X + r - p - (Iv_B/((p - r + v_B)\mu))$.*
3. *If $p = (c_n - c_d)/\mu$, then any point $(x, 1)$, where $x \in [I/(\mu(p - r + v_B)), 1]$, is an equilibrium of the inspection game. The supplier's and the buyer's equilibrium profits are $\pi_S(X, p) = X + p - c_n$ and $\pi_B(X, p) = -X - I + (r - p)(1 - x\mu) - xv_B(1-\mu)$.*

Lemma 1 has the following implications. First, when $\mu p < c_n - c_d$ (i.e., the expected loss of contingent payment for the supplier is less than the gain from adulteration), part 1 asserts that the supplier will definitely cheat and the buyer will conduct 100% inspection.

Second, when $\mu p > c_n - c_d$ (i.e., the expected loss of contingent payment for the supplier is greater than the gain from adulteration), part 2 reveals that the supplier does not always cheat ($x^* \in (0,1)$) and the buyer does not always inspect ($y^* \in (0,1)$). Observe that $x^* > 0$ even when the payment $p$ is very large or when the inspection is perfectly accurate ($\mu = 1$). This observation suggests that the inspection mechanism cannot completely deter the supplier from product adulteration.

Finally, when $p = (c_n - c_d)/\mu$, part 3 suggests that the inspection game has multiple equilibria. However, by noting that the buyer's profit $\pi_B(X, p)$ decreases in the supplier's adulteration probability $x$ and the supplier's profit $\pi_S(X, p)$ is independent of $x$, we can focus on the smallest $x$ as the "payoff dominant equilibrium" as stated in the following corollary.

Corollary 1. *If $p = (c_n - c_d)/\mu$, then the inspection game has a unique mixed strategy payoff dominant equilibrium: $x^* = I/(\mu(p - r + v_B))$ and $y^* = 1$, where $x^* \in (0,1)$. The supplier's and the buyer's profits are $\pi_S(X, p) = X + p - c_n$ and $\pi_B(X, p) = -X + r - p - (Iv_B/((p - r + v_B)\mu))$.*

### 5.3. Optimal Inspection Contract

By using the payoffs stated in Lemma 1, we now solve the buyer's problem:

$$\max_{X\geq 0,\, p\geq 0} \quad \pi_B(X, p) \tag{4a}$$

$$\text{s.t.} \quad \pi_S(X, p) \geq 0, \tag{4b}$$

where (4b) is the standard supplier's participation constraint. The following is the solution of (4). The details of the derivation are described in the proof.

Proposition 2. *The optimal inspection contract, the buyer's optimal payoff, and the supplier's optimal payoff associated with the inspection game can be described as follows:*

1. *If $I/\mu > v_B/4$, then the buyer should not participate in the inspection mechanism.*
2. *If $I/\mu \leq v_B/4$ and $r - c_n > v_B - \sqrt{Iv_B/\mu}$, then the optimal inspection contract $(X^*, p^*) = (0, p^0)$, where $p^0 = r - v_B + \sqrt{Iv_B/\mu} \geq c_n$. The buyer's optimal profit is $\pi_B(X^*, p^*) = v_B - 2\sqrt{Iv_B/\mu} > 0$ and the supplier's optimal profit is $\pi_S(X^*, p^*) = p^0 - c_n > 0$. The equilibrium probabilities are $x^* = \sqrt{I/\mu v_B}$ and $y^* = (c_n - c_d)/(p^0\mu)$.*
3. *If $I/\mu \leq v_B/4$ and $v_B - \sqrt{Iv_B/\mu} \geq r - c_n \geq v_B/2 - \frac{1}{2}\sqrt{v_B^2 - 4(Iv_B/\mu)}$, then the optimal inspection contract $(X^*, p^*) = (0, c_n)$. The buyer's optimal profit is $\pi_B(X^*, p^*) = r - c_n - Iv_B/((c_n + v_B - r)\mu) > 0$ and the supplier's optimal profit is $\pi_S(X^*, p^*) = 0$. The equilibrium probabilities are $x^* = I/((c_n + v_B - r)\mu)$ and $y^* = (c_n - c_d)/(c_n\mu)$.*
4. *If $I/\mu \leq v_B/4$ and $r - c_n < v_B/2 - \frac{1}{2}\sqrt{v_B^2 - 4(Iv_B/\mu)}$, then the buyer should not participate in the Inspection mechanism.*

In view of Proposition 2, consider Mattel's 100% inspection policy. First, from statement 3, if the cost of producing defective product $c_d$ goes to zero (or becomes small relative to $c_n$) and the inspection is perfect, $\mu = 1$, then inspection probability approaches one. In the Mattel's case, testing for lead is fairly accurate ($\mu = 1$) (compared with less accurate testing for, say, melamine) and Mattel may perceive that its suppliers have a strong incentive to cheat. Second, Mattel may be subject to political pressure from the government and the public and might be choosing 100% inspection to signal to those parties that it is taking quality seriously. Such signalling by Mattel is outside the scope of our model.

### 5.4. Properties of the Optimal Inspection Contract

Observe from parts 2 and 3 of Proposition 2 that only the buyer's optimal inspection probability $y^*$ depends on the supplier's cost for producing adulterated product $c_d$. To elaborate, consider the case when $c_d$ is low so that the supplier has more incentive to cheat. However, the supplier will not increase her adulteration probability $x^*$ because the supplier anticipates the buyer would increase its inspection probability $y^*$. This explains why the supplier's adulteration probability $x^*$ and the supplier's optimal profit $\pi_S(X^*, p^*)$ are independent of $c_d$. Therefore, the buyer's optimal profit $\pi_B(X^*, p^*)$ is also independent of $c_d$.

From Proposition 2, the buyer's optimal inspection contract and the buyer's participation depend on two key factors: the inspection cost to inspection accuracy ratio, $I/\mu$, and the profit margin when producing unadulterated products, $r - c_n$. Thus, we present results of Proposition 2 in Figure 3 in terms of these two factors. When the profit margin, $r - c_n$, is sufficiently high ($r - c_n > v_B - \sqrt{Iv_B/\mu}$; see part 2), it is optimal for the buyer to set its optimal contingent payment $p^* = p^0 > c_n$. To keep the supplier's adulteration probability $x^*$ at bay, the buyer cannot fully extract the supplier's surplus. When the profit margin $r - c_n$ is in the intermediate

**Figure 3** **Optimal Inspection Contract as a Function of Inspection Cost to Inspection Accuracy Ratio, $I/\mu$, and Profit Margin, $r - c_n$**

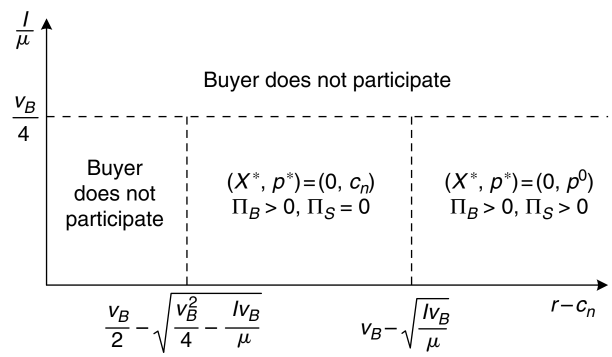
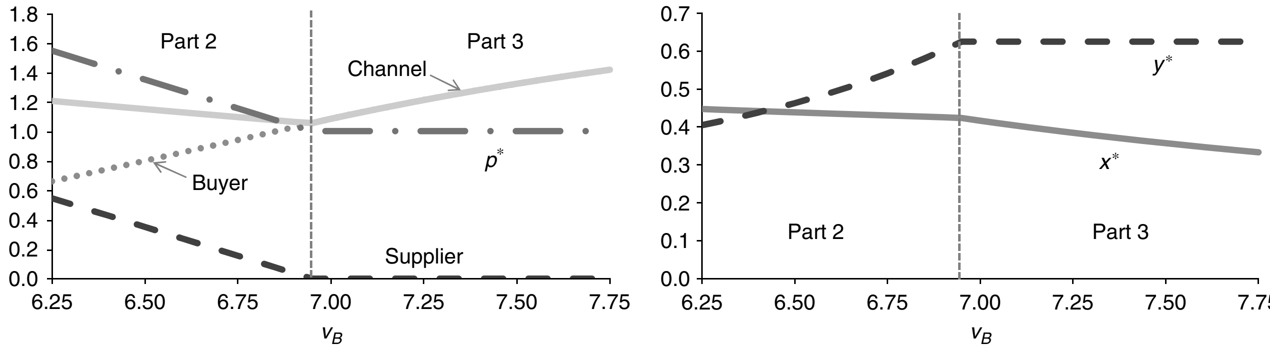


**Figure 4** **Inspection Optimal Contract, Comparative Statics with Respect to $v_B$**




*Notes.* Left panel: Optimal $p^*$, buyer's, supplier's, and channel profits. Right panel: Optimal $x^*$ and $y^*$. Parameter values: $r = 5$, $c_n = 1$, $c_d = 0.5$, $I = 1$, $\mu = 0.8$. The centralized system profit is $r - c_n = 4$.

range $(v_B - \sqrt{Iv_B/\mu} \geq r - c_n \geq v_B/2 + \frac{1}{2}\sqrt{v_B^2 - 4(Iv_B/\mu)}$; see part 3) the buyer's optimal payment $p^* = c_n$, which is the minimum payment for the supplier to produce unadulterated products. In this case, the buyer fully extracts the supplier's surplus.

We now examine the comparative statics of the optimal inspection contract $(X^*, p^*)$, the resulting equilibrium probabilities $(x^*, y^*)$, and profits with respect to the buyer's product liability $v_B$. Although all comparative statics have been proven analytically, we shall omit formal proofs to simplify the exposition and present results in Figure 4 instead. Under the optimal contract, the supplier's adulteration probability, $x^*$, is decreasing in $v_B$ and the buyer's inspection probability, $y^*$, is increasing in $v_B$. This result is due to the "mutual anticipation" of the supplier and the buyer in equilibrium. That is, when the buyer's liability $v_B$ becomes higher, the supplier anticipates that the buyer will inspect more; and hence, the supplier reduces its adulteration probability $x^*$. Interestingly, the optimal contingent payment $p^*$ is decreasing in liability $v_B$. A possible explanation for this result is that instead of increasing the contingent payment $p^*$ it is more effective to increase the inspection probability to provide the same incentive to the supplier not to adulterate the product. It is also interesting that the channel profit is not monotone in liability $v_B$. For small liability values, the supplier's profit is significant and for large liability values the buyer's profit is significant. But regardless of the value of $v_B$, for the same parameter values as were used in the discussion of the optimal deferred payment contract as in §4.4, the channel profit under the inspection contract is only a small fraction of the value of the centralized system's profit, $r - c_n = 4$. We shall discuss the choice between the deferred payment and inspection mechanism in §7.

Because we are using the inspection mechanism primarily as the benchmark for the deferred payment and combined mechanisms, we omit discussion of other comparative statics.

## 6. Combined Inspection and Deferred Payment Contract

The sequence of events associated with the combined mechanism is as follows. The buyer offers a contract $(X, p, q, T)$ to the supplier, where $X \geq 0$ is the upfront payment and $p$ is the payment at time 0 contingent on the inspection not discovering any defects. If no defects were discovered, the product is sold to the customers. In this case, $q$ is the second contingent payment to the supplier if the customer does not discover adulteration by time $T$, where $T$ is the deferred payment duration.

Because the combined mechanism "combines" the inspection and the deferred payment mechanism, we can use the supplier's and the buyer's payoffs under both mechanisms, as reported in Tables 1 and 2, to determine the supplier's and the buyer's profit under the combined mechanism, as reported in Table 3. For example, consider the case when the supplier produces defective product $(a = d)$ and the buyer inspects $(i = 1)$. By noting that the supplier receives the upfront payment $X$, incurs the production cost $c_d$, receives the first contingent payment $p$ with probability $(1 - \mu)$ at time 0 (i.e., the probability that the

**Table 3** **The Supplier's (Top Expression) and Buyer's (Bottom Expression) Expected Discounted Profits for Any Combination of Pure Strategies Selected by the Players Under the Combined Inspection and Deferred Payment Contract** $(X, p, q, T)$

| | $i = 0$ (do not inspect) | $i = 1$ (inspect) |
|---|---|---|
| $a = n$ (nondefective) | $(X + p + q_S - c_n,$ $r - X - p - q_B)$ | $(X + p + q_S - c_n,$ $r - X - p - q_B - I)$ |
| $a = d$ (defective) | $(X + p + q_S\eta - c_d,$ $r - v_B - X - p - q_B\eta)$ | $(X + (p + q_S\eta)(1-\mu) - c_d,$ $(r - v_B - p - q_B\eta)(1-\mu) - X - I)$ |

inspection fails to report adulteration at time 0), and receives the second contingent payment $q$ at time $T$ with probability $(1-\mu)\eta$ (i.e., the probability that the inspection fails to report adulteration multiplied by the probability that the customer fails to discover adulteration by time $T$), we conclude that the supplier's payoff under this pair of pure strategies ($a=d$, $i=1$) equals $X-c_d+(1-\mu)p+(1-\mu)\eta q_S$. Similarly, we determine the buyer's payoff under this pair of pure strategies.

By definition, the combined contract $(X,p,q,T)$ has more decision variables than either the inspection or the deferred payment contracts. Hence, the buyer's profit under the optimal combined contract should be greater than or equal to the maximum of the buyer's profits obtained in either the optimal inspection or the optimal deferred payment contracts. We establish the following interesting result in this section: The buyer's profit is exactly equal to the maximum of the buyer's profits obtained in either the optimal inspection or the optimal deferred payment contracts. Hence, the more complex combined contract is redundant, because one of the simpler contracts will suffice.

For any combined contract $(X,p,q,T)$, we now determine the equilibria (mixed and pure strategy). As described in §5, $x$ represents the supplier's adulteration probability ($x \stackrel{\text{def}}{=} \Pr[a=d]$), and $y$ represents the buyer's inspection probability ($y \stackrel{\text{def}}{=} \Pr[i=1]$). The profits of the supplier and the buyer for any combination of the pure strategies are given in Table 3. The following lemma presents the equilibria for any combined contract.

Lemma 2. *For any given combined contract $(X,p,q,T)\geq 0$, the equilibria of the combined mechanism can be described as follows*:

1. *If $c_n-c_d<q_S(1-\eta)$, then the pure strategy $(x^*=0, y^*=0)$ is a unique equilibrium. The corresponding equilibrium profits are $\pi_S(X,p,q,T)=X+p+q_S-c_n$ and $\pi_B(X,p,q,T)=r-X-p-q_B$.*
2. *If $c_n-c_d=q_S(1-\eta)$, then any point $(x,0)$, where $x\in[0, I/(\mu(p+q_B\eta+v_B-r))]$, is an equilibrium. The supplier's and the buyer's equilibrium profits are $\pi_S(X,p,q,T)=X+p+q_S-c_n$ and $\pi_B(X,p,q,T)=r-X-p-q_B-x[v_B-q_B(1-\eta)]$.*
3. *If $q_S(1-\eta)<c_n-c_d<q_S(1-\eta)+\mu(p+q_S\eta)$, then the combined inspection and deferred payment game has a unique mixed strategy equilibrium: $x^*=I/(\mu(p+q_B\eta+v_B-r))$ and $y^*=(c_n-c_d-q_S(1-\eta))/(\mu(p+q_S\eta))$, where $x^*\in(0,1)$ and $y^*\in(0,1)$. The supplier's and the buyer's equilibrium profits are $\pi_S(X,p,q,T)=X+p+q_S-c_n$ and $\pi_B(X,p,q,T)=r-X-p-q_B-(I[v_B-q_B(1-\eta)])/(\mu(p+q_B\eta+v_B-r))$.*
4. *If $c_n-c_d=q_S(1-\eta)+\mu(p+q_S\eta)$, then any point $(x,1)$, where $x\in[I/(\mu(p+q\eta+v_B-r)),1]$, is an equilibrium of the combined inspection and deferred payment game. The corresponding supplier's and buyer's profits are $\pi_S(X,p,q,T)=X+p+q_S-c_n$ and $\pi_B(X,p,q,T)=r-X-I-p-q_B-x[v_B-q_B(1-\eta)-\mu(v_B+p+q_B\eta-r)]$.*
5. *If $c_n-c_d>q_S(1-\eta)+\mu(p+q_S\eta)$, then the pure strategy $(x^*=1, y^*=1)$ is a unique equilibrium. The corresponding equilibrium profits are $\pi_S(X,p,q,T)=X+(p+q_S\eta)(1-\mu)-c_d$ and $\pi_B(X,p,q,T)=-X-I-(v_B+p+q_B\eta-r)(1-\mu)$.*

Because the combined mechanism combines the inspection and the deferred payment mechanisms, it is not surprising to see that the results stated in Lemma 2 resembled the results stated in Lemma 1 from the inspection mechanism. Therefore, Lemma 2 has a similar interpretation as Lemma 1. We omit the details.

Similar to part 3 of Lemma 1, parts 2 and 4 of Lemma 2 reveal that the combined mechanism has multiple equilibria when $c_n-c_d=q_S(1-\eta)$ or when $c_n-c_d=q_S(1-\eta)+\mu(p+q_S\eta)$, respectively. By noting from part 2 that the buyer's profit is decreasing in the supplier's adulteration probability $x$ because $v_B\geq r\geq q_B>q_B(1-\eta)$ and that the supplier's profit is independent of $x$, we can focus on a unique (payoff) dominant equilibrium by choosing the smallest $x$ for the case as stated in part 2. Also, we can use the same approach to determine a unique (payoff) dominant equilibrium by choosing the smallest $x$ for the case as stated in part 4. Consequently, we can rewrite Lemma 2 as the following corollary.

Corollary 2. *For any given combined contract $(X,p,q,T)\geq 0$, the payoff dominant equilibrium of the combined mechanism can be described as follows*:

1. *If $c_n-c_d\leq q_S(1-\eta)$, then the pure strategy $(x^*=0, y^*=0)$ is a unique equilibrium. The corresponding equilibrium profits are $\pi_S(X,p,q,T)=X+p+q_S-c_n$ and $\pi_B(X,p,q,T)=r-X-p-q_B$.*
2. *If $q_S(1-\eta)<c_n-c_d\leq q_S(1-\eta)+\mu(p+q_S\eta)$, then the combined inspection and deferred payment game has a unique mixed strategy equilibrium: $x^*=I/(\mu(p+q_B\eta+v_B-r))$ and $y^*=(c_n-c_d-q_S(1-\eta))/(\mu(p+q_S\eta))$, where $x^*\in(0,1)$ and $y^*\in(0,1)$. The supplier's and the buyer's profits are $\pi_S(X,p,q,T)=X+p+q_S-c_n$ and $\pi_B(X,p,q,T)=r-X-p-q_B-(I[v_B-q_B(1-\eta)])/(\mu(p+q_B\eta+v_B-r))$.*
3. *If $c_n-c_d>q_S(1-\eta)+\mu(p+q_S\eta)$, then the pure strategy $(x^*=1, y^*=1)$ is a unique equilibrium. The corresponding equilibrium profits are $\pi_S(X,p,q,T)=X+(p+q_S\eta)(1-\mu)-c_d$ and $\pi_B(X,p,q,T)=-X-I-(v_B+p+q_B\eta-r)(1-\mu)$.*

Corollary 2 resembles Corollary 1 under the inspection mechanism. For instance, when the cost gap $(c_n-c_d)$ is like part 2, the supplier has incentive to cheat. In this case, only the buyer's optimal inspection probability $y^*$ depends on cost gap $(c_n - c_d)$ in equilibrium as observed in parts 2 and 3 of Proposition 2 under the inspection mechanism.

Corollary 2 states the buyer's and the supplier's payoffs for any given combined contract $(X, p, q, T)$. We now determine the optimal combined contract by using the same approach as in §4 to determine the optimal deferred payment contract by solving the buyer's problem. Unlike problem (2), which has three decision variables, the buyer's problem associated with the combined contract has four decision variables: $(X, p, q, T)$. Nevertheless, we manage to solve the buyer's problem analytically and determine the optimal combined contract in the following Proposition.

Proposition 3. *The optimal combined contract* $(X^*, p^*, q^*, T^*)$ *can be described as follows: Either* $(X^*, p^*, q^*, T^*) = (0, p^*, 0, 0)$ *or* $(X^*, p^*, q^*, T^*) = (0, 0, q^*, T^*)$, *where* $p^*$ *is the optimal contingent payment under the inspection mechanism as given in Proposition* 2 *and* $(q^*, T^*)$ *are the optimal deferred contingent payment and deferred payment duration under the optimal deferred payment contract as given in Proposition* 1.

Even though the combined contract has more decision variables than the inspection contract and the deferred payment contract as discussed in earlier sections, Proposition 3 reveals that we can retrieve the optimal combined contract from the optimal inspection contract or the optimal deferred payment contract established earlier. The buyer's profit under the optimal combined contract is equal to the profit that the buyer can obtain from choosing the "dominant mechanism" between either the pure inspection mechanism or the pure deferred payment mechanism as discussed in §7. Hence, it is unnecessary for the buyer to offer the combined mechanism. From the perspective of mathematical programming, this result is unexpected because more decision variables should enable the buyer to obtain a higher profit. However, from the perspective of game theory, this result can be due to the fact that the supplier can choose between only two actions: adulterate or not. Because there are only two discrete actions that the supplier can choose from, having more decision variables by combining inspection and deferred payment may not help the buyer to obtain a higher profit (Png 2010). It is also known in game theory that adding more dimensions or actions or information could lead to players in a game ending up in either a "win-win" or a "lose-lose" situation. In our combined mechanism both Nash game and sequential game are present. Therefore, there is no obvious explanation we could deduce. Therefore, to our best knowledge, formal analysis in Proposition 3 is the only way to demonstrate this unexpected result. When the product is subject to multiple categories of adulteration, as discussed in §8, we think the combined mechanism can strictly dominate either of the pure ones. Proposition 3 continues to hold even if one imposes a constraint on the duration of the contract, i.e., if $T \leq \hat{T}$.

We wish to clarify that the combined mechanism may not be the best among all "possible mechanisms." It certainly does not achieve the centralized solution, because if it relies on its inspection "arm," the decentralized supply chain system pays inspection costs to an external entity (which the centralized system would not). However, our combined mechanism is the best policy within the class of deferred payment mechanisms and inspection mechanisms.

## 7. Choosing the Mechanism

Knowing that the combined mechanism is redundant, there are only two mechanisms left to compare: the inspection mechanism, and the deferred payment mechanism. Proposition 1 presents the optimal contract and the corresponding profits for the deferred payment mechanism. Proposition 2 does that for the inspection mechanism. To keep the discussion interesting, we shall focus on the cases when the buyer's profit is positive under at least one of these mechanisms.

From Propositions 1 and 2, parameters $a = (\alpha_S - \alpha_B)/\lambda$ and $c_d$ affect only the deferred payment mechanism, and parameters $I/\mu$ and $v_B$ affect only the inspection mechanism. This observation facilitates the following analysis.

### 7.1. Effect of the Inspection Cost and the Inspection Accuracy

Based on the intuitive findings in §5, the buyer's profit under the inspection mechanism is decreasing in ratio of the inspection cost over inspection accuracy, $I/\mu$, and the buyer's profit under the deferred payment mechanism is unaffected. Ultimately, if $I/\mu > v_B/4$, the buyer's profit under the inspection mechanism becomes zero. Therefore, an intuitive conclusion is that *high inspection cost or low inspection accuracy encourages the use of the deferred payment mechanism.*

### 7.2. Effect of the Buyer's Product Liability

Again, using comparative static results from §5, the buyer's profit under the inspection mechanism is increasing in liability $v_B$ and the buyer's profit under the deferred payment mechanism is unaffected. If the liability is too small (for example, $v_B/4 < I/\mu$), the buyer's profit under the inspection mechanism is zero. Thus, a less intuitive takeaway from our analysis is that *for low-liability businesses, deferred payment is a better mechanism.*

This observation has potential policy implications. The government could influence the buyer's choice of mechanisms through $v_B$. Suppose that $v_B$ comes from legal penalties levied on the buyer and these penalties comprise compensatory and punitive damages. In some circumstances, if the punitive damages part is removed, this might lower $v_B$ sufficiently to make the deferred payment mechanism attractive to the buyer. Recall that the probability of adulteration is strictly positive under the inspection mechanism and zero under the deferred payment one. Thus, by removing punitive damages, the government could remove the possibility of adulteration from the system.

### 7.3. Effect of the Financing Cost Gap and the Defect Discovery Rate

Next, let us turn to the parameters that affect the buyer's profit under the deferred payment mechanism only. From the analysis in §4, the buyer's profit under the deferred payment mechanism is decreasing in the financing cost gap $\alpha_S - \alpha_B$ and is increasing in the rate of adulteration discovery by customers, $\lambda$ (these parameters appear together as $a = (\alpha_S - \alpha_B)/\lambda$). If $a = (\alpha_S - \alpha_B p)/\lambda$ is very large, then the buyer makes zero profit under the deferred payment mechanism. Therefore, two very intuitive conclusions from our model are *for systems with large financing cost gap and slow rate of defect discovery by customers, inspection is a better mechanism.*

### 7.4. Effect of the Defective Product Cost

Under the deferred payment mechanism the buyer's profit is increasing in $c_d$, and the profit under the inspection mechanism is unaffected. Thus, as the cost of defective product $c_d$ is getting closer to the cost of nondefective product $c_n$, the deferred payment becomes a more attractive mechanism for the buyer. This does not necessarily mean that the buyer would choose the deferred payment mechanism over the inspection mechanism. In this case, the choice depends on the value of other problem parameters and one needs to compare corresponding profit expressions to determine the best mechanism. The following propositions present sufficient conditions for the buyer to prefer the deferred payment mechanism.

Proposition 4. *Consider the case when $I/\mu \le v_B/4$ and $r - c_n > v_B - \sqrt{I v_B/\mu}$. If $c_d/c_n > a/(1+a)$ and $I/\mu \ge c_n/2[(c_d/c_n)^{-a} - 1]$, or if $c_d/c_n < a/(1+a)$ and $I/\mu \ge c_n/2[(1 - c_d/c_n)(1+a)(a/(1+a))^{-a} - 1]$, then the deferred payment mechanism dominates the inspection mechanism.*

Although we cannot make as an unequivocal a statement as we did earlier, the overall direction of the result is that *the buyer is more likely to rely on the deferred payment mechanism if the cost of adulterated product is close to the cost of unadulterated product.*

Next, let us study informational aspects of the mechanism choice. Specifically, to implement contracts in practice we need to consider which information is available to the buyer (even though the model does not directly address asymmetric information other than actions of the supplier). Likely, the values for revenues $r$, liabilities $v_B$, inspection cost $I$, inspection accuracy $\mu$, and financing gap $\alpha_S - \alpha_B$ are known to the buyer. The buyer may also know the supplier's cost of producing nondefective products $c_n$. However, the buyer is unlikely to know the cost of producing defective products $c_d$. Thus, contracts that do not require this knowledge are preferable for the buyer. By this criterion, the buyer prefers the inspection mechanism to the deferred payment mechanism because the optimal contract terms in the inspection contract do not depend on $c_d$. Similarly, if the buyer does not know the rate at which customers discover defects, $\lambda$ (this can depend on how the supplier adulterated products), then inspection mechanism is preferable. However, the deferred payment mechanism might provide a good solution in the region corresponding to part 1 of Proposition 1, where $q_S^* = c_n$. If $T^*$ is set as an industry standard and as long as the buyer is confident that the cost ratio $c_d/c_n$ is within certain bounds, (as we discussed in §4.4) this mechanism is quite robust in deterring supplier's adulteration. Furthermore, whereas the inspection contract does not require knowledge of $c_d$, the inspection probability depends on this value. Therefore, although the buyer can offer the optimal inspection contract without the knowledge of $c_d$, the buyer cannot implement this contract. Finally, if the buyer does not know how defective product will affect the customers (i.e., the buyer does not know $v_B$), then the deferred payment mechanism might be preferable because it eliminates the incentive for the supplier to produce adulterated product entirely.

## 8. Conclusions

We have studied three forms of contingent payment mechanisms that are intended to deter product adulteration: the deferred payment, the inspection, and the combined mechanisms. We have analyzed inspection subgames for the inspection and combined mechanisms, derived analytical expressions for the optimal contracts in all mechanisms, and studied effects of various parameters on the performance of these mechanisms.

For the optimal deferred payment mechanism, we observed that as the cost of producing adulterated products decreases (so that the incentive to cheat for the supplier increases), the buyer manages that incentive first by extending the deferred payment duration and then by raising the contingent payment amount. The deferred payment mechanism can be implemented via a common financial contract—trade credit. We showed that under reasonable assumptions on the financing cost gap, the unadulterated/adultarated product cost gap, and the rate at which customers discover adulteration, a "net 30" trade credit contract (a popular example of trade credit contracts) can be effective at controlling the supplier's incentives.

We use the inspection mechanism as the benchmark for the performance of the deferred payment mechanism. Still, several interesting observations can be made about the inspection mechanism itself. For instance, we have shown that the optimal contingent payment under the inspection mechanism decreases in the buyer's liability (Intuitively, when the buyer's liability increases one would expect that the buyer would increase its contingent payment to entice the supplier not to adulterate the product). The explanation for this result is that the equilibrium inspection probability under the optimal contract is increasing in the buyer's liability, so the contingent payment itself can be lower. Under the optimal inspection mechanism, we have found that there is always a positive probability of the supplier producing adulterated product, which ultimately ends up with the customer. In contrast, we have shown that the optimal deferred payment mechanism can deter the product adulteration entirely.

Intuitively, one would expect that the combined mechanism should generate higher profits for the buyer. Interestingly, although the combined contract has more decision variables, the buyer's profit under the optimal combined contract is equal to the profit that the buyer can obtain from choosing the "dominant mechanism" between either the pure inspection mechanism or the pure deferred payment mechanism. Hence, it is unnecessary for the buyer to offer the combined mechanism.

By comparing the buyer's profits obtained under the deferred payment and inspection mechanisms, we have established conditions under which one mechanism dominates the other. Specifically, the dominance is based on four key factors: (a) inspection cost relative to inspection accuracy, (b) buyer's liability, (c) difference in financing rates relative to the rate at which customers discover defects, and (d) incentive for the supplier to cheat that is measured in terms of cost gap between unadulterated and adulterated products. The influence of the factors (a) and (c) is intuitive. High inspection cost or low inspection accuracy make the deferred payment mechanism more attractive. High financing gap or low defects discover rate make the inspection mechanism more attractive. The role of factors (b) and (d) is more interesting. Either low buyer's liability for defective products or low cost gap, both meaning that the threat from adulteration is low, make the deferred payment mechanism preferable for the buyer over the inspection mechanism.

In future research, one could explore a number of directions, such as different categories of adulteration. Some categories of adulteration can be better managed by inspection (when the buyer knows what to test for, inspection cost is reasonable, and the risk from adulterated products for the buyer is significant) and other categories by deferred payments (when the cause of adulteration is difficult to test for, and the financing gap relative to the defect discovery rate is not large). When a product is potentially subject to multiple categories of adulteration simultaneously, we believe that the combined mechanism will strictly dominate either of the pure mechanisms.

We have assumed that the buyer is responsible for the entire product liability. In view of the recent episodes of product adulteration and the fact that the manufacturer can rarely claim supplier's product liability, this assumption captures the reality well. However, it is of interest to examine a situation in which the supplier shares the product liability with the buyer, as examined in Chao et al. (2009). We believe that incorporating supplier liability into the model will not change our main conclusions. Next, to capture the reality of the opportunistic behavior of the overseas suppliers, we used a static contracting model (in this regard, our model is similar to the majority of the contracting literature). Both suppliers and the buyers in practice behave as if they had very short-term objectives (hence, the record number of product recalls due to adulteration) and frequently, buyers do not have much history with the suppliers, which can be useful to form strategies. However, one can also think of situations where the buyer and the supplier interact repeatedly over a very long time. Analytically, this creates difficulties because of the multiplicity of equilibria due to the folk theorem. Also, the theory of dynamic games with asymmetric information is not as well developed as the theory of static games.

Clearly, there are many other interesting extensions (e.g., issues of risk aversion, asymmetric information about the supplier's cost or production capability, asymmetric information about the buyer's demand, and the comparison of the deferred payment mechanism with product warranty mechanism). For instance, the buyer, being closer to the customers, may have private information about the defect discovery rate $\lambda$. Alternatively, suppliers, knowing the nature of adulteration, may have private information about $\lambda$. It is also possible that the asymmetric information is double sided. Our results would have to be revisited because in addition to adulteration incentives the contract design would also have to account for information incentives. Thus, the contract design problems would be a combination of moral hazard and signalling or adverse selection problems, which are difficult to handle. These are left for future research.

## Electronic Companion

An electronic companion to this paper is available as part of the online version that can be found at http://msom.journal.informs.org/.

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