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Supply Diagnostic Incentives under Endogenous Information Asymmetry

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This paper develops a dyadic supply chain model with one buyer who contracts the manufacturing of a new product to a supplier. Due to the lack of experience in manufacturing, the extent of supply risk is unknown to both the buyer and supplier before the time of contract. However, after the contract is accepted, the supplier may invest in a diagnostic test to acquire information about his true reliability, and use this information when deciding on a process improvement effort. Using this setting, we identify both operational and strategic benefits and costs of the diagnostic test. Operationally, it helps the supplier to take the first-best level of improvement effort, which would increase efficiency of the total supply chain. Strategically, it enables the buyer to reduce the agency costs associated with implementing process improvement on the supplier. Besides these benefits, diagnostic test increases the degree of information asymmetry along the supply chain. This in turn provides the supplier with proprietary information, whose rent would be demanded from the buyer in equilibrium. Benefit-cost analysis reveals two key factors in determining the value of diagnostic test: (i) degree of endogenous information asymmetry between supply chain firms, and (ii) the relative cost of a diagnostic test with respect to process improvement cost. Our results indicate that when both are high, the mere presence of a diagnostic test can result in less reliable supply chain. This implies that when incentives are not properly aligned, information asymmetry amplified due to diagnostic test neutralizes all its benefits.

Key words: supply risk; contract design; information acquisition; diagnostic test; endogenous information asymmetry
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1. Introduction

When a new product project fails, the failure is usually blamed on culprits such as tough competition, insufficient promotion and advertising strategies or weak market research. That said, the results from a survey of 252 new product launches at 123 firms reveal equally important factors pertaining to the (mis)management of some of the key supply-side processes needed for a successful new product launch (Cooper 1988). Among the most crucial supply-side processes in a new product introduction stands out trial/test production, which serves as an early warning system that would help to detect potential disruptions and provide invaluable information to the manufacturing system to respond (Handfield et al. 1999, Primo and Amundson 2002). However, in more than half of the new product projects studied in the above survey, the diagnostic processes are either conducted improperly, or not conducted at all.

Mis-management of diagnostic activities in new product manufacturing not only leads to supply side disruptions, such as yield problems, inflexibility in production capacity, lead-time variability and long set-up time, but also it may lead to huge loss on the demand side, such as customer goodwill or market share loss due to a fast follower. For example, the IBM's $150 million first-quarter loss in 2004 is attributed mostly to the yield problems that are realized when the company introduced an untested process technology to manufacture a new semiconductor-based product at its microelectronics plant in East Fishkill, New York (Tang and Tomlin 2008). Indeed, due to the heavy use of contract manufacturing among OEMs (Clark 1989, Helper 1991), the diagnostic tests become important not only for in-house operations but also for the out-sourced ones. During the launch of some of the popular ThinkPad models (T20 and A40), IBM had to suffer a huge backorder in the sales that persisted over a month due to some of its key component suppliers' (particularly the suppliers of DVD and CD-RW parts) inability to cope with the production problems surfaced during initial production stages (Sheffi 2007).

These examples spotlight on one hand how untested supply chain systems can directly result in opportunity costs on the supply side of the chain, and on the other hand, when conducted properly, how the diagnostic test can create a competitive edge for the time-critical supply chains. The main focus of this study is therefore to explore the benefits and potential consequences of such a test production on the supply chains that face with unique challenges due to the new product development. Particularly, in this paper, we restrict our attention to diagnostic tests that are taken on the supply side and define them as "any costly effort, either conducted directly by the supplier or subsidized by the buyer, to identify the nature and source of a potential random disruption in the supplier's production process."

Usually, in the context of contract manufacturing, the diagnostic test is implemented via a contractual business model between supply-chain parties known as "Build-To-Specification" (BTS) or "Black-Box Engineering" in product development literature (Karlsson et al. 1998, Petersen et al. 2005). According to this model, the buyer generates overall requirements on product functionality and performance, and cost targets, then communicates this information to the supplier, who carries out detailed *engineering* and *testing* (Totaro 2011). Under BTS agreement, the supplier has the sole responsibility to take a costly diagnostic test to learn the extent of its supply disruption he may face due to the newness of the product and its production process, and use the results to fine-tune both the product specifications and its production process for the final production period.

As with the growing trend in outsourcing, BTS relationship becomes quite popular in development and manufacturing of new products, particularly, in the defense industry. For example, Military Aircraft Division of IAI (Israel Aircraft Industries), one of the largest industrial companies in Israel with annual sales exceeding \$4.5 billions in 2012, uses with its customers BTS contracts according to which IAI not only manufactures but also designs and tests the product as well as production infrastructure associated with the product (Kasse 2008). BTS contracts grow significantly in the recent years between the companies in developed and emerging markets as the suppliers in these emerging markets build significant capabilities in not only manufacturing but also design, testing, and integration processes, particularly, in aerospace, metalworking, and electronics. For example, the share of the manufacturers with BTS capabilities among all private defense contractors in India that manufacture equipments for the global markets increased significantly in the last three years and is estimated to reach to 20% in 2014 from 8% in 2010 (Ghosh 2014). Similarly, Foxconn, the world's largest electronics contract manufacturer that includes many famous brands in consumer electronics such as iPhone (Dean 2007), BlackBerry (USA Molina 2013), and Kindle (Computer Nystedt 2010), delivers to its customers not only basic manufacturing capabilities (moulding, machining, etc). but also recently starts to build high-level BTS capabilities such as design, testing, and integration (Foxconn 2014).

The main benefit of BTS is that the supplier holds the sole responsibility and, therefore, *liability*, in conducting the costly diagnostic efforts, which reduces the overhead for the buyer since she does not need to maintain a non-core competency to conduct such efforts (Totaro 2011). Also, the supplier use the information gathered via diagnostic tests to take necessary action to improve the overall supply chain reliability. The handicap of offering a BTS contract, however, is that the supplier would *privately* own the information obtained from the diagnostic tests and hence demand for its rent from the buyer. A typical BTS contract for an electronics equipment, for example, radar, needs to include following section that regulates conditions and payments from buyer to supplier in order to transfer the proprietary information developed as a result of supplier's diagnostic efforts (Sensor-Concepts-Inc 2013):

> *Section (—). Proprietary Information and Confidentiality*
> Any data, drawing, design, equipment or other material or information which is provided by Supplier, *but paid by Buyer as a part of the Products' purchase price*, shall be solely owned by Buyer and shall be considered Buyer's proprietary and confidential information.

One of the key challenges in such contracts that involve information sharing is the credibility of information. This is particularly important in this case because the diagnostic test is typically conducted by the supplier without any involvement from the buyer. Therefore, the buyer cannot verify the credibility of diagnosis information even if the supplier discloses it. Nor can the buyer check whether the diagnostic test has been conducted or not unless the buyer incurs a cost for verification. Hence, if the buyer wants to have access to the outcome of the supplier's diagnosis test in a credible fashion through a contract, he needs to provide the supplier with right set of incentives.

The above discussion suggests that there is a need to explore the structure of optimal incentives that induces the supplier to conduct the diagnostic test and its value in a decentralized supply chain setting. This necessitates taking a holistic approach that considers both benefits and costs, and identify the business settings when it is valuable (and when it is not). Along these lines, in this study, we address the following research questions:

Research Question 1. Should the buyer induce the diagnostic test on the supplier? If yes, how can the buyer incentivize the supplier to conduct diagnostic test and share its outcome with the buyer in a credible fashion?

Research Question 2. What is the value of diagnostic test on the buyer, supplier and total supply chain?

In order to answer the above research questions, we develop a dyadic supply chain model where a buyer outsources the production of a new product to a supplier who faces a supply risk. Furthermore, due to lack of experience in production, the extent of risk is *ex ante* unknown by both the buyer and supplier. In order to reduce the extent of risk, the supplier has to decide whether to improve his process at a cost before starting the actual production. We consider two variants of this model on the basis of whether the diagnostic test is available to the supplier or not. Under the first case, where the diagnostic test is not available, the supplier makes his process improvement decision without taking any diagnostic decision. On the other hand, in the second case, the supplier can invest in a costly diagnostic test (such as running a test production) to learn the true state of his reliability, and make optimal process improvement accordingly. We analytically characterize and compare the optimal incentive contracts and decisions for the above two models to answer our research questions.

First, we identify the costs and benefits of each setting with respect to the first-best solution for both individual supply chain parties and total supply chain. In the analyses of inefficiencies resulting from the absence of the diagnostic test, we identify two as in the following: (i) one for the total supply chain, namely, in the absence of diagnostic test, supply chain deviates from its efficient level of reliability due to uninformed supplier's suboptimal process improvement decision, and (ii) one for the individual supply chain parties, namely, the cost of (inefficient) process improvement has to be subsidized by the buyer, which results in liability rent (resp. cost) for the uninformed supplier (resp. buyer). Next, the analysis of model in the presence of diagnostic test reveals that both of these inefficiencies can be overcome with the help of a diagnostic test. However, it comes with its own inefficiencies. Again, we identify two, both of which are related to the increased information asymmetry between buyer and supplier due to the diagnostic test. First, an informed supplier armed with a private information would ask for the rent of his private information from the uninformed buyer. Second, this rent potentially leads the buyer not to induce the diagnostic test on the supplier in order to avoid having to pay information rent. This in turn provides disincentives for supplier's process improvement effort. While the first effect of a diagnostic test makes exactly one of the supply chain parties worse off (and the other one better off), the second one can actually make both parties worse off because the disincentives for the process improvement indeed results in less reliable supply chain.

The above analysis also helps us to identify the overall value proposition of a diagnostic test for the supply chain parties and to assess how it changes with varying business environment. In general, the total value of the diagnostic test critically depends on two factors: (i) the degree of (proprietary) informational content of the diagnostic test, and (ii) its relative cost with respect to cost of process improvement. Ceteris paribus, the decrease in relative cost or informational content of the diagnostic test makes it more valuable for the buyer. On the other hand, the diagnostic test is more valuable for the supplier when either cost of process improvement is low and information content of the diagnostic test is high or vice versa.

These results corroborate with expectations and concerns of the supply chain practice with respect to BTS model (Totaro 2011). On one hand, BTS improves the overall supply chain efficiency and reduces the liability cost of the buyer. That is a plus. On the other hand, when it is used in global supply chains with potentially high degree of incentive and information asymmetries, it needs to be managed with utmost care. Along these lines, our analysis provide a theoretical framework that helps to pinpoint those specific business settings where BTS can amplify both types of asymmetries across the supply chain and potentially hurt all its parties. Specifically, the advantages and disadvantages of BTS should be carefully weighed by the firms in aerospace, defense and high tech industries (such as IAI, and IBM) where the diagnostic procedures are very costly, and the degree of information asymmetry that results from obtaining a private information is highly crucial.

The plan for our study is as follows. In the next section, we review the related literature. In section 3, we build our model framework and analyze it under symmetric information setting to characterize the first-best solution. We then analyze the contract design problem in decentralized supply chain in section 4. Specifically, we analyze the decentralized version of our model when the diagnostic test is not available (section 4.1) and when it is (section 4.2). Comparing the results from these two sections, we characterize the value of the diagnostic test for both buyer and supplier as well as the total supply chain in section 5. Finally, we conclude in section 6.

2. Related Literature

This study contributes to the supply chain management literature that explores the joint role of the supply diagnostic test (e.g., test production) and process improvement. In our model, we consider optimal incentive mechanisms for a supplier, who is uninformed about the extent of supply risk and can endogenously gather reliability information by investing in diagnostic test. Therefore, it is related to two streams: (i) supply chain contracting literature under information asymmetry in the presence of supply risk, and (ii) the information acquisition literature that explores the impact of learning and testing in a contractual setting. Finally, we explore some of related papers in economics literature.

The models developed in the supply chain contracting literature under information asymmetry generally assumes that one of the supply chain parties has ex ante superior information than the other parties. In this context, Yang et al. (2009) considers a case where the supplier is informed about his reliability at the contracting stage and studies how an uninformed buyer provides an incentive to the supplier to elicit his true information. Chaturvedi and Martinez-de Albeniz (2011) analyze optimal procurement strategies when there exists two dimensional information asymmetry on supplier's production cost and reliability. Gurnani and Shi (2006) consider the case of a first-time interaction between a buyer and its supplier when they have different estimates of the supplier's reliability. In Gumus et al. (2012), an unreliable supplier offers price and quantity contract to compete with a reliable supplier. They study the underlying motivation for the guarantee offer and its effects on the competitive intensity and the performance of the chain partners. Most of the papers in this literature (see Aydin et al. 2011, Tang 2006, Tomlin and Wang 2011 for a recent review) assume that the extent of supply-side uncertainties is ex ante asymmetrically distributed among the supply chain parties. There is also a stream of papers in supply risk management literature that explore the value of learning in the context of supply reliability (Tomlin 2009), lead-time uncertainty (Chen and Yu 2005), and production yield risk (Choi et al. 2008), however, to the best of our knowledge, the models developed in this stream consider centralized supply chain settings. In contrast, our model framework considers a decentralized setting, where both supply chain parties are ex ante uninformed about distribution of supply uncertainty, and asymmetric information endogenously emerges as a result of one of the parties' engaging in information gathering activities.

In this aspect, our study is related to the information acquisition literature. In general, this specific literature explores the importance of testing activities that are carried out to evaluate novel design concepts and features in new product development (NPD). The information gathered from testing can reduce uncertainty for the involved parties; for the parties on the supply side in the form of technical production problems, and for the parties on the demand-side by revealing mismatches between product solution and customer needs (see Dahan and Mendelson 2001, Erat and Kavadias 2008, Guo and Iyer 2010, Thomke and Bell 2001, Xiong and Chen 2013, 2014). Upon finding such problems, either on supply or demand side, various corrective actions (such as changes in the design of both product and production process) can be implemented. Therefore, the timing of information gathering activity can significantly affect the economics of a NPD (Krishnan et al. 1997, Terwiesch et al. 2002, Thomke 1998).

Among the demand-side information acquisition papers (Guo and Iyer 2010, Xiong and Chen 2013, 2014), new information is acquired by the principal in Guo and Iyer (2010), whereas it is acquired by the agent in our model. Also, Guo and Iyer (2010) assume that if the principal decides to voluntarily share the information, she would do it truthfully. Hence, as opposed to ours, they do not impose incentive-related constraints in their model framework. Xiong and Chen (2013, 2014) consider a setting in which the customers (agent) would decide whether or not to acquire information regarding their willingness-to-pay. However, there are two differences between their timeline and ours. First, they already start their models with an ex ante information asymmetry between seller (principal) and customer (agent), whereas we consider that there is no ex ante information asymmetry between buyer (principal) and supplier (agent). Second, in Xiong and Chen (2013, 2014), the game finishes after the customers decide whether or not to learn their willingness-to-pay, whereas in our paper, after the supplier learns his reliability type there is an additional stage in which he decides whether or not to exert process improvement decision. These modeling differences result in different types of information acquisition, hence, different supply chain distortion from ours. Namely, as opposed to Xiong and Chen (2013, 2014), in our model, the diagnostic test provides the agent with *actionable* new information. Therefore, the ex post information asymmetry resulting from acquisition of new information leads to a supply chain distortion in our model, whereas it does not in Xiong and Chen (2013, 2014). We will discuss this issue in more detail in section 5.

The most related papers to ours on supply-side information acquisition literature are the recent papers by Kim and Netessine (2013) and Gao et al. (2014). Similar to us, Gao et al. (2014) consider supplier's information acquisition decision on the yield risk in the presence of decentralized supply chain setting. However, their paper differs from ours in terms of both modeling framework and research question. In their model, the supplier moves first and decides whether or not to share his private yield risk with the buyer, whereas in our model it is the buyer who moves first and offers a contract to the supplier who then decides whether to learn his reliability. Hence, their problem boils down to a sequential Bayesian game, whereas ours is cast as contract design problem. Second, they do not consider moral hazard issues that arise naturally in our setting due to process improvement decision. Finally, they assume that the supplier incurs an exogenous disclosure cost, whereas in our model, the private information of the supplier is elicited through the contract terms and the cost of elicitation is endogenously reflected on the contract terms. In the model analyzed by Kim and Netessine (2013), the buyer and supplier jointly collaborate in a cost-reduction effort, which lowers the expected production cost and its related uncertainty. Similar to us, they also assume that the new information on the production cost is realized only by the supplier, which creates information asymmetry between channel parties. However, our model differs from Kim and Netessine (2013) in three ways. First, we assume that both information-gathering and process-improvement efforts are exerted only by the supplier, which effectively leads to one-sided moral hazard problem (as opposed to two-sided moral hazard), and consequently, the hold-up problem does not arise in our setting. Second, Kim and Netessine (2013) assume that the cost-reduction effort reduces both average and variance of marginal production cost, whereas in our model, we divide the supplier's decision into two steps. In the first step, he decides whether or not to invest in a diagnostic test, and in the second step, based on the information acquired in the first step, he decides whether or not to invest in process improvement. Considering a sequential decision leads to two contrasting effects on the different sides of the supply chain. On the upstream side, it enables the supplier to make more efficient process improvement decision in the second step. Specifically, if the outcome of the diagnostic test indicates that the supplier is reliable, then the supplier can avoid investing in process improvement effort. On the downstream side, however, it restricts the power of the buyer in influencing the supplier to exert a certain action profile because of the inter-temporal relation between first- and second-stage moral hazard problems. Third, our study analyzes the impact of diagnostic test in the context of supply disruption, which differs from Kim and Netessine 2013 that consider a procurement context.

Our model is also related to the principal-agent models of adverse selection in Economics literature where the extent of information asymmetry is endogenous. In Cremer and Khalil (1992), Lewis and Sappington (1993), Kessler (1998), Cremer et al. (1998), the agent chooses whether or not to gather private information on a relation-specific parameter before contracting takes place. It is shown that remaining uninformed may have a positive strategic value for the agent. Contrary to our model, the above papers assume that the agent may acquire information before the principal offers the contract. In a more related paper to our model, Lewis and Sappington (1991) develop a model in which the principal offers the contract before agent decides on information-gathering effort. However, in addition to their context being different from ours, they also assume that the principal chooses the probability p with which the agent receives perfect private state information. They show that the agent information rent increases when principal increases p. Note also that in our model, the buyer (principal) faces with an inter-temporal two-stage moral hazard problem, which, to the best of our knowledge, has not been explored in this literature. Specifically, this is different from *two-sided moral hazard* problem in economics where both the principal and agent can exert effort, and each party's choice of effort is unobservable by the other party.

3. Model Framework

We develop a dyadic supply chain in which a buyer ("she") outsources the production of a new product to a supplier ("he"). The buyer faces a fixed demand[1] D and the expected profit per unit sold in the market is \$$r$. To satisfy her demand, the buyer contracts with a supplier whose production cost is \$$c_s$/unit. Since the product is new, the extent of the supplier's true reliability is unknown by both the buyer and supplier at the time of contract.[2] Further, we assume that supplier's true reliability can be of two types, that is, l and h, and both the buyer and supplier share common a-priori belief about the true reliability type, that is, h with probability α and l with probability $1-\alpha$, where $0 \leq \alpha \leq 1$. That is to say, from a-priori belief, the expected reliability of the supplier is $\bar{\theta} = \alpha h + (1-\alpha)l$. The h-type supplier is fully reliable in the sense that the probability of disruption is zero for him,[3] whereas the l-type supplier is unreliable and subject to the disruption. Furthermore, the supplier can mitigate the extent of supply risk by exerting a process improvement effort at cost c_p. However, the uncertainty about the true reliability type may prevent an uninformed supplier from making efficient improvement decision. In order to avoid this inefficiency, the uninformed supplier can choose to invest in a diagnostic test at the cost of c_d, which enables him to learn his true reliability before deciding on process improvement. In order to elicit the private information regarding the true reliability, the manufacturer has to provide right incentives to the supplier via the menu of contracts.

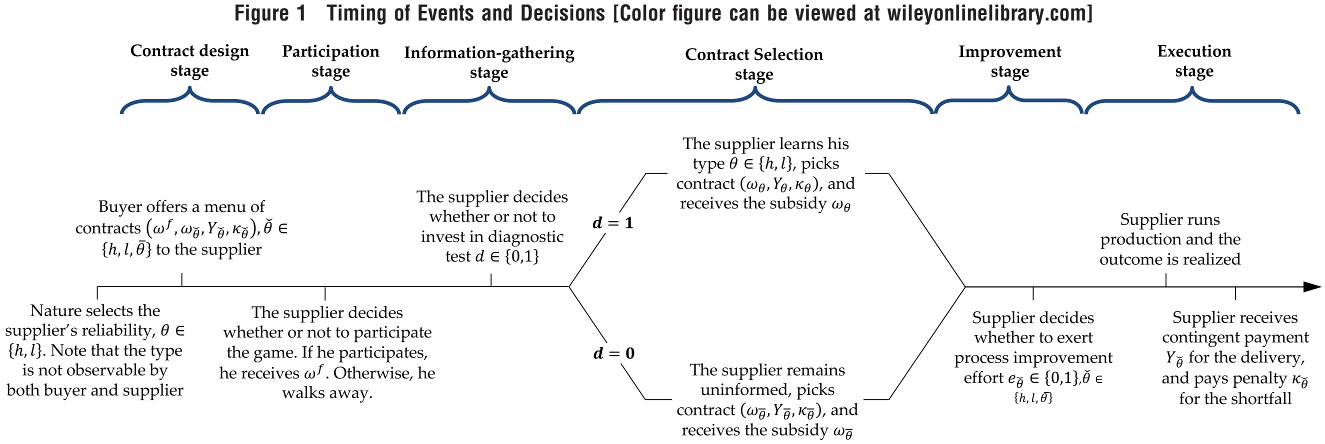
3.1. Timing of Events and Decisions

The game starts with nature selecting the state of supplier's true reliability type, that is, h with probability α and l with probability $1 - \alpha$. The true reliability is unobservable by both the buyer and supplier. This results in a fundamental difference between the regular adverse selection problem and ours. In the former, the agent knows his true type from the beginning of the game, hence makes participation and selection decisions simultaneously. However, in our model, the supplier (i.e., agent) does not know his true reliability at the time when the buyer offers a menu of contracts. As a result, in our model, the contract selection decision takes place after the supplier learns his true type.[4] The timing of events and decisions is presented in Figure 1:

- *Contract design stage:* The buyer offers a menu of contracts that is composed of both fixed and deferred contingent payment terms. It is a common practice in supply chain contracting, where the supply chain firms delay a portion or the whole part of the payment to their suppliers until certain milestones are achieved by them[5] (Opus 2013) and offer contingent payments in the form of either incentive (Babich and Tang 2012) or disincentive (Gurnani and Shi 2006, Yang et al. 2009) or both (Bubshait 2003, Chen et al. 2015) in order to induce performance on the actions of the suppliers (Lee 2004). Similarly, one of the authors of this paper recently worked with a cable manufacturer in Europe to help minimize the impact of changeovers in the quality of custom-made cables and witnessed that a two-stage contract is commonly used between the cable manufacturers and their customers in design and production of custom-made industrial electric cables. The first-stage term consists of fixed up-front payment to cover the production costs associated with test runs. Given the degree of diagnostic efforts exerted during the test runs and its outcomes, the cable manufacturer then configures the final production, and receives the second stage payments based on the final outcome.[6]

Motivated by this and based on the revelation principle for principal-agent models with endogenous information asymmetry (see Chapter 9 of Laffont and Martimort (2002) and references therein), without loss of generality, we can restrict our attention to direct-revelation mechanisms in which the supplier follows diagnostic decision induced by the buyer, truthfully reveals his true type and obeys the recommendation on the choice of process improvement effort. As such, we consider a menu with three contracts $(\omega^f, \omega_{\check{\theta}}, Y_{\check{\theta}}, \kappa_{\check{\theta}})$ indexed by $\check{\theta} \in \{h, l, \bar{\theta}\}$. Namely, the first two contracts are designed for h and l-type suppliers, respectively provided that they are induced to learn their true reliability types, and the third one is indexed by $\bar{\theta}$ and designed for the uninformed supplier. Also, similar to the examples mentioned above, each contract is composed of fixed and contingent terms, where the first two terms ω^f and $\omega_{\check{\theta}}$ denote the fixed payments, and the last two terms $Y_{\check{\theta}}$ and $\kappa_{\check{\theta}}$ correspond to bonus and penalty payments that are paid and received to/from supplier as incentive and

Figure 1 Timing of Events and Decisions [Color figure can be viewed at wileyonlinelibrary.com]



disincentive in case of successful delivery and failure, respectively.

- *Participation stage:* Given the menu of contracts, the supplier decides whether or not to participate in the contract. If he decides to participate, he receives an upfront fixed payment ω^f and proceeds with the next stage, otherwise, he walks away. Note that in the participation stage the unknown supplier does not select any contract from the menu, therefore, all the contracts in the menu should satisfy unknown supplier's participation constraint (more details on this later in section 4).
- *Information-gathering stage:* In this stage, the uniformed supplier decides whether to learn his true reliability (e.g., by running a test production or conducting a proof-of-concept) at cost c_d. Let $d \in \{0, 1\}$ denote the supplier's decision on diagnostic test, which is not observable by the buyer, where $d = 1$ and $d = 0$ correspond to supplier's investing and not investing in the diagnostic test, respectively. After investing in diagnostic test, the supplier receives a signal about his true reliability type, and updates his a-priori beliefs by using Bayesian updating. Let $\breve{\alpha}$ be the supplier's a-posterior belief on his true reliability being of h-type. Throughout the study, we assume that the signal from the diagnostic test is perfect, hence, supplier's updated beliefs can be expressed as follows:

$$\breve{\alpha} = \begin{cases} 1 & \text{if } d = 1 \text{ and } \theta = h \\ 0 & \text{if } d = 1 \text{ and } \theta = l \\ \alpha & \text{if } d = 0 \end{cases} \tag{1}$$

  Using a-posterior beliefs, we define $\breve{\theta} = \breve{\alpha}h + (1 - \breve{\alpha})l$ to represent the supplier's updated type after the diagnostic decision. Note that when the supplier invests in the diagnostic test then $\breve{\theta}$ will be equal to h when he is of h-type and l when he is of l-type, otherwise he uses his a-priori belief and his expected reliability type would be $\breve{\theta} = \bar{\theta} = \alpha h + (1 - \alpha)l$.
- *Selection stage:* Based on the decision on the diagnostic test, the supplier self-selects a contract from the menu and receives $\omega_{\breve{\theta}}$. Note that even though the payment of $\omega_{\breve{\theta}}$ is deferred until the diagnostic test decision is made, we still assume that neither supplier's decision on diagnostic test nor its outcome are observable by the buyer. As we will see in section 4.2, the unobservability of both diagnostic test and its outcome imposes different constraints on the contract terms. Specifically, if the supplier invests in the diagnostic test and learns his true reliability, then the menu of contracts should be incentive-compatible so that the supplier truthfully reports his true reliability to the buyer.
- *Improvement stage:* In this stage, $\breve{\theta}$-type supplier decides whether to improve his process or not. Let $e_{\breve{\theta}} \in \{0, 1\}$ denote $\breve{\theta}$-type supplier's improvement decision, which is not observable by the buyer, where $e_{\breve{\theta}} = 0$ and $e_{\breve{\theta}} = 1$ represent no-effort and effort, respectively. We assume that the supplier's production outcome $q_{\breve{\theta}}$ is subject to an all-or-nothing type uncertainty whose survival probability p is a function of the supplier's both updated type $\breve{\theta}$ and improvement effort $e_{\breve{\theta}}$ as follows.

$$q_{\breve{\theta}} = \begin{cases} 1 & \text{with probability } p(\breve{\theta}, e_{\breve{\theta}}) \\ 0 & \text{with probability } 1 - p(\breve{\theta}, e_{\breve{\theta}}) \end{cases} \tag{2}$$

  where $p(\breve{\theta}, e_{\breve{\theta}})$ is provided in Table 1.
- *Execution stage:* Finally, in the execution stage the supplier runs the production, realizes the supply uncertainty, and either receives the contingent payment $Y_{\breve{\theta}}$ per unit delivered to the buyer or pays the penalty $\kappa_{\breve{\theta}}$ per unit of shortfall.

We summarize the list of notations used for the problem parameters, profit functions and decision variables in Table 2.

Throughout the study, we consider the case in which the diagnostic test and process improvement efforts are conducted solely by the supplier without any involvement from the buyer. Therefore, the buyer cannot verify the credibility of diagnosis information even if the supplier discloses it. Nor can the buyer check whether the diagnostic test and process improvement have been conducted or not. Hence, if the buyer wants to have access to the outcome of the supplier's diagnosis test in a credible fashion (which corresponds to $d = 1$ case in our model), and at the same time induce performance on the supplier's process improvement actions (which corresponds to $e_{\breve{\theta}} = 1$ in our model) through a menu of contracts, the buyer needs to design it in such a way that it satisfies

Table 1 Supplier's Survival Probability $p(\breve{\theta}, e_{\breve{\theta}})$ as a Function of His Updated Type and Improvement Effort

		Supplier's updated type		
		$d = 1$		$d = 0$
		$\breve{\theta} = l$	$\breve{\theta} = h$	$\breve{\theta} = \bar{\theta}$
Supplier's improvement effort	$e_{\breve{\theta}} = 0$	φ	1	$\alpha+(1-\alpha)\varphi$
	$e_{\breve{\theta}} = 1$	ρ	1	$\alpha+(1-\alpha)\rho$

Notes: $0 \le \varphi \le \rho \le 1$.

Table 2 Notation Used for Model Parameters and Decision Variables

Model parameters	
$\breve{\theta} \in \{\theta, \bar{\theta}\}$	Supplier's reliability types, where $\theta \in \{l, h\}$ denotes the true reliability types if he invests in diagnostic test, and $\bar{\theta}$ denotes the average type if he does not invest in the diagnostic test
α; $\breve{\alpha}$	Supplier's prior and updated (posterior) beliefs about true reliability type
c_s; c_d; c_p	Supplier's costs for unit production, diagnostic test and process improvement, respectively
φ; ρ	Probability of no-disruption for l-type supplier under $e = 0$ and $e = 1$, respectively
r	Buyer's marginal revenue
Profit functions	
$\pi^S_{\breve{\theta}}$	Expected profit for the $\breve{\theta}$-type supplier
$\pi^B_{\breve{\theta}}$	Expected profit of the buyer facing $\breve{\theta}$-type supplier
Decision variables	
d; $e_{\breve{\theta}}$	Diagnostic and process improvement decisions made by the supplier
$(\omega^f, \omega_{\breve{\theta}}, Y_{\breve{\theta}}, \kappa_{\breve{\theta}})$	The contract terms offered by the buyer

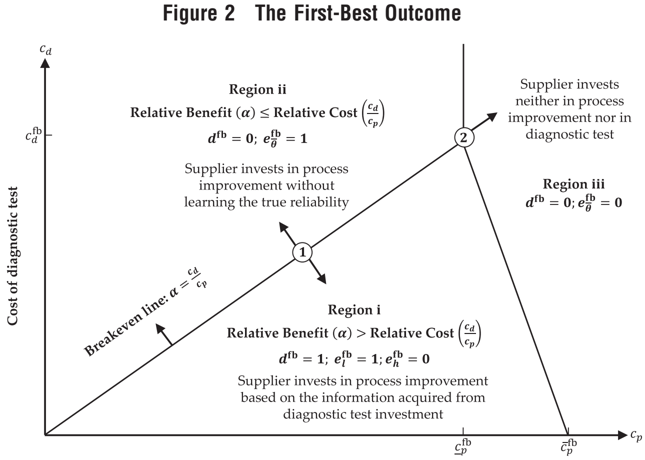
supplier's participation and incentive compatibility constraints.[7]

Before we analyze the buyer's contract design problem in the presence of endogenous information asymmetry, we first consider a first-best benchmark, in which both the diagnostic test and process improvement decisions are verifiable and contractible as well as the outcome of the diagnostic test is observable by all the parties. Based on the standard results in contract design, we can show that in this case the buyer can design a contract that would optimize the total supply chain's profit and extract the full surplus. Delegating the formulation and detailed analyses in Appendix S1, we provide the first-best characterization in the following Proposition:

PROPOSITION 1. (*FIRST-BEST OUTCOME*) *Under first-best scenario, the optimal diagnostic test and process improvement decisions for each region are described in Figure* 2 *and characterized as follows.*

- *If the cost of process improvement is low, that is,* $c_p \leq max((\rho - \varphi)r - c_d/(1 - \alpha), (1 - \alpha)(\rho - \varphi)r)$, *then diagnostic decision depends on the comparison between* $\frac{c_d}{c_p}$ *and* α *as follows:*
  - *If* $\frac{c_d}{c_p} \leq \alpha$, *then, it is optimal to invest in the diagnostic test. The supplier would exert process improvement effort if and only if the outcome of the diagnostic test is l-type.*
  - *If* $\alpha < \frac{c_d}{c_p}$, *then it is optimal to exert process improvement effort without investing in diagnostic test.*
- *If the process improvement cost is high, that is,* $c_p > max((\rho - \varphi)r - c_d/(1 - \alpha), (1 - \alpha)(\rho - \varphi)r)$, *then neither diagnostic test nor process improvement effort is exerted in equilibrium.*

Figure 2 The First-Best Outcome



Notes: $c_d^{fb} = \alpha(1 - \alpha)(\rho - \varphi)r; \underline{c}_p^{fb} = (1 - \alpha)(\rho - \varphi)r; \bar{c}_p^{fb} = (\rho - \varphi)r$.

There are two takeaways from Proposition 1. First, if the cost of process improvement effort is sufficiently high then, neither l- nor h-type suppliers would exert improvement action, therefore, investing in a diagnostic test brings no value. Hence, the optimal solution would be $d^* = e^*_{\bar{\theta}} = 0$. Second, when the cost of process improvement is sufficiently low, then it would be optimal to invest in diagnostic test, which depends on the relative cost of learning to process improvement $(\frac{c_d}{c_p})$. If c_d over c_p is sufficiently low, then it is optimal to exert process improvement *conditional* on the outcome of diagnostic test. Otherwise, process improvement should be implemented *unconditionally* without the diagnostic test.

4. Optimal Contract in Decentralized Supply Chain

Keeping in mind that the main objective of this study is to analyze the impact of diagnostic test in the presence of information asymmetry, we achieve this in two stages.

First, in section 4.1, we characterize the optimal contract under a scenario where diagnostic test is not available. Note that this enables us to identify agency costs due to moral hazard resulting from unobservable process improvement decision of the supplier. Under this setting (i.e., in the absence of diagnostic test) both supply chain parties would have access to the same reliability information both ex ante and ex post. Next, in section 4.2, we characterize the optimal contract in the presence of diagnostic test where the supplier has the opportunity to learn his true reliability type. Also, in each subsection, we identify the agency costs with respect to same first-best model characterized in section 3. Characterization of agency costs associated with the optimal contracts without and with diagnostic tests helps us analyze the value of diagnostic test for the supply chain parties as well as total supply chain in section 5.

4.1. Optimal Contract in the Absence of Diagnostic Test

Suppose that diagnostic test is not available, and therefore, both the supplier, when deciding on process improvement, and the buyer, when designing the optimal contract, share the same a-priori beliefs $\bar{\theta} = \alpha h + (1-\alpha)l$ on the supplier's true reliability type throughout the game. This however implies that the supplier cannot employ the outcome of a diagnostic test to decide whether or not to exert a process improvement effort. Consequently, under certain cases, the uninformed supplier's improvement decision would inevitably lead to either over- or under-investment compared to the first-best outcome. On the buyer's side, because the supplier cannot learn his true reliability, the buyer has to design a contract $(\omega^f, \omega_{\bar{\theta}}, Y_{\bar{\theta}}, \kappa_{\bar{\theta}})$ that does not depend on d. Hence, the buyer would offer a single contract for the uninformed supplier denoted by $\bar{\theta}$-type.

4.1.1. Model Formulation. Note that in the absence of the diagnostic test, neither information-gathering nor contract selection take place. Hence, in what follows, we derive the list of constraints for the participation and process improvement stages:

– *Participation stage:* First of all, the contract must satisfy non-negativity of the supplier's profit who decides to participate in the contract:

$$\pi^S_{\bar{\theta}}\left(\omega^f, \omega_{\bar{\theta}}, Y_{\bar{\theta}}, \kappa_{\bar{\theta}} \mid e^*_{\bar{\theta}}\right) = \alpha\pi^S_h\left(\omega^f, \omega_{\bar{\theta}}, Y_{\bar{\theta}}, \kappa_{\bar{\theta}} \mid e^*_{\bar{\theta}}\right) + (1-\alpha)\pi^S_l\left(\omega^f, \omega_{\bar{\theta}}, Y_{\bar{\theta}}, \kappa_{\bar{\theta}} \mid e^*_{\bar{\theta}}\right) \geq 0 \quad (3)$$

where

$$\pi^S_h\left(\omega^f, \omega_{\bar{\theta}}, Y_{\bar{\theta}}, \kappa_{\bar{\theta}} \mid e^*_{\bar{\theta}}\right) = \omega^f + \omega_{\bar{\theta}} - c_s + Y_{\bar{\theta}} - e^*_{\bar{\theta}}c_p \quad (4)$$

$$\pi^S_l\left(\omega^f, \omega_{\bar{\theta}}, Y_{\bar{\theta}}, \kappa_{\bar{\theta}} \mid e^*_{\bar{\theta}}\right) = \omega^f + \omega_{\bar{\theta}} - c_s + e^*_{\bar{\theta}}\left[\rho Y_{\bar{\theta}} - (1-\rho)\kappa_{\bar{\theta}} - c_p\right] + \left(1-e^*_{\bar{\theta}}\right)\left[\varphi Y_{\bar{\theta}} - (1-\varphi)\kappa_{\bar{\theta}}\right] \quad (5)$$

Note that the above constraint ensures that the uninformed supplier's expected profit where the expectation is taken with respect to average reliability $\bar{\theta}$ is non-negative. However, as shown in the following Lemma 1, we prove that even though the above constraint ensures that the uninformed supplier obtains non-negative profit if his true type θ turns out to be of h-type, it does not avoid his profit from being negative when θ becomes l.

LEMMA 1. *In the absence of the diagnostic test, an uninformed supplier's expected profit when $\theta = l$ is always non-positive, that is, $\pi^S_l = -\alpha[1-\rho](Y_{\bar{\theta}} + \kappa_{\bar{\theta}}) \leq 0$.*

Given that a contract that leads to negative expected profit (due to product failure) is rarely enforceable in emerging economies as articulated in Babich and Tang (2012), throughout the study, we impose the following constraints:

$$\pi^S_{\theta}\left(\omega^f, \omega_{\bar{\theta}}, Y_{\bar{\theta}}, \kappa_{\bar{\theta}} \mid e^*_{\bar{\theta}}\right) \geq 0, \ \theta \in \{h, l\} \quad (6)$$

Note that the above constraints (6) ensure that irrespective of $\theta \in \{l, h\}$, the uninformed supplier's expected profit under the contract is always non-negative.[8] We also discuss implications of removing equation (6) from the model formulation in section 6.

– *Process Improvement stage:* Next, since the supplier's improvement effort is not *observable*, the contract must satisfy incentive-compatibility (i.e., *moral hazard*) constraints for the process improvement stage. More specifically, the buyer can induce a given level of effort $e^*_{\bar{\theta}}$ on the supplier only by offering a contract that makes his expected profit under $e^*_{\bar{\theta}}$ more than that under $\hat{e}_{\bar{\theta}}$:

$$\pi^S_{\bar{\theta}}\left(\omega^f, \omega_{\bar{\theta}}, Y_{\bar{\theta}}, \kappa_{\bar{\theta}} \mid e^*_{\bar{\theta}}\right) \geq \pi^S_{\bar{\theta}}\left(\omega^f, \omega_{\bar{\theta}}, Y_{\bar{\theta}}, \kappa_{\bar{\theta}} \mid hate_{\bar{\theta}} \neq e^*_{\bar{\theta}}\right) \quad (7)$$

4.1.2. Contract Design Problem in the Absence of Diagnostic Test. Since constraint (3) becomes redundant in the presence of limited liability constraints (6), the buyer's problem in the absence of the diagnostic test can be formulated as an optimization problem subject to equations (6) and (7):

$$\max_{e^*_{\bar{\theta}}} \max_{\omega^f, \omega_{\bar{\theta}}, Y_{\bar{\theta}}, \kappa_{\bar{\theta}}} e^*_{\bar{\theta}}\left[p\left(\bar{\theta}, 1\right)(r - Y_{\bar{\theta}}) + \left(1 - p\left(\bar{\theta}, 1\right)\right)\kappa_{\bar{\theta}}\right] + \left(1-e^*_{\bar{\theta}}\right)\left[p\left(\bar{\theta}, 0\right)(r - Y_{\bar{\theta}}) + \left(1 - p\left(\bar{\theta}, 0\right)\right)\kappa_{\bar{\theta}}\right] - \omega^f - \omega_{\bar{\theta}}$$

Subject to Constraints (6) and (7). (8)

Working backward, we first solve the supplier's process improvement decision $e^*_{\bar{\theta}}$ as a function of the contract offering from the buyer. Note that given $(\omega^f, \omega_{\bar{\theta}}, Y_{\bar{\theta}}, \kappa_{\bar{\theta}})$, the expected benefit of exerting a process improvement for $\bar{\theta}$-type supplier can be expressed as $(1-\alpha)(p(l,1)-p(l,0))(Y_{\bar{\theta}}+\kappa_{\bar{\theta}})$, where the first term in the parenthesis denotes for the likelihood of supplier's being unreliable (i.e., l-type), the second term for the differential increase in his reliability due to process improvement, and the last one for the total contingent payment that he would receive from the buyer as a result of the change in his reliability. By comparing this expected benefit with the cost of process improvement c_p, we can characterize the following:

Lemma 2. (Uninformed Supplier's Improvement Decision) *Given the contract $(\omega^f, \omega_{\bar{\theta}}, Y_{\bar{\theta}}, \kappa_{\bar{\theta}})$ offered by the buyer, the $\bar{\theta}$-type supplier exerts process improvement (i.e., $e^*_{\bar{\theta}}=1$) if $Y_{\bar{\theta}}+\kappa_{\bar{\theta}} \geq \frac{c_p}{(1-\alpha)(\rho-\varphi)}$.*

The above Lemma 2 implies that the fixed-payment contract term (i.e., subsidy) is not enough to induce process improvement on an uninformed supplier in a decentralized supply chain, and that the buyer has to provide incentive to the supplier via either incentive or disincentive term.

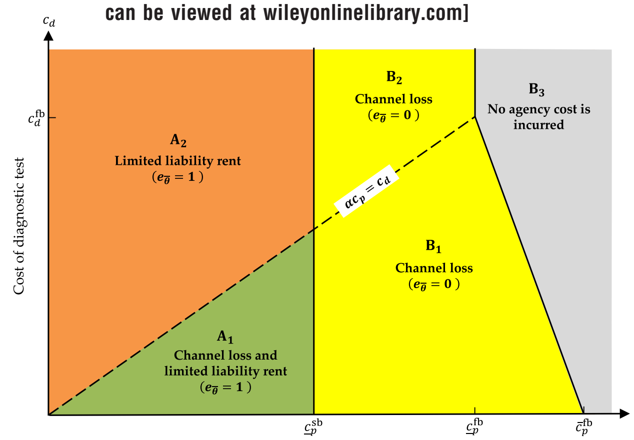
Following the two-step approach developed by Grossman and Hart (1983), we can solve buyer's contract design problem in two stages: (i) first, by finding the optimal contract terms that would implement a given effort level $e^*_{\bar{\theta}}$ on the supplier at the lowest cost, and (ii) then by comparing buyer's expected profits under $e^*_{\bar{\theta}}=1$ with that under $e^*_{\bar{\theta}}=0$. We first consider the implementation step and start with $e^*_{\bar{\theta}}=1$. Note that if the buyer chooses to implement $e^*_{\bar{\theta}}=1$, she would need to provide necessary incentives to not only l- but also h-type supplier. In the latter case, this creates an over-investment, whose cost would be indirectly borne by the buyer in the form of *channel loss*. Also, the contract terms should satisfy the limited liability constraints (6) for both l- and h-type suppliers, which leads to *limited liability rent* (resp., cost) for the uninformed supplier (resp., buyer). Next, consider the implementation of $e^*_{\bar{\theta}}=0$. In this case, the buyer does not incur any limited liability cost. However, $e^*_{\bar{\theta}}=0$ leads to under-investment on the process improvement if the supplier turns out to be of l-type, which makes the overall supply chain more risky. This in turn reduces the surplus for the buyer, causing *channel loss*. To summarize, in order to decide whether or not to implement $e^*_{\bar{\theta}}=1$, the buyer needs to compare agency costs associated with over- and under-investments and design the contract terms accordingly. We leave the details of this comparison to Appendix S1 and provide the conditions under which $e^*_{\bar{\theta}}=1$ is implemented in equilibrium, as well as equilibrium characterization for the optimal contract terms, and agency costs associated with each case in the following Proposition:

Proposition 2. (Optimal Contract in the Absence of Diagnostic Test) *When diagnostic test is not available, in equilibrium,*

1. *Process improvement effort is induced on $\bar{\theta}$-type supplier, that is, $e^*_{\bar{\theta}}=1$ if and only if $c_p \leq \underline{c}_p^{\text{sb}} = \frac{(\rho-\varphi)^2(1-\alpha)^2}{\alpha(1-\rho)+(1-\alpha)(\rho-\varphi)}r$.*
2. *The optimal contract and agency costs associated with it are fully characterized in Table 3 and Figure 3.*

Below, we summarize the main observations from Proposition 2 in comparison with the first-best outcome characterized in Proposition 1:

Figure 3 Agency Costs in the Absence of Diagnostic Test [Color figure can be viewed at wileyonlinelibrary.com]



Notes: $\underline{c}_p^{\text{sb}} = \frac{(\rho-\varphi)^2(1-\alpha)^2}{\alpha(1-\rho)+(1-\alpha)(\rho-\varphi)}r$; $\underline{c}_p^{\text{fb}} = (1-\alpha)(\rho-\varphi)r$; $\bar{c}_p^{\text{fb}} = (\rho-\varphi)r$; $c_d^{\text{fb}} = \alpha(1-\alpha)(\rho-\varphi)r$.

Table 3 Optimal Menu of Contracts and Decisions in the Absence of Diagnostic Test

Region	Optimal contract	Supplier's second-best effort	Limited liability rent	Channel loss
A_1	$\omega^f+\omega_{\bar{\theta}}=c_s+c_p$;			$\alpha c_p - c_d$
	$Y_{\bar{\theta}}=\frac{1-\rho}{(\rho-\varphi)(1-\alpha)}c_p$;	$e^*_{\bar{\theta}}=1$	$\alpha\frac{(1-\rho)}{(1-\alpha)(\rho-\varphi)}c_p$	
A_2	$\kappa_{\bar{\theta}}=\frac{\rho}{(\rho-\varphi)(1-\alpha)}c_p$			0
B_1				$(1-\alpha)((\rho-\varphi)r-c_p)-c_d$
B_2	$\omega^f+\omega_{\bar{\theta}}=c_s$; $Y_{\bar{\theta}}=0$; $\kappa_{\bar{\theta}}=0$	$e^*_{\bar{\theta}}=0$	0	$(1-\alpha)(\rho-\varphi)r-c_p$
B_3				0

- First, in comparison with the first-best outcome, channel loss occurs due to over-investment in region A_1 and under-investment in region B_1. The rationale behind these regions is related to the limited liability rent, which we will explain in the next item.
- In order to incentivize an uninformed supplier to exert effort, that is, $e^*_{\bar{\theta}} = 1$, the contract terms have to satisfy the condition provided in Lemma 2. Note that this condition gives such a leeway to the buyer so that she can decide to satisfy it by offering to the supplier either an incentive $Y_{\bar{\theta}}$ or disincentive $\kappa_{\bar{\theta}}$ (or a combination of both). However, limited liability constraints given in equation (6) imposes further restrictions on this freedom of the buyer in the sense that the disincentive should be commensurate with the incentive payment, that is, $\rho Y_{\bar{\theta}} \geq (1-\rho)\kappa_{\bar{\theta}}$. In other words, if the buyer decides to include a non-zero penalty clause in the case of failure, say $\kappa_{\bar{\theta}}$, to the contract, she also needs to provide an incentive payment in the case of successful delivery, which is at least equal to $\frac{1-\rho}{\rho} \times \kappa_{\bar{\theta}}$. This does not lead to any loss for the buyer if the supplier turns out to be of l-type because in expectation, incentive and disincentive terms cancel out each other. However, if the supplier is of h-type, he will only enjoy the incentive term in the contract, which creates a rent for the h-type buyer and cost for the buyer. Since the h-type occurs with probability α, the expected limited liability rent for a $\bar{\theta}$-type supplier will therefore be equal to:

$$\text{Limited liability rent} = \alpha \times Y_{\bar{\theta}} = \frac{(1-\rho)\alpha}{(\rho-\varphi)(1-\alpha)} c_p \tag{9}$$

Note that the optimality condition for the implementation of $e^*_{\bar{\theta}} = 1$ vs. $e^*_{\bar{\theta}} = 0$ depends on the comparison between the above limited liability rent and channel loss. As characterized in Proposition 2, the channel loss decreases in cost of process improvement c_p, whereas the limited liability rent increases in c_p. This implies that as c_p becomes sufficiently high (i.e., in Regions B_1 and B_2), the buyer would prefer inducing $e^*_{\bar{\theta}} = 0$ on the supplier and consequently incurring channel loss rather than paying him a high amount of limited liability rent.

4.2. Optimal Contract in the Presence of the Diagnostic Test

In this section, we study the case where the diagnostic test is available, and therefore the supplier has the opportunity to learn his true reliability. As we discuss in section 1, inducing a diagnostic test on the supplier brings its costs besides its benefits. On one hand, it creates information asymmetry between supply chain parties, hence the informed supplier armed with new information asks for information rent. On the other hand, the diagnostic test provides the supplier with *actionable* information, which in turn enables the buyer to implement type-dependent process improvement on the supplier. This may help eliminate the channel loss incurred due to over- and under-investment from the previous section.

In the presence of diagnostic test, the buyer's contract design problem depends on whether she induces diagnostic test on the supplier or not, that is, $d = 1$ or $d = 0$. In the former, the supplier would learn his true reliability type, whereas in the latter, he would not. Therefore, the optimal menu of contracts must contain three contracts: (i) two contracts for the informed supplier; one for h-type, and one for l-type supplier provided that he decides to conduct the diagnostic test $d = 1$ and learns his true type, and (ii) one contract for the uninformed supplier $\bar{\theta}$ if he does not conduct the diagnostic test $d = 0$. The contracts for the two types would be denoted by $(\omega^f, \omega_h, Y_h, \kappa_h)$, $(\omega^f, \omega_l, Y_l, \kappa_l)$ and the contract for the uninformed supplier would be denoted by $(\omega^f, \omega_{\bar{\theta}}, Y_{\bar{\theta}}, \kappa_{\bar{\theta}})$. Furthermore, note that these contracts should also satisfy different implementation (i.e., incentive-compatibility, moral-hazard and participation) constraints depending on whether the supplier decides to exert a diagnostic test or not. Figure 4 illustrates the decision tree faced by the supplier.

4.2.1. Model Formulation.

Note that as opposed to section 4.1, the supplier now faces two additional stages: information-gathering stage and contract selection stage. In what follows, we derive the list of constraints for each stage: – *Participation stage:* First of all, menu of contracts must satisfy the participation constraints in order to ensure that there is no incentive for the supplier to cancel the contractual relationship with the buyer once the supplier learns his true type. Since there are three types, namely, $\check{\theta} \in \{l, h, \bar{\theta}\}$, and the buyer offers one contract for each type, we require three sets of constraints. The participation constraints for l- and h-types are as follows:

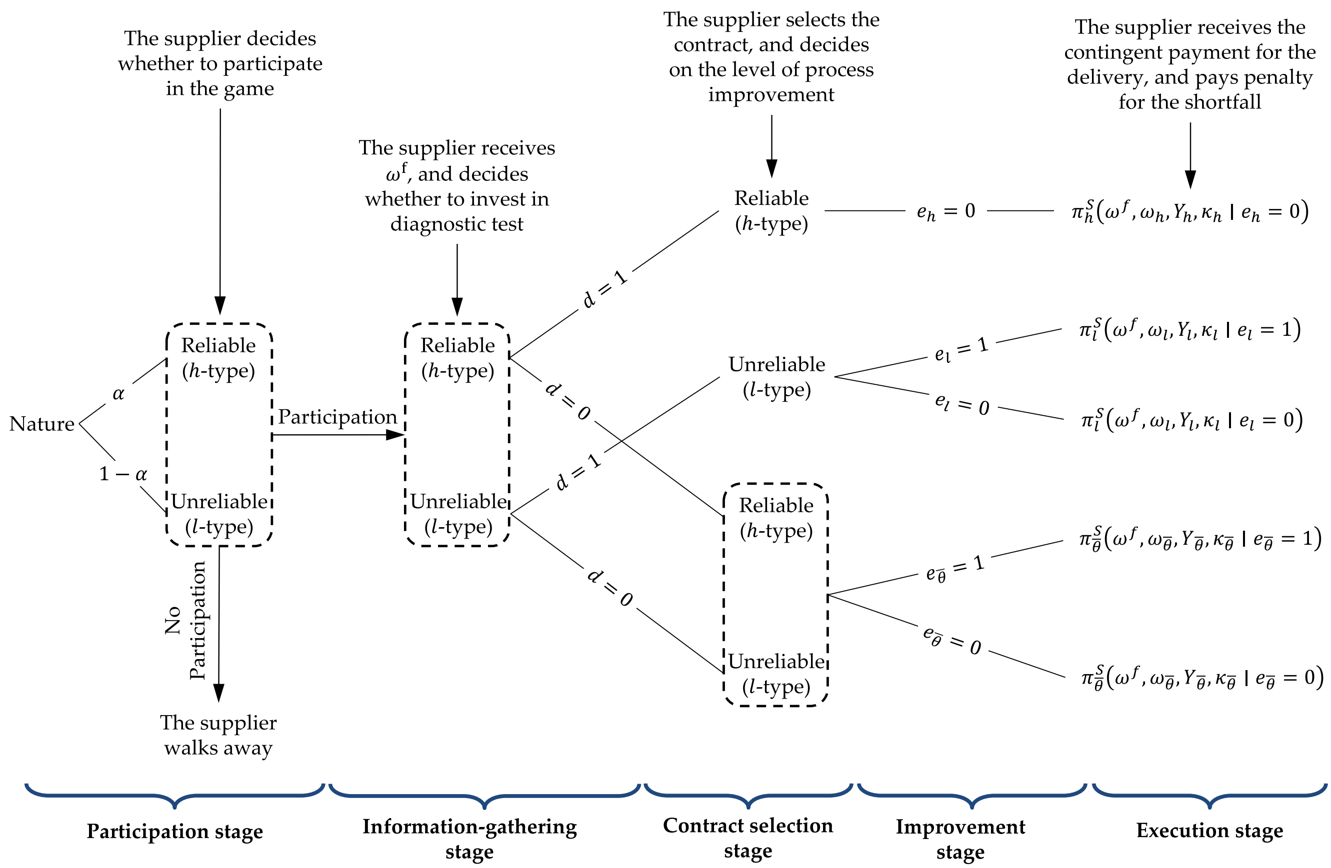
$$\pi^S_h\left(\omega^f, \omega_h, Y_h, \kappa_h \mid e^*_h\right) - c_d \geq 0 \tag{10}$$

$$\pi^S_l\left(\omega^f, \omega_l, Y_l, \kappa_l \mid e^*_l\right) - c_d \geq 0 \tag{11}$$

and the participation constraint for uninformed supplier type $\bar{\theta}$ is same as the one provided in equation (6).

– *Information-gathering stage:* After the participation, the supplier decides whether to invest in the

Figure 4 Supplier's Decision Tree [Color figure can be viewed at wileyonlinelibrary.com]



Note: The dotted lines indicate that the supplier remains unknown hence both h-type and l-type suppliers are pooled.

diagnostic test. Since the diagnostic test is not observable, the buyer must satisfy the moral hazard constraint in order to induce either $d^* = 0$ or $d^* = 1$. Suppose the buyer wants to induce $d^* = 0$. This implies that the supplier who exerts $d^* = 0$ and picks the contract designed for $\bar{\theta}$ should be better off with this decision compared to all the other (off-equilibrium) scenarios he can choose under $d = 1$:

$$\pi_{\bar\theta}^S(\omega^f, \omega_{\bar\theta}, Y_{\bar\theta}, \kappa_{\bar\theta} \mid e_{\bar\theta}^*) \geq \alpha\hat{\pi}_h^S + (1-\alpha)\hat{\pi}_l^S - c_d \tag{12}$$

where $\hat{\pi}_h^S$ and $\hat{\pi}_l^S$ denote the supplier's off-equilibrium pay-offs after he exerts $d = 1$, observes his true type and chooses the best contract from the menu:

$$\hat{\pi}_h^S = \max_{\hat{e}_h \in \{0,1\}} \{\pi_h^S(\omega^f, \omega_h, Y_h, \kappa_h \mid \hat{e}_h),$$
$$\pi_h^S(\omega^f, \omega_l, Y_l, \kappa_l \mid \hat{e}_h), \pi_h^S(\omega^f, \omega_{\bar\theta}, Y_{\bar\theta}, \kappa_{\bar\theta} \mid \hat{e}_h)\}$$
$$\hat{\pi}_l^S = \max_{\hat{e}_l \in \{0,1\}} \{\pi_l^S(\omega^f, \omega_h, Y_h, \kappa_h \mid \hat{e}_l),$$
$$\pi_l^S(\omega^f, \omega_l, Y_l, \kappa_l \mid \hat{e}_l), \pi_l^S(\omega^f, \omega_{\bar\theta}, Y_{\bar\theta}, \kappa_{\bar\theta} \mid \hat{e}_l)\}$$

Now, consider the case where the buyer wants to induce $d^* = 1$. In this case, the supplier who exerts $d^* = 1$ and picks the contract designed for either l- or h-type must receive higher profit compared to the case in which he exerts $d = 0$ and picks the best contract from the menu:

$$\alpha\pi_h^S(\omega^f, \omega_h, Y_h, \kappa_h \mid e_h^*) + (1-\alpha)\pi_l^S(\omega^f, \omega_l, Y_l, \kappa_l \mid e_l^*) - c_d \geq \hat{\pi}_{\bar\theta}^S \tag{13}$$

where $\hat{\pi}_{\bar\theta}^S$ denotes the supplier's off-equilibrium pay-off after he exerts $d = 0$, and chooses the best contract from the menu:

$$\hat{\pi}_{\bar\theta}^S = \max_{\hat{e}_{\bar\theta} \in \{0,1\}} \{\pi_{\bar\theta}^S(\omega^f, \omega_h, Y_h, \kappa_h \mid \hat{e}_{\bar\theta}), \pi_{\bar\theta}^S(\omega^f, \omega_l, Y_l, \kappa_l \mid \hat{e}_{\bar\theta}),$$
$$\pi_{\bar\theta}^S(\omega^f, \omega_{\bar\theta}, Y_{\bar\theta}, \kappa_{\bar\theta} \mid \hat{e}_{\bar\theta})\}$$

– *Contract selection stage:* Given the decision made at the information-gathering stage, each supplier type must self-select the contract that is intended for his type. Since we have three types, we require three incentive compatibility constraints. The following constraints are self-selection constraints respectively for $\bar{\theta}$-, l-, and h-types:

$$\pi^S_{\bar\theta}(\omega^f, \omega_{\bar\theta}, Y_{\bar\theta}, \kappa_{\bar\theta} \mid e^*_{\bar\theta}) \geq \max\left\{ \max_{\hat e_{\bar\theta}\in\{0,1\}} \pi^S_{\bar\theta}(\omega^f, \omega_h, Y_h, \kappa_h \mid \hat e_{\bar\theta}), \max_{\hat e_{\bar\theta}\in\{0,1\}} \pi^S_{\bar\theta}(\omega^f, \omega_l, Y_l, \kappa_l \mid \hat e_{\bar\theta}) \right\} \quad (14)$$

$$\pi^S_l\left(\omega^f, \omega_l, Y_l, \kappa_l \mid e^*_l\right) \geq \max\left\{ \max_{\hat e_l\in\{0,1\}} \pi^S_l\left(\omega^f, \omega_h, Y_h, \kappa_h \mid \hat e_l\right), \max_{\hat e_l\in\{0,1\}} \pi^S_l\left(\omega^f, \omega_{\bar\theta}, Y_{\bar\theta}, \kappa_{\bar\theta} \mid \hat e_l\right) \right\} \quad (15)$$

$$\pi^S_h\left(\omega^f, \omega_h, Y_h, \kappa_h \mid e^*_h\right) \geq \max\left\{ \max_{\hat e_h\in\{0,1\}} \pi^S_h\left(\omega^f, \omega_l, Y_l, \kappa_l \mid \hat e_h\right), \max_{\hat e_h\in\{0,1\}} \pi^S_h\left(\omega^f, \omega_{\bar\theta}, Y_{\bar\theta}, \kappa_{\bar\theta} \mid \hat e_h\right) \right\} \quad (16)$$

where $\hat e_{\bar\theta}$ denotes the supplier's off-equilibrium process improvement action if he deviates and subsequently picks the best contract.

– *Process improvement stage:* Finally, after the contract selection, the supplier decides whether to exert process improvement or not. Since the process improvement decision is also not observable, the buyer must satisfy the moral hazard constraint in order to induce either $e^* = 0$ or $e^* = 1$. Since it is never beneficial for h-type supplier to exert process improvement decision, we need two moral hazard constraints. The moral hazard constraint for $\bar\theta$-type is given in equation (7), and the moral hazard constraint for l-type is given as follows:

$$\pi^S_l\left(\omega^f, \omega_l, Y_l, \kappa_l \mid e^*_l\right) \geq \pi^S_l\left(\omega^f, \omega_l, Y_l, \kappa_l \mid \hat e_l \neq e^*_l\right) \quad (17)$$

where $\hat e_l$ denotes the supplier's off-equilibrium process improvement action for l-type supplier.

4.2.2. Contract Design Problem in the Presence of Diagnostic Test. Note that the implementation constraints provided above for $d = 0$ and $d = 1$ are not to be imposed simultaneously. Indeed, either the constraint set for $d = 0$ or that for $d = 1$ needs to be imposed depending on whether the buyer decides to induce the diagnostic test on the supplier or not. If $d = 0$ is to be induced, the buyer's expected profit would be equal to $\pi^B_{\bar\theta}(\omega^f, \omega_{\bar\theta}, Y_{\bar\theta}, \kappa_{\bar\theta} \mid e^*_{\bar\theta})$, whereas under $d = 1$, it would be equal to $E_\theta \pi^B_\theta(\omega^f, \omega_\theta, Y_\theta, \kappa_\theta \mid e^*_\theta)$, where expectation is taken with respect to buyer's a-priori beliefs for h-type and l-type suppliers, , α, and $1-\alpha$, respectively. Maximizing the buyer's expected profit with respect to decision variables and menu of contracts subject to appropriate implementation constraints would lead to the following optimization problem for the buyer:

$$\max\{P_1, P_2\} \quad (18)$$

where the sub-problem P_1 corresponds to the buyer's optimal contract and improvement effort when inducing $d = 0$:

$$P_1: \max_{e^*_{\bar\theta},(\omega^f,\omega_{\bar\theta},Y_{\bar\theta},\kappa_{\bar\theta})} \pi^B_{\bar\theta}\left(\omega^f, \omega_{\bar\theta}, Y_{\bar\theta}, \kappa_{\bar\theta} \mid e^*_{\bar\theta}\right) \quad (19)$$

Subject to Constraints (6, 7, 12, 14)

and the sub-problem P_2 corresponds to the buyer's optimal menu of contracts and improvement effort when inducing $d = 1$:

$$P_2: \max_{e^*_h,e^*_l,(\omega^f,\omega_h,Y_h,\kappa_h),(\omega^f,\omega_l,Y_l,\kappa_l)} \alpha\pi^B_h\left(\omega^f, \omega_h, Y_h, \kappa_h \mid e^*_h\right) + (1-\alpha)\pi^B_l\left(\omega^f, \omega_l, Y_l, \kappa_l \mid e^*_l\right)$$

Subject to Constraints (10, 11, 13, 15, 16, 17)

(20)

We analyze the above optimization problem (18) in two stages. In the first stage analysis, we consider the buyer's contract design problem and characterize the optimal menu of contracts for sub-problems P_1 and P_2, separately. In the second stage, we compare the buyer's optimal expected profits under P_1 and P_2, and characterize the optimal diagnostic decision d^* and menu of contracts that induces d^* on the supplier. Delegating the details of the analysis to Appendix S1, we focus on key findings as follows:

4.2.3. Analysis of Contract Design Problem for $d = 0$. We first characterize the conditions under which the process improvement is induced on the supplier under $d = 0$. A natural way to answer this question would be to follow the same approach employed for the analysis of the buyer's contract design problem in the absence of the diagnostic test as described in section 4.1. However, there is an important factor, which significantly alters the analysis under $d = 0$ from its counterpart in section 4.1. Namely, the buyer needs to take into account not only the moral hazard problem for process improvement stage but also that for diagnostic stage. Interestingly enough, the moral hazard constraints for inducing diagnostic test and process improvement on the supplier interact with each other, which in turn restricts the implementability of process improvement $e_{\bar\theta} = 1$ under $d = 0$. The following result provides the sufficient and necessary condition under which $e_{\bar\theta} = 1$ can be implemented under $d = 0$:

LEMMA 3. (IMPLEMENTATION CONDITION TO INDUCE PROCESS IMPROVEMENT UNDER $d = 0$) *When the diagnostic test is available, the buyer can induce $e_{\bar\theta} = 1$ under $d = 0$ if and only if $c_d \geq \alpha c_p$.*

Recall from Lemma 2 in section 4.1 that there always exists a feasible contract that implements process improvement in the absence of a diagnostic test. However, Lemma 3 implies that this does not hold true in general when the supplier has access to diagnostic technology. This is also known as two-stage moral hazard problem in mechanism design literature (Fuchs 2007, Jarque 2010) and related to the conflicting incentives between the sequential implementation conditions for a diagnostic test and process improvement. Note that when the condition in Lemma 3 is not satisfied, that is, $c_d < \alpha c_p$, rather than exerting process improvement effort, $\bar{\theta}$-type supplier can always lower his cost by first learning his true reliability and then improving his process only when he learns that he is of l-type. Note that by doing that, he would incur c_d but save c_p with probability α. Therefore, his net savings would be $\alpha c_p - c_d$, which is positive when $c_d \leq \alpha c_p$. To summarize, under $d = 0$, the process improvement $e_{\bar{\theta}} = 1$ can never be implemented when $c_d \leq \alpha c_p$.

4.2.4. Analysis of Contract Design Problem for $d = 1$. As opposed to $d = 0$ case, the moral hazard problems for process improvement and diagnostic decisions under $d = 1$ do not interact in such a way that would restrict the implementability of the process improvement decision of the supplier. This means that the buyer can always offer a feasible and incentive-compatible menu of contracts that would induce process improvement on the supplier under $d = 1$. However, recall that the optimal process improvement decision under $d = 1$ is type-dependent, that is, it is conducted only by l-type supplier. To differentiate the type-dependent process improvement under $d = 1$ from its type-independent counterpart under $d = 0$, we will denote the former by *conditional* and the latter by *unconditional* process improvement decisions.

From Lemma 3, the buyer cannot induce (unconditional) process improvement $e_{\bar{\theta}} = 1$ under $d = 0$ on the supplier when $\frac{c_d}{c_p} \leq \alpha$. However, when $\frac{c_d}{c_p} > \alpha$, both conditional and unconditional process improvement decisions can be implemented, therefore, we need to compare the buyer's expected payoffs under conditional and unconditional process improvement policies. Leaving the details in Appendix S1, we characterize the optimal diagnostic decision d^*, the optimal menu of contracts, supplier's decisions, and all agency costs in the following Proposition 3:

Proposition 3. (*Equilibrium Characterization when Diagnostic Test is Available*) *When the diagnostic test is available, the equilibrium can be divided into 5 regions when $\frac{1-\varphi}{1-\rho} \geq \frac{1}{1-\alpha}$ and 6 regions when $\frac{1-\varphi}{1-\rho} < \frac{1}{1-\alpha}$ as described below as well as shown in Table 4.*

- *Region A when $\frac{1-\varphi}{1-\rho} \geq \frac{1}{1-\alpha}$, and Regions A_1 and A_2 otherwise: The supplier is induced to exert a diagnostic test and conduct process improvement effort only when he learns that he is of type l, that is, $d = 1$, $e_l = 1$, and $e_h = 0$.*
- *Region B: The supplier is induced not to exert diagnostic test and conduct process improvement effort irrespective of his true type, that is, $d = 0$, $e_{\bar{\theta}} = 1$.*
- *Regions C_1, C_2, and C_3: The supplier is induced to exert neither a diagnostic test nor process improvement effort, that is, $d = 0$, $e_{\bar{\theta}} = 0$.*

Table 4 Optimal Menu of Contracts and Decisions in the Presence of Diagnostic Test

	Region	Induced Diagnostic Decision	Optimal Menu of Contracts* $\left[\omega^f, \omega_{\check{\theta}}, Y_{\check{\theta}}, \kappa_{\check{\theta}}\right]$ where $\check{\theta} \in \{h, l, \bar{\theta}\}$	Induced Process Effort	Information/ Limited liability rent	Channel loss
If $\left[\frac{1-\varphi}{1-\rho} \geq \frac{1}{1-\alpha}\right]$	A	$d^* = 1$	$\left[c_s, c_d, \frac{1-\varphi}{\rho-\varphi}c_p + \frac{1-\rho}{(\rho-\varphi)(1-\alpha)}c_d, \frac{c_p+c_d}{(\rho-\varphi)(1-\alpha)}\right]$ $\left[c_s, c_d+c_p, \frac{1-\rho}{\rho-\varphi}c_p + \frac{1-\rho}{(\rho-\varphi)(1-\alpha)}c_d, \frac{\rho}{\rho-\varphi}c_p + \frac{\rho}{(\rho-\varphi)(1-\alpha)}c_d\right]$ $\left[c_s, 0, 0, \frac{c_p+c_d}{(\rho-\varphi)(1-\alpha)}\right]$	$e_h^* = 0$ $e_l^* = 1$	$\frac{\alpha(1-\varphi)}{\rho-\varphi}c_p + \frac{\alpha(1-\rho)}{(\rho-\varphi)(1-\alpha)}c_d$	0
If $\left[\frac{1-\varphi}{1-\rho} < \frac{1}{1-\alpha}\right]$	A_1	$d^* = 1$	$\left[c_s, c_d, \frac{1-\varphi}{\rho-\varphi}c_p + \frac{c_d}{\alpha}, \frac{(c_p/(\rho-\varphi))+(c_d/\alpha)}{(1-\alpha)(1-\rho)}\right]$ $\left[c_s, c_d+c_p, \frac{1-\rho}{\rho-\varphi}c_p, \frac{\rho}{\rho-\varphi}c_p\right]$ $\left[c_s, 0, 0, \frac{(c_p/(\rho-\varphi))+(c_d/\alpha)}{(1-\alpha)(1-\rho)}\right]$	$e_h^* = 0$ $e_l^* = 1$	$\frac{\alpha(1-\varphi)}{\rho-\varphi}c_p + c_d$	0
	A_2	$d^* = 1$		$e_h^* = 0$ $e_l^* = 1$	$\frac{\alpha(1-\varphi)}{\rho-\varphi}c_p + c_d$	$c_d - \alpha c_p$
	B	$d^* = 0$	$\left[c_s, c_p, \frac{1-\rho}{(\rho-\varphi)(1-\alpha)}c_p, \frac{\rho}{(\rho-\varphi)(1-\alpha)}c_p\right]$	$e_{\bar{\theta}}^* = 1$	$\frac{\alpha(1-\rho)}{(\rho-\varphi)(1-\alpha)}c_p$	0
	C_1	$d^* = 0$	$[c_s, 0, 0, 0]$	$e_{\bar{\theta}}^* = 0$	0	$(1-\alpha)((\rho-\varphi)r - c_p) - c_d$
	C_2	$d^* = 0$		$e_{\bar{\theta}}^* = 0$	0	$(1-\alpha)(\rho-\varphi)r - c_p$
	C_3	$d^* = 0$		$e_{\bar{\theta}}^* = 0$	0	0

Notes: For regions A, A_1, and A_2, the first two contracts are offered for h- and l-types, respectively and the last one is offered for $\bar{\theta}$-type. For all the other regions, the optimal contract is of pooling type, therefore, there is single contract offered for all the types.

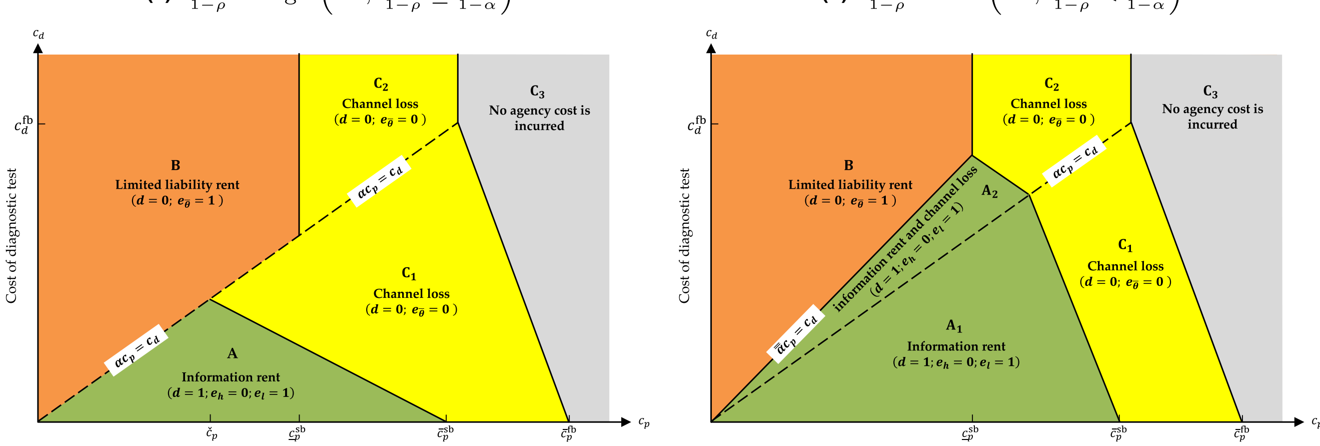
The optimal menu of contracts, and agency costs for each region are characterized in Table 4 and Figure 5.

The main observations from Proposition 3 are as follows:

- Even though there is nothing that prevents the buyer from implementing process improvement effort on the supplier under $d = 1$ when $\frac{c_d}{c_p} > \alpha$, in equilibrium, the diagnostic test is mostly induced on the supplier when $\frac{c_d}{c_p} \le \alpha$ (see Region A in Figure 5a and Region A_1 in Figure 5b) except when $\frac{1-\varphi}{1-\rho}$ is low (see Region A_2 in Figure 5b). This is due to two reasons. First, when $\frac{c_d}{c_p} > \alpha$, the cost of a diagnostic test (c_d) exceeds its benefit (αc_p). Hence, inducing the diagnostic test would lead to *channel loss* with respect to first-best outcome. Second, in the decentralized case, the diagnostic test creates information asymmetry between the buyer and supplier, which would in turn lead to *information rent*. Note that similar to limited liability rent discussed in section 4.1, information rent is also proportional to incentive payment term Y_θ in the contract. The reasoning parallels here. Namely, both incentive and disincentive terms, , Y_θ, and κ_θ, respectively, cancel out each other if the supplier turns out to be of l-type. That means, the buyer can always extract full surplus from an l-type supplier. However, the same argument does not apply to h-type supplier, who enjoys only the incentive payment Y_h. Also, the buyer cannot reduce Y_h for h-type either, because if she does, h-type supplier would imitate that he is of l-type and pick the contract designed for him. To summarize, information rent is proportional to Y_h and paid only to the h-type. Since the likelihood of supplier being of h-type is α, the expected information rent would be equal to $\alpha \times Y_h$.
- Interestingly, in Region A_2 of Figure 5b, the buyer induces the diagnostic test on the supplier even if c_d is higher than αc_p. The rationale behind this is related to the relative comparison between information and limited liability rents that buyer has to pay to the h-type supplier with and without diagnostic test, respectively. Note that the information rent (paid to the supplier if the diagnostic test is induced) increases in the degree of information asymmetry created by the diagnostic test, whereas the limited liability rent (paid if the diagnostic test is not induced) does not depend on this factor. The ratio denoted by $\frac{1-\varphi}{1-\rho}$ does exactly measure how large the information asymmetry between the partners will be after the supplier conducts a diagnostic test and learns his true type. Specifically, the numerator and denumerator capture the differences in reliabilities between h- and l-type suppliers before and after process improvement effort, respectively. That means, if this ratio is relatively high, the diagnostic test would provide the supplier with a significant *actionable intelligence* about whether or not to improve his process, which in turn results in higher information rent for the buyer. On the other hand, when $\frac{1-\varphi}{1-\rho}$ is low (which is the case in Region A_2 of Figure 5b), the informational content of the diagnostic test is not too much for the supplier. This means that the buyer is better off with inducing the

Figure 5 Agency Costs in the Presence of Diagnostic Test [Color figure can be viewed at wileyonlinelibrary.com]

(a) $\frac{1-\varphi}{1-\rho}$ is high $\left(\text{i.e., } \frac{1-\varphi}{1-\rho} \ge \frac{1}{1-\alpha}\right)$ **(b)** $\frac{1-\varphi}{1-\rho}$ is low $\left(\text{i.e., } \frac{1-\varphi}{1-\rho} < \frac{1}{1-\alpha}\right)$



Notes: $\check{c}_p = \frac{(\rho-\varphi)^2(1-\alpha)^2}{\alpha(1-\varphi)+(\rho-\varphi)(1-\alpha)-\alpha^2(\rho-\varphi)} r$; $c_d^{\text{fb}} = \alpha(1-\alpha)(\rho-\varphi)r$; $\underline{c}_p^{\text{sb}} = \frac{(\rho-\varphi)^2(1-\alpha)^2}{\alpha(1-\rho)+(\rho-\varphi)(1-\alpha)} r$; $\bar{c}_p^{\text{sb}} = \frac{(\rho-\varphi)^2(1-\alpha)}{\alpha(1-\varphi)+(\rho-\varphi)(1-\alpha)} r$; $\bar{c}_p^{\text{fb}} = (\rho-\varphi)r$; $\bar{\bar{\alpha}} = \frac{\alpha^2(1-\rho)}{2(\rho-\varphi)(1-\alpha)}$.

diagnostic test on the supplier even if $c_d > \alpha c_p$ because it allows the buyer to implement the conditional process improvement on the supplier at a lower agency cost (information rent) compared to unconditional one at a higher agency cost (limited liability rent).

- The situation facing the buyer is just opposite when $\frac{1-\varphi}{1-\rho}$ is high. In this case, because of the high degree of informational content of the diagnostic test, the buyer has incentive not to induce the diagnostic test on the supplier, and instead implement unconditional process improvement on him. But due to Lemma 3, inducing (unconditional) process improvement under $d = 0$ is not incentive-compatible for the supplier in Region C_1 of Figure 5a (because $c_d \leq \alpha c_p$). Therefore, the buyer faces with a different trade-off: (i) either she has to pay information rent under $d = 1$ if she decides to induce the diagnostic test, or (ii) she incurs channel loss under $d = 0$ if she chooses not to implement a process improvement effort at all. And since the former increases in both c_d and c_p, whereas the latter decreases in both of them (please refer to the information rent and channel loss expressions for Regions A and C_1, respectively, in Table 4 when $\frac{1-\varphi}{1-\rho}$ is high), the cost of information rent exceeds the cost of channel loss in Region C_1 of Figure 5a, where both c_p and c_d are sufficiently high. Interestingly, it implies that in Region C_1 of Figure 5a, the mere presence of the diagnostic test results in less reliable supply chain compared to the case where there is no diagnostic test available to the supply chain. We will see the impact of this on each party as well as total supply chain in more detail in the next section, when we explore the value of diagnostic test.

The above discussion provides pros and cons of diagnostic test in a decentralized supply chain. In the next section, we compare the optimal contract in the presence of diagnostic test (Proposition 3) to that in the absence of diagnostic test (Proposition 2) from the perspectives of the buyer, as well as the supplier and the total supply chain. It enables us to address the last research question of this study, namely, how information acquired by the supplier affects the buyer's and supplier's, as well as total supply chain profits.

5. Value of the Diagnostic Test

In sections 4.1 and 4.2, we consider two scenarios (i.e., diagnostic and no-diagnostic cases) between a buyer and a supplier both of whom are uninformed about the degree of supply risk, and then analyze the effectiveness of diagnostic tests as remedies for dealing with such a risk. In this section, we compare these scenarios by taking into account all sources of agency costs and analyze the value of diagnostic test for the supply chain parties. Recall that the buyer faces with a trade-off between channel-loss and limited liability for the implementation of $d = 0$, whereas the trade-off for $d = 1$ is between channel loss and information rent. Hence, in order to truly evaluate the diagnostic test, we need to consider all these three agency costs at the same time and compare their effects on the buyer's, supplier's, and total supply chain's payoffs.

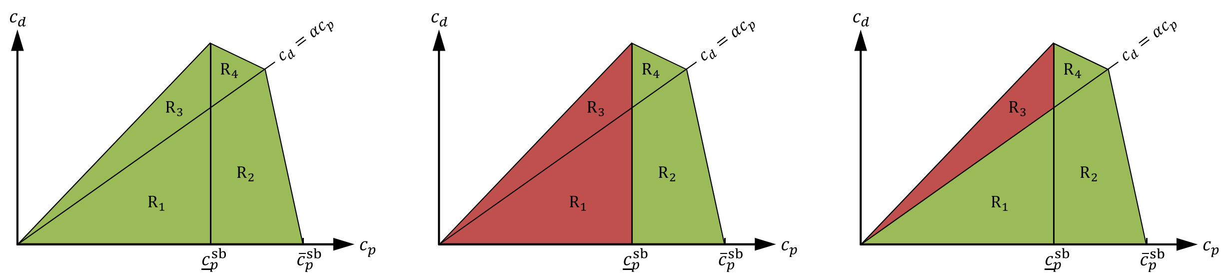
First of all, note that irrespective of whether the diagnostic test is available or not, the analyses conducted in sections 4.1, and 4.2 lead to exactly same equilibria in the regions where either the cost of process improvement c_p or the cost of the diagnostic test c_d is sufficiently high. In the former case, it is never optimal to exert the process improvement effort, whereas in the latter case, unconditional process improvement is always the best option to implement for the buyer. In either cases, the diagnostic test does not lead to any benefit to the buyer. Excluding these regions of indifference and overlapping the remaining regions of Propositions 2 and 3, we obtain four distinct comparison regions and completely characterize the value of diagnostic test (VOT) in each one of them as shown in Table 5.

For the sake of brevity, we elaborate the derivation process of VOT from the buyer's perspective. From the buyer's perspective, the value of test depends on the value of $\frac{1-\varphi}{1-\rho}$. When it is low - see the top panel in Table 5, the presence of the diagnostic test saves the buyer from incurring limited liability (in regions R_1 and R_3) or channel loss (in regions R_2 or R_4) at the expense of incurring information rent. On the other hand, when $\frac{1-\varphi}{1-\rho}$ is high - see bottom panel in Table 5, the presence of the diagnostic test saves the buyer from incurring limited liability at the expense of either information rent (in regions R_1 and L_1) or channel loss (in region L_2), and from incurring channel loss at the expense of information rent (in region R_2). Therefore, in all these cases, in order to characterize the net value associated with diagnostic test, we need to compare limited liability and/or channel loss with information rent. Delegating the details in Appendix S1, in what follows, we will provide the main insights from these comparative analyses:

- From Table 5, it is clear that the diagnostic test has both positive and negative impacts on the payoffs of supply chain parties. First of all, it is beneficial to both buyer and supplier as well as the total supply chain when the cost of process improvement is not too high and the cost of the diagnostic test is either comparable to or

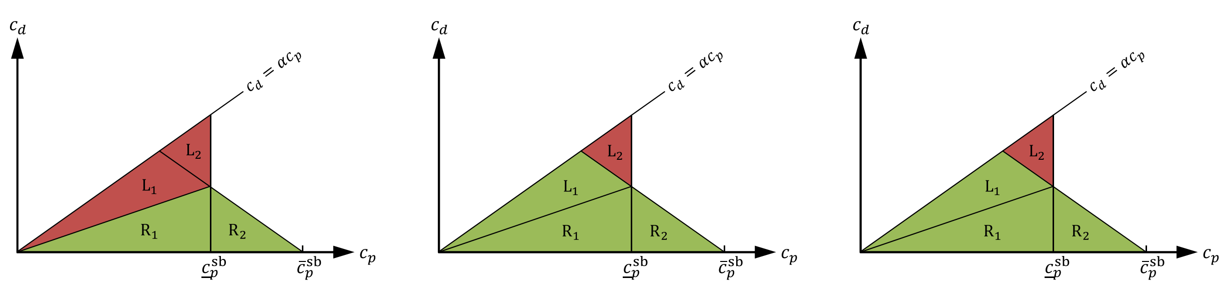
Table 5 Value of Diagnostic Test (VOT)

Region	Buyer	*h*-type supplier	Channel
		When $\frac{1-\phi}{1-\rho}$ is low (i.e., $\frac{1-\phi}{1-\rho} < \frac{1}{1-\alpha}$)	



Region	Buyer	h-type supplier	Channel
R_1	$\Pi^D \geq \Pi^{ND}$	$\Pi^D \leq \Pi^{ND}$	$\Pi^D \geq \Pi^{ND}$
R_2	$\Pi^D \geq \Pi^{ND}$	$\Pi^D \geq \Pi^{ND}$	$\Pi^D \geq \Pi^{ND}$
R_3	$\Pi^D \geq \Pi^{ND}$	$\Pi^D \leq \Pi^{ND}$	$\Pi^D \leq \Pi^{ND}$
R_4	$\Pi^D \geq \Pi^{ND}$	$\Pi^D \geq \Pi^{ND}$	$\Pi^D \geq \Pi^{ND}$

When $\frac{1-\phi}{1-\rho}$ is high (i.e., $\frac{1-\phi}{1-\rho}, \geq \frac{1}{1-\alpha}$)



Region	Buyer	h-type supplier	Channel
R_1	$\Pi^D \geq \Pi^{ND}$	$\Pi^D \geq \Pi^{ND}$	$\Pi^D \geq \Pi^{ND}$
L_1	$\Pi^D \leq \Pi^{ND}$	$\Pi^D \geq \Pi^{ND}$	$\Pi^D \geq \Pi^{ND}$
R_2	$\Pi^D \geq \Pi^{ND}$	$\Pi^D \geq \Pi^{ND}$	$\Pi^D \geq \Pi^{ND}$
L_2	$\Pi^D \leq \Pi^{ND}$	$\Pi^D \leq \Pi^{ND}$	$\Pi^D \leq \Pi^{ND}$

Notes: In the above table Π^D and Π^{ND} respectively correspond to the supply chain partner's profit with and without diagnostic test. The different colored regions in the above figures denote whether or not the diagnostic test brings value for each supply chain partner: green regions - value of diagnostic test is positive; red regions - value of diagnostic test is negative; and, white regions - diagnostic test has no value.

less than c_p. This makes sense because the main benefits of the diagnostic test come into play either if it helps the supplier (and indirectly the buyer) to exert the costly process improvement effort just when it is needed or if it saves him from incurring the cost when it is not. However, the VOT analysis shows that there are exceptions to this argument, and therefore, the diagnostic test is not always beneficial to either the buyer or supplier or interestingly under certain cases it is even detrimental to both buyer and supplier, hence, the total supply chain, *all at the same time*.

- Under a centralized supply chain, the diagnostic test is never needed when the cost c_d is more than αc_p. However, we see from the above proposition that the decentralization of supply chain leads to the diagnostic test being induced even when c_d is greater than αc_p (see Regions R_3 and R_4 when $\frac{1-\varphi}{1-\rho}$ is low). The rationale behind this is related to cost advantage of implementing process improvement effort on an informed supplier over uninformed one from the buyer's perspective. Namely, an uninformed supplier requires limited liability, whereas informed one requires information rent. Since information rent to be paid to the supplier is not too much for the buyer thanks to low degree of informational content of a diagnostic test (as measured by $\frac{1-\varphi}{1-\rho}$), the buyer is better off with inducing the diagnostic test on the supplier even if c_d is greater than αc_p.

- Interestingly, inducing the diagnostic test on the supplier even when it is too costly, that is, $c_d \geq \alpha c_p$ may sometimes be beneficial for the total supply chain (see region R_4). The reason for this is as follows. As characterized in Proposition 2 of section 4.1, the process improvement is never implemented in the absence of the diagnostic test when c_p is very high, that is, $c_p \geq c_p^{sb}$. However, as we see in Proposition 3 in section 4.2, the presence of the diagnostic test allows the buyer to implement process improvement albeit in a more costly fashion for the supply chain. This in turn increases the overall reliability of supply chain and hence the total surplus, which is shared by both parties. Similarly, when the cost of the diagnostic test c_d is less than αc_p, even though the VOT differs between buyer and supplier, it is in general positive for the supply chain (see below for the exception). In addition, if the cost of process improvement c_p is sufficiently high (i.e., $c_p \geq c_p^{sb}$), then both buyer and supplier are also better off with the diagnostic test (see region R_2 when $\frac{1-\varphi}{1-\rho}$ is both low and high).
- Finally, when both the cost of the diagnostic test and process improvement are low (i.e., $c_d \leq \alpha c_p$ and $c_p \leq c_p^{sb}$), the presence of diagnostic test may lead to quite unexpected outcomes for the supply chain parties. First of all, due to presence of diagnostic test, the unconditional process improvement under $d = 0$ can never be implemented by the buyer when $c_d \leq \alpha c_p$ (see Lemma 3). This does not cause any problem for the buyer when the degree of informational content of the diagnostic test is low because in this case, the buyer is still better off with implementing process improvement by inducing the diagnostic test on the supplier. Hence, VOT is positive for the buyer and total supply chain (and negative for the supplier) when $\frac{1-\varphi}{1-\rho}$ is low. However, things go awry for the buyer and even for the supplier when the opposite holds true, , when $\frac{1-\varphi}{1-\rho}$ is high. There are two scenarios. In the first case (see region L_1), the presence of diagnostic test hurts only the buyer. This is because implementing conditional process improvement by inducing $d = 1$ is costlier for the buyer than implementing (unconditional) process improvement in the absence of diagnostic test. In the second scenario (see region L_2), as the information rent gets too high, then the best (incentive-compatible) option for the buyer becomes not to implement any process improvement at all, which results in loss not only for herself but also for the supplier and total supply chain. As a result, in this region, the presence of diagnostic test results in a Pareto-inefficient outcome for all the parties in the supply chain.

This last point merits a remark. Recall that in a centralized setting, when c_p and c_d are not too high, improving the reliability of supply chain either conditionally or unconditionally always dominates doing nothing. However, option of diagnostic in the decentralized setting makes the first-best option too costly for the buyer, and the second-best option incentive-incompatible for the supplier, and leaves the (worst-case) third-best option of “doing nothing" as the only option for the supply chain parties.

6. Conclusion

In this study, we analyze the value of diagnostic test when supply chain parties are both uninformed about the supply-side risks due to lack of experience in new product development. This lack of information may lead to supply side problems, such as yield problems, long lead-times, and delayed production. Therefore, in order to reduce the likelihood of failure of a new product development project, the buyers may want their suppliers to invest in a costly diagnostic test technology, e.g., running a test production or conducting a proof-of-stage, before commencing the final production. This study aims to spotlight the importance of such a supply diagnostic test in a new product development project.

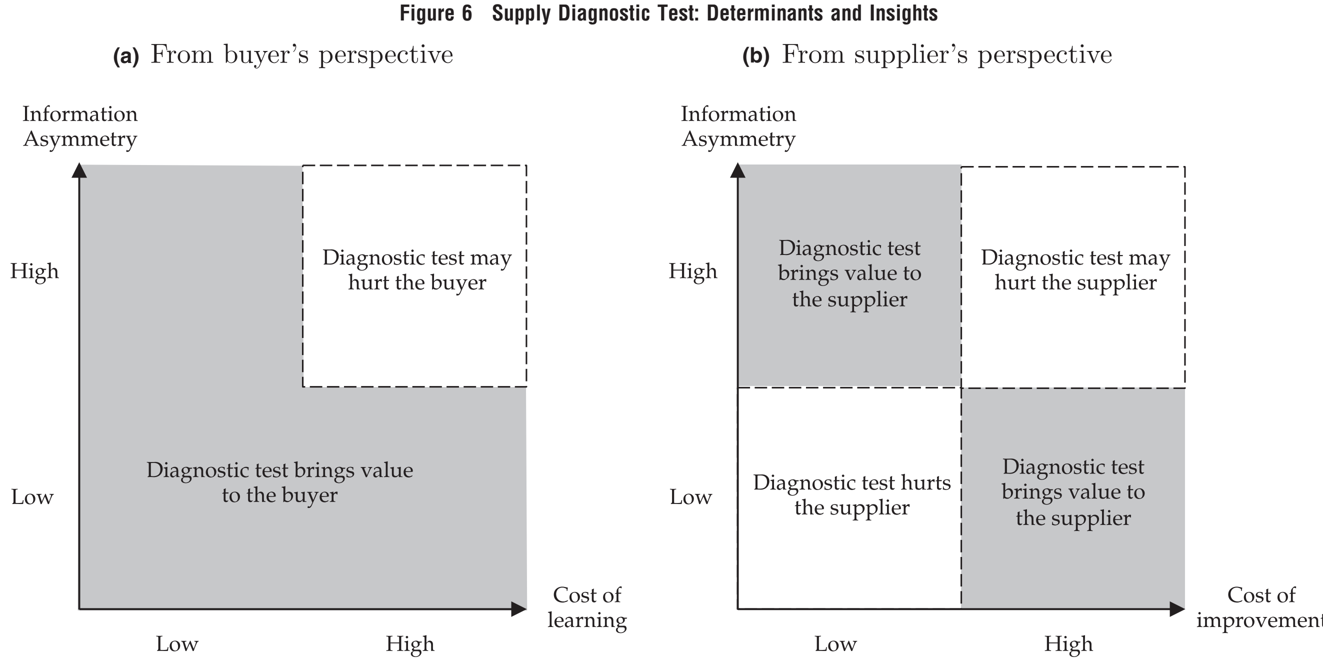
We develop a dyadic supply chain with a buyer who contracts with a supplier to manufacture a new product. Due to the lack of experience in manufacturing, the state of supply disruption is not known to both the buyer and supplier at the time of contract, hence both buyer and supplier face ex ante same uncertainty regarding the supply risk. However, the supplier may invest in an unobservable diagnostic test to acquire information about his true reliability, and use this information when deciding on an unobservable process improvement effort. Using this setting, we identify benefits and drawbacks of the diagnostic test. Specifically, if the buyer offers a contract that prevents the supplier from investing in the diagnostic test, then the supplier decides on process improvement *unconditionally* based only on his ex ante belief about his true reliability. This brings two different inefficiencies. The first one is related to inefficient improvement decision by an uninformed supplier. Specifically, due to lack of knowledge about his true reliability, an uninformed supplier may either over- or under-invest in process improvement, which results in channel loss. The second one is related to the cost of inefficient process improvement which has to be subsidized by the buyer due to the limited liability of an uninformed supplier. On the other hand, by inducing the diagnostic test on the supplier, the buyer can make supplier exert process improvement in more informed fashion, that is, *conditional* on his true reliability type. This right away eliminates the channel loss associated with the unconditional process improvement as well as the need for subsidy from the buyer in the form of limited liability rent. That being said, it creates information asymmetry between supply chain parties, hence the informed supplier armed with new information asks for information rent.

The key tradeoffs quantified above are similar to the ones faced by a buyer who decides whether or not to sign a BTS contract with her suppliers. Namely, if the buyer offers a contract that does not induce any diagnostic test, then, she would be responsible for the reliability of the final product and need to spend additional money in order to incentivize an uninformed supplier to improve the process. We quantify this as the limited liability rent. On the other hand, if the buyer offers a (BTS) contract that induces the diagnostic test on her supplier, she can eliminate the agency cost of incentivizing the supplier to exert a process improvement. However, she faces now with an informed supplier who possesses proprietary information about the new product. We quantify the price of this proprietary information as the information rent to be demanded by the informed supplier in equilibrium. Therefore, the comparative analyses between limited liability and information rents conducted in this study also help us to evaluate the benefits and costs of BTS contracts over regular contracts.

Our results suggest that the value of the diagnostic test mainly depends on the relative cost of diagnostic test over the cost of process improvement $\frac{c_d}{c_p}$ and the amount of information asymmetry (or, equivalently, actionable information) that would result from the diagnostic test $\frac{1-\varphi}{1-\rho}$. In general, diagnostic test is beneficial to all the parties as long as both $\frac{c_d}{c_p}$ and $\frac{1-\varphi}{1-\rho}$ are not too high. This is expected because if both conditions are satisfied, the diagnostic test does not create too much of information asymmetry between buyer and supplier and at the same time helps the supply chain to achieve its first-best without incurring too much cost. However, there are two exceptions. First, we find that the diagnostic test still benefits the total supply chain even if it is too costly because the alternative scenario would lead the supplier not to exert any process improvement effort at all, which would cause more damage to the supply chain. Second, even if the cost of the diagnostic test is low, its presence can make all the supply chain parties worse off. The rationale is as follows. The fact that the diagnostic test leads to information rent for the buyer creates less incentive for her to induce it on the supplier. This in turn leads to less reliable supply chain with respect to the case when such a diagnostic test is not available, and consequently it hurts not only the buyer but also the supplier and total supply chain.

These results show that the benefits and costs of the diagnostic test would need to be carefully weighed. It is true that it helps the supplier to make more

Figure 6 Supply Diagnostic Test: Determinants and Insights



informed decision (efficiency-improving benefit), and helps the buyer to reduce the agency costs (strategic benefit). However, it also creates proprietary information for the supplier. If the incentives between the supply chain parties are not aligned properly, the information asymmetry amplified due to presence of diagnostic test could indeed neutralize all the benefits of diagnostic test, leading to the worst-case outcome for all the parties. Figure 6 summarizes the key determinants and the insights into the effects of supply diagnostic test in a decentralized supply chain. To summarize, the key factors for running a diagnostic test are the degree of actionable information asymmetry between buyer and supplier that would result from the diagnostic test as well as the costs associated with learning and process improvement. For the buyer, as long as the proprietary informational content and cost of diagnostic test are not too high, the diagnostic test creates has a positive value. On the other hand, for the supplier, the diagnostic test has a positive impact for the off-diagonal cases: that is, either informational content of the diagnostic test is high and cost of improvement is low or vice versa.

The results in this study also shed some light on the use of BTS-type contracts for new product development. If the new product needs a radically different manufacturing process which has not been tested before such as disruptive innovation (e.g., a new processing technology based on RISC-based chips), then BTS contracts would probably lead to significant proprietary information on the behalf of the contract manufacturer. This in turn increases the procurement cost of the product for the retailer. In this case, a less costly approach for the retailer would be to offer regular contracts, where all the new product risk is born by the retailer. Alternatively, if the new product is incrementally different from the previous versions such as sustaining innovations (e.g., CISC-based chips), then, our results suggest that BTS contracts would work better because the supplier-side diagnostic test would generate limited proprietary information. Secondly, the relative cost of diagnostic systems plays an important role on the value of BTS contracts. For example, the product innovations that are composed of multiple modules require less complicated detection system compared to the ones that are composed of tightly integrated systems. This implies that the relative cost of diagnostic test would be lower for a modular product than that for an integrated system. This suggests that BTS contracts create more value for the retailer when they are used in the manufacturing of modular innovations compared to integrated ones. Finally, if the new product contradicts with the existing competence of the contract manufacturer (i.e., competence-destroying innovation), then the cost of process improvement would be too high to be subsidized by the retailer. In this case, BTS contract enables the contract manufacturer to invest in costly process improvement just-in-time, and hence indirectly helps the retailer to reduce the agency costs.

Last but not least, we acknowledge that the model developed in this study can be extended in several ways. First, we assumed that the uninformed supplier's expected profit is always non-negative irrespective of θ. We repeated the entire analysis in sections 4 and 5 by relaxing these constraints and find that in this case the buyer does not have to pay the limited liability rent to the h-supplier in the absence of diagnostic test. This in turn decreases the value of the diagnostic test for the buyer and h-type supplier and increases for l-type supplier. Second, the contract analyzed in this study has a fixed term that is common for all the supplier's types and paid before the supplier makes contract selection decision. We explored the value of diagnostic test under a different contract in which all the terms are contingent on the supplier's type and the supplier makes both participation and contract selection decisions after the diagnostic stage, and showed that our results from section 5 hold true. Third, we assume that fully reliable supplier (h-type) does not need process improvement. One can relax this and consider that both l- and h-type suppliers have to improve their processes albeit at different levels. We expect that this extension would decrease the value of diagnostic test, and make unconditional process improvement more beneficial to the supply chain partners. Also, we assume that the supply chain parties only interact through contracts. Alternatively, one can consider several other strategies such as information sharing, audit, and other collaborative strategies (e.g., Kim and Netessine 2013) which would affect the degree of incentive and information asymmetries between supply chain parties. We firmly believe that endogenous information acquisition has both operational and strategic impacts on the evolving supply chains, where characteristics of products and supply risks faced by the firms are dynamically changing and parties have to make sourcing and production decisions without insight into these characteristics. Along these lines, the models and results presented in this study would contribute toward capturing the impact of endogenous information in a decentralized supply chain setting.

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Notes

[1]To avoid more complexity, and focus on supply-side risk in new product launch and the impact of diagnostic test on that, we assume that the market demand is known at the time of the contract and, without loss of generality, we normalize demand to be one unit, that is, $D = 1$.

[2]The same assumption is made in most of new product development literature (see Kim and Netessine 2013 and references therein) where due to the newness of the product, both buyer and manufacturer share the same a-priori beliefs about the operational characteristics (such as cost and reliability) of the product at the beginning.

[3]We acknowledge that considering the h-type as fully reliable supplier simplifies the equilibrium characterization, and at the same time, it gives the opportunity of answering the main research questions of this study. We discuss the potential implications of relaxing this assumption in section 6.

[4]As we will show latter, this fundamental difference, which is particularly important in different situations such as new product development project, causes different source of inefficiencies in buyer's optimal contract design problem. This type of problem is known as adverse selection with *"endogenous information structures"*. Refer to Laffont and Martimort (2002) for a detailed discussion.

[5]According to Opus 2013, this trend has resulted in approximately half of $15.9 trillion in global merchandise trade being realized via deferred payment method (also known as "open accounts").

[6]Similar contracts are also used between manufacturers and customers in aerospace and defense industry, where the manufacturers are expected to incur costly investments to resolve several product and manufacturing related uncertainties for large-scale custom-made products.

[7]This approach constitutes the basis for any dynamic interaction between two uninformed parties, one of which may receive new but non-verifiable information over time - see Xiong and Chen (2013, 2014) that follow similar mechanism design approaches to address the incentive-compatibility problem through contracting in the case of endogenous information asymmetry.

[8]These constraints are also referred to as *limited liability* constraints in the economics literature. Please refer to Chapter 3 in (Laffont and Martimort 2002).

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Appendix S1: Proofs.