

Are Supply and Plant Inspections Complements or Substitutes? A Strategic and Operational Assessment of Inspection Practices in Biotechnology

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Abstract

This paper theoretically and empirically examines the conventional wisdom in procurement management that often portrays supply inspections and supplier plant inspections as substitutes. We develop a theoretical model that focuses on potential internal spillover costs of the buyer receiving low-quality inputs and external spillover costs should low-quality inputs go undetected. Key to our analysis is the condition of whether a buyer can commit to the intensity of supply inspection or not. If a buyer cannot commit, supply inspections and plant inspections are substitutes as widely believed. The two types of inspections, however, may become complements when a buyer is able to commit to the intensity of supply inspection. Complementarity is especially likely when external spillovers are less than expected internal spillovers, which depends on the level of buffer inventory, or when knowledge sharing between buyer and supplier becomes more effective as the supplier allocates more resources to learning for quality improvement or hiding aspects of the production processes is easier for suppliers. We empirically evaluate our model with a new data set drawn from a large biotechnology manufacturer. Empirical results provide broad support for theory, which, we argue, may help to explain variation in inspection practices across industries. Our theory and empirical analysis contribute to the literatures on strategic management, organizational economics, and procurement management by highlighting the organizational and strategic use of inspection practices.

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1. INTRODUCTION

The literature on supplier management usually portrays inspection of supplies and inspection of supplier facilities as substitutes for one another (e.g., Concannon 1989, Ghinato 1998). This literature instructs buyers to inspect supplier production facilities (i.e., plant inspections) in order to improve quality at the source so that only supplies of sufficient quality are delivered to the buyer thereby obviating the need for supply inspections (e.g., Deming 1982). This perspective is not universally accepted as some researchers still recommend inspecting supplies because of the motivation it provides for suppliers (e.g., Starbird 1994) while others examine optimal inspection sampling techniques (e.g., Herer and Raz 2000). Casual observations of many industries, like the one studied here, biotechnology, confirms that supply inspections have not been universally cast aside in favor of plant inspections only. For instance, while buyers inspect only supplier plants for some inputs, they inspect only supplies or inspect both plants and supplies for other inputs. Still other inputs receive no inspections at all. If ensuring quality inputs is necessary to a firm's competitive position, which is widely asserted by the quality and strategy literatures, what explains the variation in the choice of inspection practices?

Deciding what and how intensively to inspect has received little attention in the literature. Research on a buyer's decision to inspect supplies is limited and theoretical (e.g., Reyniers and Tapiero 1995), rarely including empirical analysis, and does not consider supplier plant inspections. Similarly, the literature on supplier evaluation and selection (e.g. Degraeve and Roodhooft 1999, Jayaraman et al. 1999, Tagaras and Lee 1996) does not assess the role of supply

and plant inspections as part of ongoing supports for the exchange. Previous research on buyer-supplier exchanges typically has focused on contractual clauses (e.g., take-or-pay, exclusivity, price adjustments) or on informal/non-contractual safeguards. But again, these studies rarely look at how practices such as inspections support the exchange. The purpose of our paper is to begin to fill this gap in the literature by investigating theoretically and empirically the buyer's choice of inspection practices.

In the first part of this paper, we develop a general formal model of the buyer's decision to inspect supplies, inspect a supplier's plant, or both as well as how intensive the inspections should be. We condition the model, and the empirical analysis that follows, on the transaction being organized through a market interface rather than through vertical integration. The model assumes that, for some supplies, the buyer is particularly sensitive to low quality and that undetected low quality creates spillover costs. Our model highlights two types of potential spillover costs. First, the buyer may have a production process that would shut down, imposing opportunity costs or costs for switching production capacity to another product, or would cause work-in-process to spoil or otherwise be rendered valueless, should an undetected low-quality input enter the manufacturing process. Such spillover costs are often referred to as internal costs in the quality literature (Montgomery 1991). Second, the buyer may have a valuable reputation for a high-quality product and its reputation with consumers or regulators (if the product or production is regulated) could be devalued should an undetected low-quality input enter the manufacturing process and lead to the selling of low-quality output. Such spillover costs are referred to as external costs in the quality literature (Montgomery 1991).

Spillover costs are vexing to a buyer because they often are non-verifiable and thus non-contractible. For instance, while replacing defective inputs is easily verified by a third party and

hence contractible, contracting for supplier liability when the buyer's actions influence the size of liability or the size of the liability is difficult to measure (e.g., damage to reputation, lost sales) or is not readily feasible because of verification difficulties. Such verification problems can give rise to a moral hazard in which a supplier under-provides effort and hence quality. We assume that plant and supply inspections, while costly, not only increase the likelihood that only high-quality inputs are used in production but also may influence supplier behavior to produce high-quality supplies. Thus, inspections provide a means by which potential spillover costs can be reduced or avoided.

Our model analyzes the cost minimizing intensity of supply and plant inspections by incorporating potential spillover cost, the probability of their occurrence, and the cost of inspections in the buyer's objective function. Our model also includes and evaluates the role of inventory buffers in avoiding spillover costs because along with the elimination of supply inspections, much of the quality literature also calls for the elimination of inventory buffers. Yet, such buffers can play a role in avoiding at least internal spillover costs by providing quick replacement for inputs found through inspections to be of low quality.

Our model generates two types of conclusions. First, when a buyer can credibly commit to the intensity of its supply inspection, supply inspections and buffer inventories are complements with each other but plant inspections substitutes for these. Hence, we can systematically predict what happens as the cost of inspections or holding buffer inventory increases. Second, our model shows that supply inspections and plant inspections can be complements under certain circumstances. A buyer being able to commit to the intensity of supply inspection is a necessary although not sufficient condition for complementarity. Third parties, as we discuss below, such as regulators of certification agencies may be need to provide such buyer commitment. Additional

conditions are that external spillovers are less than expected internal spillovers, which depend on the level of buffer inventory, or when knowledge sharing between buyer and supplier becomes more effective as the supplier allocates more resources to learning for quality improvement or hiding aspects of the production processes is easier for suppliers. Thus, contrary to the prescriptions of much of the quality literature, using supply inspection can increase the efficacy of plant inspection or vice versa, even if there are no direct spillovers in learning.

In the second part of this paper we operationalize and empirically test our theory in the context of the procurement practices of a biotechnology manufacturer. Biotechnology offers a useful empirical context because it facilitates the examination of both internal and external spillovers. First, manufacturing drugs typically involves a batch manufacturing process with inputs that are perishable. Line stoppages arising from low-quality inputs or late delivery can result in costly loss of work-in-process, opportunity costs from product delays, or costs incurred by switching production capacity to another product. Second, biotechnology firms, and pharmaceutical producers more generally, have valuable reputations with customers as well as with Food and Drug Administration (FDA) regulators that can be significantly devalued if a low-quality input is not identified during the production process and results in a low-quality, potentially harmful, final product. Of course, not all inputs generate such spillover effects. But, the damage from both types of spillovers when they do arise is costly to the buyer and non-verifiable, which are the preconditions on which our theory is based. Biotechnology also offers a context in which the buyer can commit to supply inspections for those inputs that are on production recipes because, once stipulated to the FDA, the FDA requires the buyer to adhere to its commitment or else face regulatory sanctions.

Biostar¹, a large biotechnology firm in the San Francisco Bay Area, provided access to purchasing department personnel and to their supplier contracts, which resulted in the collection of qualitative and quantitative data on a sample 122 supply contracts. Our interviews and data demonstrate heterogeneity across inputs in the use of both types of inspection practices and in buffer inventories, depending on the input. Taking advantage of empirical regularities in the data, we estimate a two-stage reduced-form model that informs our theory. The empirical results are generally consistent with the central thrust of our theory and show that supply and plant inspections can be complements for some particular industry sectors.

This paper contributes to organization theory, strategic management, and procurement management literatures in three ways. First, the paper calls into question the conventional wisdom in supply-chain management that buyers should always substitute away from supply inspections toward plant inspections (e.g., Deming 2000: 421, Walton 1986: 35). The paper discusses how such a prescription is likely to vary systematically by industry and by products inputs within an industry. For instance, supply and plant inspections are more likely to be substitutes in assembly industries like automobiles and consumer electronics where internal spillover costs are relatively small, production processes are more transparent and relatively easier to inspect than in the pharmaceutical industry we are looking at. Second, this paper highlights the interaction between down-stream spillover costs and up-stream measurement costs in determining how firms manage supply transactions. While spillovers and the cost of monitoring under certain conditions can impact organizational form, we show that under other conditions they also explain variations in the management of supply transactions. Thus, the paper offers a new way of thinking about how

¹ We use the pseudonym “Biostar” to protect the firm’s identity.

to match procurement management practices to the attributes of the supply transaction. Third, the paper highlights the strategic implications of procurement management. Poor management of supply risk can defeat the best business strategy, which makes appropriate procurement management a necessary condition for successful business strategies. Excessive inspection can lead to higher costs than competitors, while inadequate inspection can lead to significant losses from production-related and/or losses in reputation.

The article is organized as follows. Section 2 develops our formal model and generates testable predictions. Section 3 introduces the context of the biotechnology industry and develops an empirical methodology for examining our theory in the context of biotechnology procurement. The data are described in Section 4, and results are presented in Section 5. Section 6, then, discusses the results and concludes.

2. A MODEL OF INSPECTION PRACTICES AND SPILLOVERS

When deciding about the intensity of inspection practices, managers also have the opportunity to procure internally or from the market. The measurement branch of transaction cost economics suggests that measurement difficulty is one reason firms may want to vertically integrate a transaction. For instance, if any key dimension of the output of an agent is costly to measure, then an incentive (or outcome)-based contract is problematic and the principal may prefer to couple low-powered incentives with administrative oversight of the agent (Holmstrom and Milgrom 1991). Anderson (1985) empirically examined this logic and showed that these incentive issues led to a preference for integration of the sales force when output was difficult to measure. More recently, Nickerson and Silverman (2003) argue and find empirical support for vertical integration (in the for-hire trucking industry) when a transaction involves both costly monitoring (i.e., inspections) and spillovers that are costly to a buyer, which arguably is the case

with Anderson's (1985) sales force data. Thus, vertical integration is a response to measurement difficulties coupled with spillovers. In the theory developed below, we investigate the effect of spillovers on inspection practices in a setting where we assume that inspections are sufficiently low in cost to organize the exchange through a market. Thus, our model does not directly inform the make v. buy decision but nonetheless is theoretically related to this literature.

Model Preliminaries. We develop a single period model and assume that a buyer purchases a single input from a supplier and with it produces an output. Assume the following events. The buyer inspects the supplier's plant, receives a delivery of an input from a supplier, and inspects the input. Supply inspection produces signals about whether the input is of either low quality (bad) or high quality (good). These signals are important because, as we describe below, they can help the buyer avoid various spillover costs.

We assume that the buyer potentially can incur two types of spillover costs, S_1 and S_2 . S_1 is incurred if the input arrives and turns out to be bad and results in loss of work-in-process, switch over costs as production capacity is shifted to another product, or stoppage of production.² Of course, production lines that are flexible will incur smaller S_1 because production line change-over costs are lower. Also, the buyer does not incur this type of cost if the supply inspection indicates the input is good or a buffer inventory of sufficient quality and size is available to substitute for the low-quality input. The buyer incurs the external cost of S_2 (i.e., cost of product recalls, litigation, brand and reputation diminution) if the input is in fact bad but nonetheless is used to produce an output that is bad and sold into the market place, assuming that consumers

² It can be argued that some of these costs can be negotiated and codified in a supply contract in a way to facilitate third-party verification. For instance, a buyer might specify a penalty clause for which if a shipment shows up after an agreed upon time the supply pays a financial penalty. S_1 , then, represents those internal costs that are not verifiable.

eventually discover that the product is bad. We assume that both spillover costs are non-verifiable by the courts, which makes such costs non-contractible.

Assume that a supply inspection provides a signal, I_s , with one of two signals: a signal that the input is good (i.e, above acceptable quality limits) or bad (i.e, below acceptable quality limits). We label these signals g and b respectively. If the input actually is good we label it g and if it is actually bad we label it b . Both plant and supply inspections can vary by intensity, which we define as p and q , respectively. As we explain later, an increase in $p \in [0, \bar{p})$ raises the supplier's cost but reduces its marginal cost of effort to improve quality. We assume that q is the probability of receiving the “correct” signal from supply inspection, with q increasing asymptotically to one with the intensity of inspection. We assume, however, that this inspection never causes false-negative type I errors: the inspection does not show b when the output is actually g . More precisely, $\text{Prob}(I_s = b|b) = q$ and $\text{Prob}(I_s = b|g) = 0$.³ Notation for the model is summarized in Table 1.

$\text{Prob}(g)$, the probability of the input actually being good should increase with supplier effort and, for simplicity, we assume $\text{Prob}(g) = e$, where e is supplier effort. This relationship also implies that $\text{Prob}(b) = 1-e$, which is the probability that the input actually is bad. We formulate probability of detecting bad inputs as:

$$\text{Prob}(I_s = b) = \text{Prob}(I_s = b|b) \text{Prob}(b) = q(1-e). \tag{1}$$

The likelihood of incurring S_2 is the probability that the input actually is bad even though supply inspection signals the input is good. That is

³ When we include the potential for a type I error, in which the input is good but the inspection signals the input is bad, Equation (1) has to be changed to $\text{Prob}(I_s = b) = \text{Prob}(I_s = b|b) \text{Prob}(b) + \text{Prob}(I_s = b|g) \text{Prob}(g) = q(1-e) + (1-q)e$. We ignore the potential for type I error because it simplifies our model and interpretation without qualitatively affecting our results.

$$\text{Prob}(\mathbf{b} \cap I_s = g) = \text{Prob}(I_s = g \mid \mathbf{b}) \text{Prob}(\mathbf{b}) = (1-q)(1-e). \quad (2)$$

Equation (2) uses Bayes rule to calculate the probability of a false-positive type II error—concluding that the input is good when, in fact, it is bad.

Note that the intensity of supplier plant inspection p does not directly affect the likelihood of incurring spillover costs, but indirectly does so by influencing the supplier's choice of effort. Hence, *we assume that the supplier chooses its effort e after observing the buyer's plant inspection intensity p and that the buyer commits to its plant inspection policy.* This assumption is reasonable because suppliers can observe plant inspections directly and immediately and a buyer will lose its credibility if it fails to conform to the announced plant inspection policy. On the contrary, although buyers typically describe their supply inspection policies in the contracts, buyers may or may not be able to commit to them. In most industries, suppliers cannot know whether their buyers have conducted supply inspections according to the agreement and, therefore, the buyers always want to announce stringent inspection policies but cut back inspections to save money. But, in some industries such as pharmaceuticals, cosmetics, or food, government regulation or certifying process required by a self-regulatory industry organization (i.e., organic certification, some chemicals) may force manufacturers to follow their approved inspection rule. In these types of industries, we can assume that suppliers choose their effort level knowing the actual supply inspection policy. We will consider both commitment and no-commitment cases for supply inspection and show how this difference affects the relationship between plant and supply inspections.

Now, we turn to the decision problems the buyer and the supplier face, respectively.

Buyer's objective. The buyer's objective is to maximize its profit by minimizing the expected internal (S_1) and external (S_2) spillover costs, the cost of holding buffer inventory, and

inspection costs. Since the likelihood of incurring S_1 depends on the size of the buffer inventory, we define r as the probability that the amount of buffer inventory is sufficient to avoid internal spillover costs. $C(p, q, r)$ gives the sum of the cost of effort for plant and supply inspection and the cost of holding buffer inventory. Finally, let R be the expected buyer's revenue from the transaction, which is independent of p, q and r . With these terms defined, the buyer maximizes its expected profit $E\pi_B$:

$$\begin{aligned}
\max E\pi_B &= R - S_1 \text{Prob}(I_s = b) (1-r) - S_2 \text{Prob}(\mathbf{b} \cap I_s = g) - C(p, q, r) \\
&= R - S_1 q(1-e)(1-r) - S_2(1-q)(1-e) - C(p, q, r) \\
&= R - (1-e) \{S_1(1-r)q + S_2(1-q)\} - C(p, q, r) \tag{3}
\end{aligned}$$

where the second line is obtained by substituting in (1) and (2).

This objective function implies that the likelihood of incurring S_1 is the probability that supply inspection delivers a signal that the input is bad, times the probability that the buyer has insufficient buffer inventory to keep production running. We assume that suppliers will pay for transportation and rework or replacement costs when a bad input is identified, thus the buyer incurs S_1 only when there is insufficient buffer inventory to keep the production line going. The probability of incurring S_2 is the probability of the supply inspection signaling a good input, the incorrect signal, conditional on the input actually being bad, times the probability of the input actually being bad. In our model, management can maximize (3) based on decisions concerning three variables: intensity of supply inspection, intensity of supplier plant inspection, and the level of buffer inventory.

We assume that $C(p, q, r)$ is twice differentiable and takes a separable form $C^1(p) + C^2(q) + C^3(r)$ because the inventory level should not affect the cost of supply and plant inspections. Our discussions with buyers also lead us to conclude that the cost of testing most pharmaceutical

inputs will not vary based on the intensity of plant inspections. Likewise, the cost of inspecting the plants will not be influenced by the extent of supply inspection. Note, however, that this assumption may not be appropriate in another industry if a plant inspection could facilitate input inspections by providing the buyer with useful information about the supplier's capability. We assume that C^i 's are all convex with $C^i_{x_i}(x) \geq 0$ and $\lim_{x \rightarrow \sup(x_i)} C^i_{x_i}(x) = +\infty$ where $C^i_{x_i}(x) = dC^i(x)/dx_i$ and $(i, x_i) = (1, p), (2, q), (3, r)$. These assumptions ensure that the only possible corner solutions are those that involve $p = 0, q = 0$ or $r = 0$.

Supplier's objective. We begin by specifying the supplier's problem as one of minimizing the expected costs of a bad product or process being detected, efforts to improve quality or to avoid any costly detection, and bad reputation caused by bad products. When a bad input is detected by supply inspection, the supplier is penalized by the return of the input, which results in their disposal, rework or reproduction. Assume that this penalty adds T to the cost for the supplier. Plant inspection also increases the cost incurred by the supplier (e.g., cost of new technology and method adoption, new investment in facilities, retraining of employees, production stoppage during change-over etc.) if the production process is found to have defects. But it also helps the supplier to improve product quality more efficiently by sharing knowledge and information between the buyer and the supplier. Additionally, the supplier may lose future business opportunities by shipping a bad-quality input or the buyer may conduct more inspections on the supplier's inputs or facilities in the future if the quality is revealed and harms the supplier's reputation in the long run regardless of whether they are detected immediately by supply inspection or not. We can include this reputation cost in our cost function, too.

Let q^* be the supplier's expectation of the buyer's supply inspection intensity. q^* is the actual choice of q when the buyer can commit to q , and the equilibrium choice of q otherwise.

Then, the supplier minimizes its expected total cost of quality ECQs:

$$\text{Min}_e \text{ ECQ}_s = T \text{ Prob}(I_s = b) + c(e, p) = T q^* (1-e) + c(e, p) \quad (4)$$

where the first term is the cost of a bad input being detected and the second term $c(e, p)$ captures the rest of all the costs discussed above including the cost of efforts to improve the product quality and the cost of fixing the defects in processes detected during plant inspections, etc.. We chose the supplier's objective function to be as general as possible, because $c(e, p)$ could include many effects on the supplier profitability caused by the choice of e and p . But what is key to our analysis is the interaction between e and p in $c(e, p)$, which can be interpreted in three ways. All three of the following interpretations imply that the supplier cost function has decreasing differences in p and e (i.e. the cross-derivative of the cost function with respect to p and e is negative).

First, knowledge and information provided to the supplier through inspections could facilitate the supplier's learning to improve quality. Hence, an increase in plant inspection intensity should decrease the marginal cost of quality. Second, as agency theory would predict, monitoring in the form of a plant inspection is likely to encourage supplier effort to supply high quality because the detection of a deficiency in its production process could lead to a costly investment to improve the production process or else lose the opportunity of future orders. In this interpretation, an increase in p raises the expected penalty that the supplier incurs by choosing a low e . Finally, suppose that in addition to effort to improve product quality the supplier also can exert effort to hide bad elements of its production process. Hiding deficiencies may be more effective than trying to improve quality, especially if plant inspection intensity is low. High plant

inspection intensity or simultaneous adoption of supply inspection raises the benefit of efforts to improve quality relative to those to hide defects. This substitution effect should cause the supplier cost function to have decreasing differences in p and e .

We assume c is convex and twice differentiable, and $c_p > 0$, $c_{ep} < 0$, $c_e(0, p) < 0$ for $p > 0$ and $\lim_{e \rightarrow 1} c_e(e, p) = +\infty$.⁴ $c_p > 0$ and $c_{ep} < 0$ reflect our earlier discussion that plant inspections directly impose some costs on the supplier and the supplier cost function has decreasing differences in p and e . The last two assumptions and the convexity (i.e. $c_{ee} > 0$) ensure the unique interior solution unless $p = q = 0$.

Definition of Complementarity Let us now define formally what we mean by complements or substitutes. Recently, economists especially in the fields of organizational economics use the term *complements* “not only in its traditional sense of a relation between pairs of inputs but also in a broader sense as a relation among groups of activities” (Milgrom and Roberts 1990). Two activities are called *complements* if an increase in the level of one activity raises the marginal return to an increase in the other activities. The notion of complementarity can be extended to n activities. The profit or payoff function is called *supermodular* when all activities are complements with each other. More formally, consider a function $F(a_1, \dots, a_n)$ and let $a_k' > a_k$ for all k . Then, F is supermodular when F has non-decreasing differences in (a_1, \dots, a_n) . Namely, $F(a_1, \dots, a_i', \dots, a_j', \dots, a_n) - F(a_1, \dots, a_i', \dots, a_j, \dots, a_n) \geq F(a_1, \dots, a_i, \dots, a_j', \dots, a_n) - F(a_1, \dots, a_i, \dots, a_j, \dots, a_n)$ for any $i \neq j$. When this objective function is twice differentiable, this characterization is equivalent to the condition that the cross derivatives of the function are all non-

⁴ The subscripts e and p denote derivatives (e.g. $c_e = \frac{\partial c(e, p)}{\partial e}$, $c_{ep} = \frac{\partial^2 c(e, p)}{\partial e \partial p}$). We use the same notation throughout the paper.

negative. Suppose, in addition, F depends on parameters (τ_1, \dots, τ_k) and F is supermodular in $(a_1, \dots, a_n, \tau_1, \dots, \tau_k)$. Then, the optimal levels of those activities co-vary toward the same direction as parameters shift. See Topkis (1998), Milgrom and Shannon (1994), and Milgrom and Roberts (1990) for more comprehensive discussion of the framework.

We use this definition of supermodularity below to characterize whether p , q , and r are complements or supplements. We now characterize the equilibrium in two cases: when the buyer can commit to its supply inspection policy q and when it cannot.

No commitment case. In this case, after p is chosen and announced, the buyer and the supplier choose q and e simultaneously (*i.e.* they make decisions without knowing the other's actual choice). The first-order condition of the supplier problem (4) is

$$c_e(e, p) = T q^* \tag{5}$$

Then, by the implicit function theorem, there exists a function g such that the optimal choice of effort for the supplier is

$$e = g(p, T q^*) \tag{6}$$

and:⁵

$$\frac{de}{dp} = \frac{dg}{dp} = -\frac{c_{ep}}{c_{ee}} > 0 \tag{7}$$

Equation (7) implies that an increase in plant inspection intensity raises a supplier incentive to improve quality. Since the actual supply inspection intensity cannot affect the supplier's effort e , $de/dq = 0$. By substituting (6) into (3), the buyer's problem can be expressed by

$$\max \ E\pi_B = R - (1 - g(p))\{S_1(1-r)q + S_2(1-q)\} - C(p, q, r)$$

⁵ See, for example, *Mathematics for Economists* by Simon and Blume; although, all standard calculus textbooks discuss implicit function theorem. Note that, since $c_{ee} > 0$ and $c_{ep} < 0$ for all $e \in [0, 1)$ and $p \in [0, \bar{p})$, the function g is uniquely determined on $[0, \bar{p})$.

$$\text{subject to } 0 \leq p < \bar{p}, 0 \leq q < 1, \text{ and } 0 \leq r < 1. \quad (8)$$

where the second argument of $g, T q^*$, is omitted for convenience. The interior solutions for problem (8) should satisfy the following first order conditions:

$$\{S_1q(1-r) + S_2(1-q)\} \frac{de}{dp} = C_p^1(p) \quad (9a)$$

$$(1-g(p))\{S_2 - S_1(1-r)\} = C_q^2(q) \quad (9b)$$

$$(1-g(p))S_1q = C_r^3(r). \quad (9c)$$

These conditions indicate that the buyer will undertake inspection efforts and invest in buffer inventories up to the point where the marginal benefit of doing so equals the marginal cost. (9b) implies that, when $S_2 - S_1(1-r) < 0$, the buyer has no incentive to conduct supply inspection no matter how low is the cost of inspection. Hence, it chooses $q = 0$. This finding enables us to rewrite the problem in (8) as follows:

$$\begin{aligned} \max \quad E\pi_B' &= R - (1-g(p))\{S_2 - |S_2 - S_1(1-r)|^+q\} - C(p, q, r) \\ \text{subject to } &0 \leq p < \bar{p}, 0 \leq q < 1, \text{ and } 0 \leq r < 1 \end{aligned} \quad (8')$$

where $|x|^+ = x$ for $x \geq 0$ but $|x|^+ = 0$ for $x < 0$. Since the profit functions in (8) and (8') are identical when $S_2 - S_1(1-r) \geq 0$ or $q = 0$, and $q = 0$ is optimal when $S_2 - S_1(1-r) < 0$ for both problems, the two maximization problems are identical. With this objective function, we can show that the profit function in (8') is supermodular in $(-p, q, r)$. (See the proof for Proposition 1 in the Appendix.) This means that q and r are complements but p and q or p and r are substitutes. Using the “monotone method” framework developed by Topkis (1998) and Milgrom and Shannon

(1994), we can show that q and r decrease but p rises as the cost of inventory or supply inspection increases or the cost of plant inspection drops.⁶

Finally, note that, except where $E\pi_B'$ is not differentiable (i.e. at the points where $S_2 - S_1(1-r) = 0$),

$$\frac{\partial^2 \pi_B}{\partial p \partial q} = -|S_2 - S_1(1-r)|^+ \frac{de}{dp} \leq 0, \quad (10)$$

which implies that the degree of substitutability is increasing in S_2 and decreasing in S_1 . We state our result in Proposition 1.

Proposition 1: When the buyer cannot commit to its supply inspection policy, supply and plant inspections are substitutes. Moreover, buffer inventory holding is a complement to supply inspections but a substitute to plant inspections. The degree of substitutability between the two types of inspections is increasing in S_2 and decreasing in S_1 .

Proof is in the Appendix.

One can easily verify that the function in (8') is supermodular if $S_2 - S_1(1-r) \geq 0$.⁷

However, the function is actually supermodular over the entire domain. The impact of changes in S_1 and S_2 on the buyer choices is ambiguous because the function (8') is not supermodular in $(-p, q, r, S_1)$ or $(-p, q, r, S_2)$.

⁶ The old comparative statics method that involves manipulating Hessian matrices requires an additional assumption about convexity and rather messy computation. Strictly speaking, since the monotone method allows multiple optima, we have to clarify what we mean by “increase” and “decrease” for the set of solutions. Instead of introducing the lattice theory here, however, we simply assume that the solution is always unique. But, such assumption is just for simplicity and not necessary.

⁷ One only needs to show that all cross-derivatives are non-negative because π_B is assumed to be twice continuously differentiable. For example, $\frac{\partial^2 \pi_B}{\partial (-p) \partial q} = (S_2 - S_1(1-r)) \frac{de}{dp} \geq 0$.

Proposition 1 explains why there is a strong belief among researchers and practitioners that supply and plant inspections are substitutes. Our theory indicates that plant and supply inspections are substitutes in most industries because, as we describe below, in most industries buyers can not commit to the intensity of input inspections.

Commitment case. We now discuss what happens when the buyer can commit to its supply inspection policy. In this case, the supplier's optimal effort choice depends on the buyer's actual supply inspection intensity:

$$e = g(p, Tq) \quad (6')$$

and

$$\frac{de}{dq} = \frac{dg}{dq} = \frac{T}{c_{ee}} > 0. \quad (7')$$

Then, the buyer's profit function $\pi_B = R - (1 - g(p, Tq))\{S_1(1-r)q + S_2(1-q)\} - C(p, q, r)$ is not supermodular in the entire range. Hence, complementarity and substitutability can be defined only locally.

Since the buyer strategically choose q knowing its impact on e , (9b) is replaced by

$$(1 - g(p, Tq))\{S_2 - S_1(1-r)\} + \{S_1q(1-r) + S_2(1-q)\} \frac{de}{dq} = C^2_q(q). \quad (9b')$$

Note that, as is indicated by $\{S_1q(1-r) + S_2(1-q)\} \frac{de}{dq} > 0$, the ability to commit to its supply

inspection policy encourages the buyer to choose higher supply inspection intensity. It is because the buyer now takes into consideration the effect of higher supply inspection policy to induce a higher effort by the supplier. And, for $p > 0$ and $q > 0$,

$$\frac{\partial^2 \pi_B}{\partial p \partial q} = -\{S_2 - S_1(1-r)\} \frac{de}{dp} + \{S_1q(1-r) + S_2(1-q)\} \frac{d^2 e}{dpdq}$$

$$= - \{S_2 - S_1(1-r)\} \left(\frac{de}{dp} + q \frac{d^2e}{dpdq} \right) + S_2 \frac{d^2e}{dpdq}. \quad (11)$$

In this case, it is possible that p and q are complements around the interior solution. There are two sources of complementarity. First, when $S_2 - S_1(1-r) < 0$, an increase in q actually raises the total spillover cost for the buyer. Hence, $q = 0$ is *ex post* optimal. The buyer, however, may still want to commit to a positive q in order to give an incentive to the supplier to raise the product quality (i.e. if $\frac{de}{dq} = \frac{T}{c_{ee}}$ is large enough in (9b')). Therefore, $q > 0$ may be *ex ante* optimal. This may cause p and q to be complements because the increase in the total spillover costs generated by high supply inspection intensity is likely to raise the benefit of quality improvement by plant inspection. Second, when supply and plant inspections have complementary effects on the supplier's effort (i.e., $\frac{d^2e}{dpdq} > 0$), p and q will be complements if $S_2 - S_1(1-r)$ is low enough but not too low (so that the optimal $q \neq 0$). Note that

$$\frac{d^2e}{dpdq} = \frac{d}{dp} \frac{de}{dq} = - \frac{T}{c_{ee}^2} (c_{eee} \frac{de}{dp} + c_{eep}) = \frac{T}{c_{ee}^2} (c_{eee} \frac{c_{ep}}{c_{ee}} - c_{eep}). \quad (11)$$

Because $c_{ee} > 0$ and $c_{ep} < 0$, the sign of this cross derivative is indefinite and depends on c_{eee} and c_{eep} . In order for $\frac{d^2e}{dpdq}$ to be positive, the efficacy of plant inspections in encouraging the supplier effort to improve quality has to be increasing in the incentive given by supply inspections. Now, we summarize the result in Proposition 2.

⁸ Note that this cross derivative measures the direct interaction between p and q : how the marginal cost of q (p) changes when p (q) increases given r is constant. Alternatively, we can measure both direct and indirect interaction

Proposition 2: When the buyer can commit to its supply inspection policy, the buyer chooses higher supply inspection intensity than otherwise. Moreover, supply and plant inspections can be complements in the region where $S_2 - S_1(1-r) < 0$ and/or $\frac{d^2e}{dpdq} > 0$. When $\frac{de}{dp} + q \frac{d^2e}{dpdq} > 0$, the degree of complementarity is increasing in S_1 and decreasing in S_2 .

Proposition 2 naturally raises two questions. First, when can buyers commit to the intensity of supply inspections? We argue buyers can commit only when third parties, who can punish the buyer if it shirks, either regulate the buyer's inspection activities (e.g., FDA) or provide supply inspections and certify the input's quality.⁹ Third parties are needed because once the supplier's level of effort, e , is chosen, neither buyer nor supplier has an incentive to verify the supply inspection intensity. Second, in what contexts will $S_1(1-r) > S_2$ or $\frac{d^2e}{dpdq} > 0$? In the case of the former, the condition is likely to hold in those industries and for those inputs where internal spillovers are large than external spillovers and buffer inventories are perishable. Food, pharmaceuticals, cosmetics, chemicals, and other process industries are candidates. In the case of the latter, the second derivative is likely to be positive when knowledge sharing between buyer and supplier becomes more effective as the supplier allocates more resources to learning for quality improvement (i.e. $c_{ep} < 0$) or hiding aspects of the production processes is easier for suppliers. When q is low, it may be more effective for the supplier to allocate resources to hide

between p and q : how the marginal cost of q (p) should change when p (q) increases given r is chosen optimally. Because the qualitative implication is the same, we omit the latter analysis.

⁹ When the industry is heavily regulated, the reader might ask if profit maximization is the right problem to solve. But assuming that the buyer maximizes social welfare in choosing its inspection policy (under regulation) does not change our results. Simply interpret S_1 and S_2 as the spillover costs to the society and every argument we made holds for this social welfare maximization problem.

deficiencies of its production process than actually improve quality and thus $\frac{de}{dp}$ is low. As q increases, it will become more effective to shift more resources to improve quality and cooperate with the buyer's plant inspection, because hiding defects now will result in more bad inputs detected by the buyer. This argument implies $\frac{d^2e}{dpdq} > 0$. We now use these findings to develop predictions for biotechnology manufacturing.

3. BIOTECHNOLOGY

The manufacturing of pharmaceuticals combined with the FDA's tight regulatory control over production provides the context for us to generate and empirically test propositions from our general model. Biotechnology production typically involves batch manufacturing to turn raw materials into a pharmaceutical product. Successful production requires that each step be performed in a specific sequence and often for a specific amount of time. Once a batch has been started, it cannot be stopped and stored without a high risk of contamination or of interfering with a necessary chemical or biological reaction, which would result in the loss of the entire batch. Given this high cost of line stoppage and the difficulty in reworking on or recycling returned product, we can conclude that S_1 and T are high in this industry. One might assume that biotechnology firms keep a large supply of each input on hand to ensure that such stoppages do not occur. However, due to the perishable nature of many production inputs and to the substantial expense of purchasing and maintaining storage containers for buffer inventories, holding extensive buffer inventory, while sometimes done, is a costly practice. This implies that r may be kept low or zero despite the fact that the internal spillover costs are high. Hence, the pharmaceutical

industry may provide a case in which $S_2 - S_1(1-r) < 0$, one condition that enhances the likelihood that supply and plant inspections are complementary.

FDA regulatory oversight provides an institutional environment that introduces a number of issues that buyers must deal with when deciding on how to organize an exchange. Stringent and comprehensive requirements, set and administered by the FDA, must be met before a pharmaceutical product is approved for sale to the public, for the FDA carefully scrutinizes both the approval process and the ongoing manufacture of each pharmaceutical. Firms must provide to the FDA a “recipe” that contains the manufacturing processing steps, ingredients of the drug, and each supplier and alternative supplier, if one is chosen, who have been formally qualified to supply each input or component. The FDA does not inspect suppliers unless they are providing the active ingredient for a drug. Manufacturers must demonstrate to the FDA that their suppliers and recipe are with acceptable quality limits.

It is up to the pharmaceutical firm whether it would like to have only one approved source or multiple approved sources for a component, but the pharmaceutical firm, even when the inputs are purportedly identical, must submit for FDA approval data on each supplier’s input and its affect on the recipe.

Interviews with buyers at Biostar indicated that the FDA approval process for a new product or changes to an existing recipe is time-consuming and expensive and is not a “rubber stamp.” The process for approving an input typically involves submitting samples to the FDA for analysis and, potentially, audits of the supplier’s manufacturing process to ensure an effective quality system that complies with the pharmaceutical industry’s current Good Manufacturing Practices (cGMPs). This process can take anywhere from one to several months and may cost into the tens of thousands of dollars (depending upon the type of input and the history of the supplier

and the buyer with the FDA). The FDA approves the recipe and the firm's production process. The FDA does not mandate how the supplier produces the good, but they can hold up approvals if they feel the process is not well designed. The FDA does not mandate inspections at certain points in the production process nor does it dictate when biotechnology firms must inspect their suppliers but it does periodically evaluate a firm's manufacturing process for adherence to cGMPs.

The FDA has the ability to impose costs on the firm in several ways. First, the FDA determines how often and how rigorously to inspect the firm's final output. Second, the FDA determines how much documentation to require during periodic audits of the firm's production process. Third, the FDA determines how much data to require when the firm attempts to qualify new suppliers. But the FDA also has limited resources with which to examine firms engaging in the development and manufacturing of biotechnology and pharmaceutical products. Biostar's buyers stated that they believe the FDA forms opinions of firms over time as they interact with them; and firms with poor reputations (due to process problems, poor quality, poor documentation, etc.) tend to receive more scrutiny than firms with a history of high-quality processes and good documentation. This belief was echoed in discussions with individuals from other pharmaceutical firms as well as representatives from the FDA. Hence the loss of a good reputation with the FDA can greatly increase a firm's costs by increasing the amount of documentation it must produce to satisfy FDA regulators.

If an FDA audit determines that a firm should have scrapped a batch rather than sending it out to consumers, either the firm or the FDA can initiate a recall. Biostar's buyers generally believe that recalling a drug incurs large costs because of recall expenses, potential damage to their brand name capital, and subsequent potential lawsuits.

Biostar, as with all pharmaceutical firms, inspects some inputs and not others. When inspections are employed, they can differ by the mix of inspections (supply, supplier plant, or both), their frequency, and their intensity. For instance, supplier plant inspections, which are for the purpose of evaluating the quality level of a supplier's production process, vary by frequency of inspection. Interviews with Biostar's buyers indicate that supplier plant inspections can be as frequent as every year or as infrequent as every three to four years. These inspections are costly for the firm in terms of both travel expenses and commitment of employee time.¹⁰ The buyers believe that the probability of the input meeting a buyer's desired quality and the cost of verification generally increases with the frequency of inspections. The buyers indicated that such inspections do not guarantee delivery of the desired level of quality but do assess the quality of production processes that, if present, increase the probability that inputs will meet the buyer's desired quality level. In contrast, supply inspections largely vary by the extent to which the entire shipment of an input is tested. Inspection procedures vary from random testing to evaluation of the entire shipment. While the latter provides a higher probability of the input meeting the buyer's desired quality level, it also is more costly than random testing.

The specific industry context of the biotechnology industry allows us to generate clear predictions from our theoretical model. Given the fact that a firm's manufacturing process has to adhere to cGMPs and FDA requires that manufacturers follow the inspection procedures and their requirements on recipes they have submit and received approval for by FDA, we assume that suppliers know exactly how often and how rigorously their supplies are inspected before starting production. On the contrary, manufacturers have much greater flexibility in changing inspection

¹⁰ As the complexity of the supplier's production process increases, supplier site inspections can require from one to fifteen people.

intensity for ingredients and production material not included on recipes and thus there is of uncertainty about the actual intensity of supply inspections. Hence, the assumption for our commitment case applies to ingredients on recipes while our no-commitment case corresponds to inputs not on recipes.

Furthermore, earlier in this section, we already argue that $S_2 - S_1(1-r) < 0$ may not be uncommon in the pharmaceutical industry because of high internal spillover costs and inventory cost. Additionally, we argue that $d^2e/dpdq > 0$ is quite possible in this industry, another condition that make supply and plant inspections more likely to be complements. Note that techniques to improve quality are mostly proprietary in the pharmaceutical industry because technological innovation is rapid and production processes in this industry often are a source of competitive advantage, which encourages firms to maintain secrecy about production recipes. Under this circumstance, the supplier's disclosing its proprietary technology to the buyer and cooperating with plant inspections may be quite important in facilitating knowledge transfer from the buyer. Adopting a stringent supply inspection should provide the supplier with more incentives to do so. Moreover, with its complex proprietary technology, a supplier may manipulate what the buyer observes in plant inspections more easily in the biotechnology industry. The above discussion implies that the efficacy of plant inspections is likely to be enhanced by raising the intensity of supply inspections.

Before stating predictions for the biotechnology industry based on the results of the model, we want to address why we think managers would act according to equilibrium predictions. In the course of our interviews with Biostar personnel, we learned two things that gave us confidence in our ability to draw equilibrium predictions from the model. First, the director told us that Biostar had been in business for a while and had made many "mistakes" along the way about how they

manage suppliers and, in particular, how they choose inspection practices. After every supply management “problem,” he and his team would investigate what happened and would modify or develop policies for managing suppliers, which included choosing when and how intensely to inspect (factors that the director indicated were important aspects of the policies). The director felt that the frequency of problem occurrences had diminished substantially from the early days, which suggested to us that Biostar might be nearing an “equilibrium” set of policies. Second, the director went on to say that they were not yet to an equilibrium set of policies because during the past year Biostar had experienced problems with two suppliers. Nonetheless, far fewer problems had arisen compared to earlier periods in Biostar’s history. Moreover, the actual inspection policies for these two suppliers differed from what our model predicted and Biostar reportedly changed its inspection policies for these suppliers after the problems occurred (and after we collected our data) such that the new policies were much closer to our model’s predictions. Our interviews suggest that while Biostar may not yet be at the equilibrium set of policies, their policies are not chosen randomly and have been refined over the years and should be approaching an equilibrium.

To sum up our predictions for Biostar, Proposition 1 and 2 imply that the supply inspection intensity should be greater for inputs on recipes than those not on recipes all else being equal, and that supply and plant inspections may be complements for inputs on recipes but will be substitutes for those not on recipes. If the two types of inspections are complements, the degree of complementarity is increasing in S_1 and decreasing in S_2 . We now turn to an empirical evaluation of our propositions using data collected from Biostar.

4. DATA AND METHOD

4.1. Data

Testing our predictions requires detailed transaction level data on supply contracts. We gathered the data to test our theory from Biostar. Biostar's purchasing function is centralized and is comprised of 15 buyers organized into four groups: (1) capital equipment, maintenance and operating supplies, (2) construction purchasing, (3) general purchasing, and (4) raw materials for production. Capital equipment and maintenance contracts include procuring manufacturing equipment (e.g., fermenters, instrumentation) and maintaining this equipment.¹¹ Each year Biostar purchases supplies from more than 1,000 suppliers.¹² Because collecting data on every contract was impractical due to time and cost constraints, we collected data on 122 supplier contracts in use in 1996. The sample is stratified in the sense that we asked each buyer to select a set of contracts that represented the range of contracts they managed. We sought to achieve a sample that includes major and minor suppliers, as well as suppliers from each of the four groups in the purchasing area. Also, for our sample Biostar chooses among six different boilerplate contracts, each of which is chosen depending on the nature of the product and can be customized. These contracts range from one-page purchase orders to multi-page contracts specialized for various types of goods. The sample of contracts represents approximately 25% of the dollar value of Biostar's annual purchases and approximately 10% of its contracts. In essence, we under-sampled a large number of contracts for which Biostar's purchases amount to no more than a few hundred dollars a year for each contract. These under-sampled contracts are typically non-recurring spot

¹¹ Research and development alliances and equity joint ventures are not managed by the purchasing department and are not included in our study.

¹² We were unable to ascertain the exact number of suppliers, as this number will vary each year, but the total number of suppliers is between 1,000 and 1,500.

market exchanges. For each contract in our sample we interviewed the buyer and filled out a questionnaire on the attributes of the exchange. Data for the questionnaire came from both the buyers and the contracts themselves. While not a random sample, we believe the sample is representative of the firm's consequential transactions.

4.2. Dependent Variables

We begin by discussing the two inspection variables that serve as our primary dependent variables in the econometric analysis that follows. Summary statistics for all variables are displayed in Table 2. Inspection of purchased supplies, **InspectSupplies**, indicates the extent to which Biostar inspects purchased inputs for conformance to quality specifications when they arrive at Biostar's facilities. **InspectSupplies** ranges from 0, when there is no inspection of received material from the supplier, to 2, which indicates that each entire shipment was intensely inspected. The intermediate value indicates the each shipment is randomly inspected.

Inspection of a supplier's plant, **InspectPlant**, indicates the frequency that Biostar physically visits and inspects a supplier's facility. **InspectPlant** ranges from 0, when supplier facilities are not inspected at all, to 3, when supplier facilities are inspected annually or more frequently. Categories of 1 and 2 indicate that the supplier's facility is inspected less frequently than every two years and every 1 to 2 years, respectively. We note that the two types of monitoring are neither mutually exclusive nor completely overlapping. A cross-tabulation of **InspectSupply** and **InspectPlant** is shown in Table 3, and reveals that 49 exchanges (40%) had no inspections, 4 exchanges (3%) had only supplier plant inspections, 24 exchanges (20%) had only supply inspections, and the remaining 45 exchanges (37%) had both supply and supplier plant inspections.

A third dependent variable is buffer inventory, **Buffer**, is a dummy variable that is coded 1 if Biostar holds buffer inventories for the inputs provided by each supplier in the sample.

Otherwise, it is coded 0. Buffer inventory is held for 52 of the exchanges (43%) in our sample.

4.3. Exchange Conditions

Whether the input is on a recipe or not is indicated by two variables **OnRecipe_WithSub** and **OnRecipe_NoSub**. **OnRecipe_WithSub** is coded 1 if the input is listed on the FDA recipe with more than one approved supplier and **OnRecipe_NoSub** is coded 1 if the input is listed on the FDA recipe with only one approved supplier; otherwise, they are coded 0. Biostar has a general policy of having multiple suppliers, when available, for inputs on the recipe. Therefore, if a FDA recipe shows only one approved supplier, it is typically because no alternative supplier exists for these inputs. We distinguish those two cases because whether you have only one approved supplier or multiple suppliers affect spillover costs. The potential for harm to Biostar's reputation with the FDA and customers (S_2) is high for all ingredients on a recipe because it is only those inputs on the recipe that could affect the quality of the drug. Therefore, **OnRecipe_WithSub** and **OnRecipe_NoSub** should also be interpreted as proxies of S_2 . However, **OnRecipe_WithSub** reflects less the potential for production-related spillovers (S_1) because the existence of an FDA-approved alternative supplier presumably allows Biostar to quickly switch to another supplier, which provides a low cost means of minimizing the risk of supply disruptions.

We additionally capture the potential internal spillover effect S_1 by examining whether or not supply disruptions impose additional production costs to Biostar. As might be expected, a quantitative proxy for measuring this potential cost was unavailable, so we employed a qualitative proxy. **ProdCostImpact** is a binary variable coded 1 if the buyer indicated that undetected poor quality or late delivery of the input would have a large financial impact (greater than \$10,000) on

production cost, else 0. This variable was developed in conjunction with Biostar’s director of manufacturing, who indicated that the production cost impact of undetected poor quality or late delivery of the input was bi-modally distributed—it either had a substantial impact on production cost or not. We investigated this view with buyers by informally exploring how their responses to our questions might differ if we doubled or halved the threshold. Their answers were robust to our queries. While endogeneity is a potential concern because the buyer’s response might be influenced by the inspection regime chosen, we think that this problem is minimal because of the apparent bi-modal distribution of the impact this variable attempts to codify.

4.4. Control Variables

Contract customization, **Custom**, is a five-point Likert scale that identifies what percent of a contract is customized from a standard “boilerplate” contract.¹³ Custom ranges from 0, which indicates no customization, to 5, which indicates complete customization. We asked the buyers for estimates of the extent to which a contract was customized, and verified many of these by reviewing the actual contract. We coded the addition of a price schedule to a boilerplate contract as *zero* for customization because all boilerplate contracts require a price schedule. Buyers reported that quality specifications are one of the principal reasons behind customizing contracts.

Contract duration, **Duration**, is a measure of the length of the contractual agreement in years. In our sample, Duration ranges from 0 for spot market contracts to 15 years. Most of the agreements in our sample range from 0 to 3 years.

SupplyInspectCost is a categorical variable that captures the cost of inspecting supplies upon receipt. While some variables are inspected inexpensively (e.g., with a quick visual inspection), others are very costly to fully inspect (e.g., with laboratory and/or destructive testing

required to verify desired quality levels). SupplyInspectCost is a measured by a Likert scale ranging from 1 for an input that is inexpensive to fully inspect, to 7 for an input that is costly to fully inspect.

Distance is a categorical variable that is one of two proxies used to capture the cost of inspecting a supplier's facility. Distance is a categorical variable that captures the distance of the supplier's facility from Biostar. Presumably, supplier plant inspection costs increase with distance. Distance categories are 1 corresponding to (0-50 miles), 2 corresponding to 50 to 200 miles, 3 corresponding to 200 to 1,000 miles, 4 corresponding to 1,000 to 3,500 miles, and 5 corresponding to over 3,500 miles. The Director of Purchasing at Biostar helped construct the scale to represent increasing levels of cost. For instance, a value of 1 represents a one-day drive on up to a 5, which requires a trip to Europe or Asia.

Complex is a second variable, measured on a 7-point Likert scale, to proxy the cost of inspecting supplier facilities by evaluating how difficult it is to verify the quality of the supplier's production process. Buyers believe that complex production processes are more time-consuming and costly to fully inspect than simple processes. The Director of Purchasing helped construct this proxy and evaluate the complexity of supplier production processes. Complex ranges from 1 for a very simple production process to 7 for very complex production processes.

Unfortunately, neither SupplyInspectCost, Distance, nor Complex provides a good measure of marginal cost of inspection. Given various constraints, we were unable to develop questions that would accurately capture marginal cost of inspections. Instead, SupplyInspectCost, Distance, and Complex capture total cost of inspection, which, while sufficient to provide proxies

¹³ Customization is measured independent of which of the six boilerplates was selected.

for inspection cost, limits our ability to examine marginal cost implications on the choice of inspection practices.

Breadth is a polychotomous variable that indicates the number of different types of products or product lines purchased from a supplier (0-a single product, 1-a single product line, and 2-multiple product lines). The wider the breadth of products purchased from a supplier, the greater Biostar's ability to retaliate against a supplier for shirking (de Figueiredo and Teece 1996), which might lessen Biostar's need to inspect supplies or supplier plants.

Relationship is the number of years that Biostar has had an ongoing relationship with the supplier (i.e., the number of years Biostar has bought inputs from the supplier). A striking aspect of our sample is that contract duration in almost all instances was three years or less, whereas the average length of a commercial relationship in our sample is 9 years (see Table 2). Such long relationships allow us to evaluate how an antecedent of relational governance affects the adoption of inspection practices.

Sales is the log of Biostar's annual purchases from the supplier. Sales controls for any relationship between the volume of supply purchased and the adoption of inspection practices.

Correlations are generally small to moderate in magnitude, which suggests that multicollinearity does not raise a problem for our estimation.

4.5. Econometric Specification

The above discussion provides sufficient insight to help us construct a reduced-form econometric specification to evaluate the relationship between the intensity of plant inspections, p , and the intensity of supply inspections, q . We specify a reduced-form econometric model for testing these relationships with the following:

$$q^* = \mathbf{X}'\boldsymbol{\beta}_1 + \gamma_{11}Z_{1A} + \gamma_{12}Z_{1B} + \gamma_{13}Z_2 + \gamma_{14}C_q + (\delta_{11} + \delta_{12}Z_{1A} + \delta_{13}Z_{1B} + \delta_{14}Z_2)p + \varepsilon_1 \quad (13a)$$

$$p^* = \mathbf{X}'\boldsymbol{\beta}_2 + \gamma_{21}Z_{1A} + \gamma_{22}Z_{1B} + \gamma_{23}Z_2 + \gamma_{24}C_p + (\delta_{21} + \delta_{22}Z_{1A} + \delta_{23}Z_{1B} + \delta_{24}Z_2)q + \varepsilon_2 \quad (13b)$$

$$\text{Prob}(r=1) = \mathbf{X}'\boldsymbol{\beta}_3 + \gamma_{31}Z_{1A} + \gamma_{32}Z_{1B} + \gamma_{33}Z_2 + \gamma_{34}C_r + \varepsilon_3 \quad (13c)$$

where \mathbf{X} is a vector of control covariates; C_i are the marginal cost of each practice and are used to identify each equation; Z_{1A} , Z_{1B} , and Z_2 are *OnRecipe_WithSub*, *OnRecipe_NoSub*, and *ProdCostImpact*, respectively; ε_i are normally distributed and independent errors for each equation; and $r = 1$ if buffer inventory is greater than 0 else $r = 0$. While q^* and p^* are unobserved, we do observe ordered categories such that $q = 0$ if $q^* \leq 0$, $q = 1$ if $0 < q^* \leq \mu_s$, and $q = 2$ if $\mu_s < q^*$ and such that $p = 0$ if $p^* \leq 0$, $p = 1$ if $0 < p^* \leq \mu_{p1}$, $p = 2$ if $\mu_{p1} < p^* \leq \mu_{p2}$, and $p = 3$ if $\mu_{p2} < p^*$. Hence, we use an ordered Probit procedure to estimate equations (13a) and (13b).

The coefficients $\gamma_{.1}$ and $\gamma_{.2}$ are central to evaluating the impact of buyer commitment. Both coefficients should be positive because supply inspection intensity should be higher for inputs on recipes.

The critical coefficients for evaluating substitutability and complementarity are $\delta_{.1}$, $\delta_{.2}$, $\delta_{.3}$, and $\delta_{.4}$. Positive coefficients indicate an increase in complementarity while negative coefficients predict an increase in substitutability. Our first proposition predicts that $\delta_{.1}$ is negative, which implies that q and p are substitutes for inputs not on recipes. Our second proposition predicts that $\delta_{.2}$ and $\delta_{.3}$ are positive but $\delta_{.2}$ should be larger than $\delta_{.3}$, which implies that q and p are complements for the inputs on recipes and the complementarity is greater when internal spillovers are large. Both propositions indicate that $\delta_{.4}$ is positive because the degree of complementarity (substitutability) is greater (smaller) when internal spillovers are large.

Estimating equations (13a), (13b), and (13c) are challenging because our variables are categorical or binary and we have a simultaneous set of non-linear equations in which the nonlinearity arises in the endogenous terms (see Greene, 1997, p.719). To simplify our empirical analysis we take advantage of an empirical regularity in the data. The cross-tabulation of q and p

shown in Table 3, reveals four of our observations involve only monitoring supplier plants. This small number is prima facie evidence that p is employed almost only in addition to q. While at first glance this regularity may suggest that p and q are complements, it remains the case that p may allow for the use of lower cost and less rigorous input inspections and thus q and p may still be substitutes. The structure of the data allows us to specify a two-stage estimation procedure in which, after omitting the interaction terms, we first estimate equation (13a). We then construct an estimate of the expected level of q, substitute it into (13b) along with constructed interaction terms, and estimate p for only those observations where q is non-zero. Thus, the model's first stage evaluates adoption of q and the second stage evaluates adoption of p given that q has been chosen. This assumption implies that the error structure for (13a) is independent of (13b).

5. RESULTS

Table 4 reports regression results. In the first column of Table 4, Model 1 displays the results of an ordered Probit analysis of the determinants of inspecting supplies. Model 2 analyzes supplier plant inspection without including any interaction terms. Model 3 adds interaction terms based on our estimate of q from Model 1. Model 4 displays the results of a Probit analysis of control variables that might influence when Biostar holds buffer inventory and Model 5 displays results of the Probit analysis including our variables that examine exchange attributes.

Model 1 provides explanatory power with a pseudo R^2 of 0.30. The control variables largely are insignificant, with one exception. The coefficient for Custom indicates that additional contract customization corresponds to more inspection of supplies ($p < 0.05$).¹⁴ Interviews with buyers indicate that this relationship is likely a result of customization associated with the

incorporation of detailed quality specifications into the contract. As for the variables measuring different types of exchange conditions, we first note that the coefficients for OnRecipe_NoSub ($p < 0.10$) and OnRecipe_WithSub ($p < 0.01$) both lead to greater levels of supply inspection, which is consistent with Proposition 2. The fact that the coefficient for OnRecipe_NoSub, which captures potential spillover effects of S_1 , is smaller than that for OnRecipe_WithSub is consistent with the first-order effects of S_1 and S_2 expressed by (9b). Namely, the buyer has more incentive to conduct supply inspections when the cost of external reputation spillovers (S_2) is larger than the expected cost of internal production-related spillovers ($S_1(1-r)$). Moreover, the coefficient for ProdCostImpact, capturing only internal spillovers, is not significant.

Columns 1b and 1c report results from varying specification of the error structure, which anticipates concerns over certain limitations in our data. For instance, our findings could be driven by persistent differences in buyers and the way each negotiates and writes contracts. Alternatively, our findings could be driven by variation in choice of boilerplate contract, of which there are six. To evaluate such concerns, we re-estimated each model by allowing for clustering of errors by buyer and by contract type, respectively. These checks indicate that our findings generally are robust to clustering by buyers, although OnRecipe_NoSub is no longer weakly significant. Clustering by contract type causes a number of additional control variables to be significant while Custom and OnRecipe_NoSub are insignificant. Combined, these alternative specifications indicate that our main results are robust.

Model 2 shifts our analysis from the inspection of supplies to the inspection of the supplier facilities. The model has a pseudo R^2 of 0.353. Coefficients for all control variables except

¹⁴ We realize that Duration and Custom may be chosen contemporaneously with inspection practices. Thus inclusion in a reduce-form analysis might lead to biased estimates. We re-estimated all five models omitted Duration and Custom and found qualitatively equivalent results as the ones reported in Table 3.

Distance are insignificant. The coefficient for Distance ($p < 0.05$) is significant and positive, indicating that distance, intended to be a proxy for inspection cost, influences the intensity of plant inspections in the opposite direction. Long distance presumably encourages plant inspection because it is more difficult to observe the quality performance of a supplier at a distance (e.g. reputation among other buyers). In other words, distance may be a proxy for asymmetric information rather than inspection cost. Coefficients for OnRecipe_NoSub ($p < 0.01$), OnRecipe_WithSub ($p < 0.01$), and ProdCostImpact ($p < 0.01$) all are positive and significant, which implies that higher levels of each lead to more frequent supplier plant inspections. These findings may indicate that both types of spillovers—production-related and reputational—increase plant inspections, which look consistent with their predicted first-order effects on p . The first-order condition for p in (9a) indicates that increases in both types of spillovers raise the return to the supplier effort, which in turn increases the benefit of plant inspections. Our specification checks on Model 2, reported in Columns 2b and 2c, indicate that our findings generally are robust.

Model 3 adds to Model 2 the interaction terms that are key to evaluating Proposition 1 and 2. Model 3 has a pseudo R^2 of 0.383. The possibility that the interaction terms are not significant factors in explaining plant inspections is rejected at approximately the 90% confidence interval ($\chi^2 = 7.310$), which indicates that the added variables enhance the model's explanatory power. The coefficient for our control variables are little changed.

The addition of interaction terms affected coefficient estimates for the exchange conditions. The coefficients for OnRecipe_NoSub and OnRecipe_WithSub are now insignificant compared to Model 2, although, as described below, coefficients for their interaction terms are significant. The coefficient for ProdCostImpact is significant ($p < 0.01$) and positive like in Model 2 but has a significantly larger magnitude now that interaction effects are considered.

The interaction terms provide support for our theory on the effect of commitment and spillover costs on the relationship between the two types of inspection practices. The coefficient for `InspectSuppliesHat`, which measures the impact of supply inspection on plant inspection for those inputs that are not included on recipes, is negative, implying that they are substitutes, but insignificant. The coefficients for the interaction terms of `InspectSuppliesHat*OnRecipe_NoSub` ($p < 0.10$) and `InspectSuppliesHat*OnRecipe_WithSub` ($p < 0.05$) are both positive and greater than the coefficient for `InspectSuppliesHat`, indicating that supply inspections and supplier plant inspections are complements for inputs on the FDA recipe. Moreover, the coefficient for `InspectSuppliesHat*OnRecipe_NoSub`, which captures the cost of production-related spillovers, is greater and more significant than `InspectSuppliesHat*OnRecipe_WithSub`. This implies that the degree of complementarity is increasing in S_1 , providing further support for Proposition 2. It is interesting to note that while `ProdCostImpact` is positive and significant, the interaction between `InspectSuppliesHat` and `ProdCostImpact` is insignificant, which, counter to the prior finding, does not provide support for Proposition 2. Our specification checks on Model 3 and reported in Columns 3b and 3c indicate robustness to our findings.

Model 4, with a pseudo R^2 of 0.092, provides some explanatory power for the use of buffer inventories. The coefficients for `Relationship` ($p < 0.05$) and `Sales` ($p < 0.05$) are positive and significant, which implies that inputs provided by suppliers with whom Biostar has a long-term relationship and inputs that represent a large annual dollar volume correspond to the holding of buffer inventories. The coefficient for `Custom` is highly significant ($p < 0.01$) and negative. This result may imply that holding buffer inventories for customized inputs is more costly than for standard inputs because the former cannot be used for any other purposes.

Model 5 adds to Model 4 our exchange attribute variables. Model 5 has a pseudo R^2 of 0.3875. With the addition of these variables, only the coefficient for Custom, which has the same sign and magnitude, remains significant ($p < 0.01$) among the control variables.

Although OnRecipe_NoSub was specified in our model, it predicted Buffer perfectly for the 18 observations where OnRecipe_NoSub equals 1. Hence, we conclude that OnRecipe_NoSub indeed is a significant predictor of holding buffer inventory. Note that these 18 observations are dropped during the estimation of Model 5, which is now based on 104 observations compared to 122 observations for Model 4. The coefficients for OnRecipe_WithSub ($p < 0.01$) and ProdCostImpact ($p < 0.05$) are both significant and positive and lead to a greater probability of holding buffer inventory. To understand these results, recall that OnRecipe_NoSub and OnRecipe_WithSub are positive, and weakly significant and significant, respectively, in Model 1 implying that the buyer's commitment to its supply inspection policy raises the intensity of the inspections. Also note that q and r are complements no matter what relationship p and q have. When taken together, they imply that more intense supply inspections encourage the buyer to hold more buffer inventory for those inputs that are on the FDA recipe. The results that OnRecipe_NoSub and ProdCostImpact have more significant explanatory power for Buff than for InspectSupplies are consistent with the first-order conditions in (9b) and (9c). A higher cost of production-related spillovers (S_1) necessitates the possession of high buffer inventory but will discourage supply inspections. Our specification checks on Models 4 and 5 and reported in Columns 4c, 4d, 5c, and 5d, indicate that our findings generally are robust.

6. DISCUSSION

We begin our discussion with the limitations of our empirical analysis. Our data sample is stratified and not random, which may bias our results. The stratified sample was necessary

because of the difficulty and cost in collecting data on all contracts. Although we did not randomly select the contracts we studied, our reliance on each buyer to select a representative sample should limit bias unless all buyers are subject to systematic biases, which we believe is unlikely. The fact that our results did not substantially change when we allowed for errors to be clustered by buyer provides at least some comfort that our results were not driven by buyer-induced biases.

Another limitation stems from our proxies for the cost of inspections. Given data collection constraints we were unable to develop proxies that captured marginal cost, which limits our ability to assess the effect of the marginal cost of inspections on the choice of inspection practices. Moreover, we were unable to develop any proxy for the cost of holding buffer inventory and this is why we relied on a reduced-form econometric model.

These limitations notwithstanding, our empirical analysis of Biostar's inspection and buffer inventory practices nonetheless provides broad support for our theoretical model. First, the paper shows that the buyer's ability to commit to its inspection policy significantly affects the suppliers' incentives and thus the optimal choices of the buyer's inspection intensity and frequency. This finding may imply the importance of government regulation or industry self-regulation to improve quality in the industry where supplier turnover is high.

This paper calls into question the unqualified conventional wisdom of many popular press books in supply-chain management that buyers should always substitute away from supply inspections toward supplier plant inspections. Walton (1986:35) states that "quality comes not from inspection [of supplies] but from improvement of the process." The third of Deming's famous fourteen points directs firms to cease dependence on mass inspection of supplies. Likewise, the Six Sigma quality process also urges firms to build quality into the process to the

point that they can eliminate inspection of supplies (Harry and Schroeder 2000: 35). Inspection of the supplier's plant is a way for the buyer to help the supplier build quality into their process. Our model shows that these two inspection practices may be more complementary in regulatory environments. Indeed, our parameter estimates for interaction terms in Model 3 indicate that dp/dq is positive and thus supply and supplier plant inspections are complements for supplies that are regulated by FDA in the biotechnology industry.

Our model also helps explain why plant and supply inspections are used more as substitutes in most industries. They are indeed substitutes in the industries where buyers are unable to commit to their supply inspection policy. Furthermore, even when buyers can commit, plant and supply inspections become complements only when internal spillover costs and inventory costs are sufficiently high and/or the two types of inspections have complementary effects on the supplier effort (i.e. $d^2e/dpdq > 0$). Products and production technologies differ by industry, which implies that potential internal spillover costs and inventory costs vary systematically by industry. For instance, internal spillover costs are likely to be greater in process-related industries such as chemical, biological, and pharmaceutical production than in than in most assembly-based manufacturing industries because the former often uses batch manufacturing, which requires the entire batch to be thrown away if contaminated by low-quality inputs. In contrast, low-quality inputs or late delivery of inputs can disrupt assembly-based industries to a smaller degree and with a much lower cost because such assembly-based products can be reworked on a unit basis and thus can be corrected, typically at low cost, even in a just-in-time production process. Thus, our theory predicts that in these latter industries plant and supply inspections are more likely to be substitutes.

Second, potential spillover costs, both internal and external, have a strong influence on a buyer's adoption of supply and supplier plant inspections and of buffer inventories. Our finding is similar to Nickerson and Silverman's (2003) research on whether trucking firms employ company drivers or hire independents. They argued that when late delivery of a shipment would lead to either devaluation of the carrier reputation (external costs) or increased shipping costs due to missed connections in a hub-and-spoke logistics system (internal costs), carriers used company drivers instead of owner-independents. Unlike trucking, for which remote monitoring was technically unfeasible and hence prohibitively costly until recently, supply and supplier plant inspections in biotechnology are costly but not prohibitively so. Conditional on continuing to use the market, measurement costs that are not prohibitive lead to monitoring and verification efforts instead of vertical integration as in trucking. Our paper adds to this measurement cost literature by highlighting the interaction of potential spillover costs and measurement costs in structuring the organizational supports, in this case inspection practices and the holding of buffer inventory. This finding also highlights that procurement management is an important strategic activity. Activities are strategic if they affect the ability of the firm to gain or sustain a competitive advantage over rivals. To our knowledge, inspection practices have never been discussed in a strategic context. They are only mentioned in books devoted to quality or operations management. Most people view inspection practices as little more than a standard operational issue primarily impacting efficiency and with little more strategic importance than good work instructions or a safe factory floor. Our model and results, however, show that inspections have strategic value because they are a part of the firm's systematic response to its market and regulatory environment as well as its technology and could impact the firm's competitive position by managing risks and costs. Without appropriate choices of inspection practices and buffer

inventory, firms run the risk of either devaluing expensive and difficult to build reputations or incurring high internal costs and expensive inspection or buffer inventory costs, which could erode if not destroy a firm's competitive position. Typically activities associated with operations, such as inspections, are considered more important for firms following a low cost strategy, but we show that they are also critical to firms trying to follow a differentiation strategy as well. Our results also suggest that firms with a differentiated market position may have higher levels of reputational spillovers because of the differentiating brand image than firms in the same industry following a low cost strategy and thus may more likely to view the two types of inspection as complementary. Excessive inspection could make low cost firms uncompetitive, while inadequate inspection could cost differentiated firms their market position. Firms can't just benchmark against other firms in their industry; they must calculate their own potential internal and external spillover costs to determine their unique optimal levels of plant and supply inspections that are needed to protect their market positions.

Appendix

Proof of Proposition 1

We show that $E \hat{\pi}_B = R - (1 - g(p))\{S_2 - |S_2 - S_1(1-r)|^+ q\} - C(p, q, r)$ is supermodular in $(-p, q, r)$. Since you can easily verify that the cross-derivatives of $E \hat{\pi}_B$ with respect to $(-p, q, r)$ are all non-negative in $\{(p, q, r) \mid S_2 - S_1(1-r) \geq 0\}$ or in $\{(p, q, r) \mid S_2 - S_1(1-r) < 0\}$ where $E \hat{\pi}_B$ is differentiable, we only need to check the behavior of $E \hat{\pi}_B$ across the plane $S_2 - S_1(1-r) = 0$.

Namely, for any $p' > p$, $q' > q$, and $r' > r$ such that $S_2 - S_1(1-r') > 0 > S_2 - S_1(1-r)$, show

$$E \hat{\pi}_B(p', q, r') - E \hat{\pi}_B(p, q, r') \leq E \hat{\pi}_B(p', q, r) - E \hat{\pi}_B(p, q, r)$$

$$E \hat{\pi}_B(p, q', r') - E \hat{\pi}_B(p, q, r') \geq E \hat{\pi}_B(p, q', r) - E \hat{\pi}_B(p, q, r).$$

Actually,

$$\begin{aligned} E \hat{\pi}_B(p', q, r') - E \hat{\pi}_B(p, q, r') &= (g(p') - g(p))[S_2 - \{S_2 - S_1(1-r')\}q] - C(p', q, r') + C(p, q, r') \\ &< (g(p') - g(p))S_2 - C(p', q, r') + C(p, q, r') = E \hat{\pi}_B(p', q, r) - E \hat{\pi}_B(p, q, r) \end{aligned}$$

$$\begin{aligned} E \hat{\pi}_B(p, q', r') - E \hat{\pi}_B(p, q, r') &= (1 - g(p))\{S_2 - S_1(1-r')\}(q' - q) - C(p, q', r') + C(p, q, r') \\ &> -C(p, q', r') + C(p, q, r') = E \hat{\pi}_B(p, q', r) - E \hat{\pi}_B(p, q, r). \end{aligned}$$

This concludes the proof.

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Table 1: Definition of terms.

S_1	The internal spillover cost, which is incurred if the input arrives and turns out to be bad and results in loss of work-in-process, switch over costs as production capacity is shifted to another product, or stoppage of production.
S_2	The external spillover cost (i.e., cost of product recalls, litigation, brand and reputation diminution) if the input is in fact bad but nonetheless is used to produce an output that is bad and sold into the market place, assuming that consumers eventually discover that the product is bad.
I_s	The signal, positive (g) or negative (b), resulting from a supply inspection.
g	A signal that an input was good based on a supply inspection.
b	A signal that an input was bad based on a supply inspection
g	An input proved to be good.
b	An input proved to be bad.
p	The intensity of plant inspections
q	The intensity of supply inspections (the likelihood of receiving a correct signal from the supply inspection).
e	Supplier effort
r	The level of buffer inventory.
R	Expected buyer's revenue
$C(p, q, r)$	The sum of the cost of effort for plant and supply inspection and the cost of holding buffer inventory.
$E\pi_B$	The buyer's expected profit.
T	The supplier's penalty when a bad input is returned.
q^*	The supplier's expectation of the buyer's intensity of supply inspections.
B	The buyer.

Table 2: Descriptive Statistics

	Mean	Std Dev	Min	Max	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1 InspectSupplies	0.62	0.58	0	2	1													
2 InspectPlant	0.63	0.85	0	3	0.51	1												
3 Buffer	0.43	0.5	0	1	0.47	0.71	1											
4 Custom	18.4	34.89	0	100	0.26	-0	-0.2	1										
5 Duration	1.33	2.14	0	15	-0	-0	-0	0.51	1									
6 OnRecipe_NoSub	0.15	0.36	0	1	0.16	0.34	0.47	-0.2	-0.1	1								
7 OnRecipe_WithSub	0.22	0.42	0	1	0.42	0.49	0.41	-0.1	-0.1	-0.2	1							
8 ProdCostImpact	0.47	0.5	0	1	0.37	0.54	0.47	0.16	0.18	0.31	0.33	1						
9 Breadth	1.23	0.61	0	2	-0.1	0.08	0.08	-0.2	-0.1	0.15	0.06	0.1	1					
10 Relationship	9.07	4.54	0	20	0.18	0.21	0.17	0.02	-0.1	0.32	0	0	0.2	1				
11 Sales (log)	5.46	0.88	2.7	7.7	0.26	0.12	0.06	0.51	0.37	0.11	-0.1	0.3	0	0	1			
12 Distance	2.61	1.49	1	5	0.18	0.44	0.46	-0.2	-0.2	0.33	0.27	0.3	0.1	0.2	-0.1	1		
13 Complex	3.81	1.91	1	7	0.12	0.26	0.31	0.23	0.19	0.26	0.12	0.4	0	0.1	0.41	0.4	1	
14 SupplyInspectCost	3.34	1.67	1	7	0.45	0.39	0.46	0.21	0.15	0.28	0.33	0.5	0	0.2	0.26	0.4	0.6	1

N = 122

Table 3: Cross Tabulation of q and p

InspectSupplies	InspectPlant				Total
	0	1	2	3	
0	49	1	3	0	53
1	21	22	20	0	63
2	3	0	1	2	6
Total	73	23	24	2	122

Table 4: Regression Results: Including Test for Clustering on Buyers and Contract Types

Variables	1 (a) (b) (c)			2 (a) (b) (c)			3 (a) (b) (c)			4 (a) (b) (c)			5 (a) (b) (c)		
	InspectSupplies			InspectPlant			InspectPlant			Buff ¹			Buff ¹		
Constant										-2.290 *	*		-2.050 *	†	*
Breadth	-0.292		*	-0.295			-0.253			-0.105			-0.350		*
Relationship	0.380			0.057	†		0.070	*		0.061 *	†	*	0.025		
Sales	0.338			0.311		**	0.395		†	0.345 *			0.205		
Custom	0.010 *	**		-0.001			0.006			-0.015 **	*	*	-0.018 **	**	**
Duration	-0.126 †	†	*	0.019			-0.058			0.061			0.130 †	†	
SupplyInspectCost	0.178 †		*												
Complex				-0.056			-0.061								
Distance				0.238 *	†	**	0.255 *	*	**						
OnRecipe_NoSub	0.675 †			1.070 **	**	†	-2.642	†	**						
OnRecipe_WithSub	1.463 **	**	**	1.587 **	**	*	0.500						1.702 **	**	**
ProdCostImpact	0.159			1.020 **	**	**	2.194 **						0.773 *	*	**
InspectSuppliesHat							-1.725								
InspectSuppliesHat*No_Sub							5.536 †	**	**						
InspectSuppliesHat*Sub							3.442 *		*						
InspectSuppliesHat*ProdCostImpact							-1.436								
Pseudo R ²	0.304			0.353			0.383			0.092			0.375		
Log Likelihood	-72.331			-79.633			-75.978			-75.833			-41.518		
N	122			122			122			122			104		

One-tailed test for hypothesized variables and two-tailed test for control variables.

** 99% Confidence Interval

* 95% Confidence Interval

† 90% Confidence Interval

¹ OnRecipe_NoSub could not be estimated because it perfectly predicts holding buffer inventory, which results in the loss of 18 observations.

(a) Initial results

(b) Results for allowing correlation among buyers

(c) Results for allowing correlation among contract types

