Supply Disruptions, Asymmetric Information, and a Backup Production Option

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We study a manufacturer that faces a supplier privileged with private information about supply disruptions. We investigate how risk-management strategies of the manufacturer change and examine whether risk-management tools are more or less valuable in the presence of such asymmetric information. We model a supply chain with one manufacturer and one supplier, in which the supplier's reliability is either high or low and is the supplier's private information. On disruption, the supplier chooses to either pay a penalty to the manufacturer for the shortfall or use backup production to fill the manufacturer's order. Using mechanism design theory, we derive the optimal contract menu offered by the manufacturer. We find that information asymmetry may cause the less reliable supplier type to stop using backup production while the more reliable supplier type continues to use it. Additionally, the manufacturer may stop ordering from the less reliable supplier type altogether. The value of supplier backup production for the manufacturer is not necessarily larger under symmetric information; for the more reliable supplier type, it could be negative. The manufacturer is willing to pay the most for information when supplier backup production is moderately expensive. The value of information may increase as supplier types become uniformly more reliable. Thus, higher reliability need not be a substitute for better information.

1. Introduction

In March 2007, following the deaths of numerous pets, Menu Foods Corp., a producer of pet food, had to recall more than 60 million cans and pouches of dog and cat foods for more than 100 pet food brands. Myers (2007) reports that the deaths were linked to melamine, an industrial chemical suspected of causing kidney and liver failure. The melamine was traced to wheat gluten, which Menu Foods (a Canadian firm) had bought from ChemNutra (a U.S.-based supplier), which, unbeknownst to Menu Foods, had outsourced it to Xuzhou Anying Biologic Technology Development Co. Ltd. (a Chinese supplier). This example illustrates that, as supply chains are extended by outsourcing and stretched by globalization, disruption risks and lack of visibility into a supplier's status can both worsen. The possible causes for supply disruptions are myriad, for instance, supplier bankruptcy, labor strikes, and machine breakdown (Sheffi 2005).

As supply risks increase, it is crucial for manufacturers to learn how to anticipate, prepare for, and manage potential supply disruptions. The losses due to supply disruptions can be huge. For example, shortly after initial recalls were issued on March 16, 2007, the market capitalization of Menu Foods Corp. lost about half its value, dropping to $70 million. Generally, Hendricks and Singhal (2003; 2005a, b) find that firms that experienced supply glitches suffer from declining operational performance and eroding shareholder value (e.g., the abnormal return on stock of such firms is negative 40% over three years).

A manufacturer has a number of choices when managing its supply risk, including supplier qualification screening, multisourcing, flexibility, and penalties levied for supplier nonperformance. Intuitively, the effectiveness of risk-management tools used by a manufacturer depends on information the manufacturer has about the supplier. For example, risk-management measures put into place by Menu Foods

would likely have been different, had it known that ChemNutra was outsourcing to a Chinese supplier. In practice, suppliers often have better information about their likelihood of experiencing a production disruption than the manufacturers they serve, because of the suppliers' private knowledge of their financial status, state of operations, or input sources. However, most of the extant research on supply disruptions assumes that the manufacturer and supplier are equally knowledgeable about the likelihood of supply disruptions. The majority of papers that incorporate asymmetric information do so in the context of suppliers' costs, and only a few model asymmetric information about supply disruptions. There is a crucial difference between asymmetric information about suppliers' costs and about supply disruptions. Supply disruptions affect not only the manufacturer's cost, but also the manufacturer's risk profile (risk-return trade-off). As a consequence, to handle uncertainty about supply disruptions, the manufacturer can not only design information-eliciting contracts (as considered in the economics literature), but can also avail itself of various operational risk-management tools.

To address these gaps in the current literature, we investigate the interaction between risk-management strategies and asymmetric information about supplier reliability. We address the following questions:

Research Question 1: How do a manufacturer's risk-management strategies change in the presence of asymmetric information about supply reliability?

Research Question 2: How much would the manufacturer be willing to pay to eliminate information asymmetry?

Research Question 3: Are risk-management tools more or less valuable when there is information asymmetry?

Research Question 4: How do answers to the above questions depend on changes in the underlying business environment, such as supply base heterogeneity or the manufacturer's contracting flexibility?

In answering these questions, we limit our consideration within the set of possible risk-management strategies. We examine penalties for nondelivery and a manufacturer's ability to offer contract alternatives to a supplier. Penalty clauses in contracts are a common means for buyers to recover damages for nondelivery.[1] The penalty amount is mutually agreed on at the time of contracting as a proactive way to avoid costly litigation for damages in the event of nondelivery. We assume that, had litigation occurred, the supplier would have been found to be at fault for the disruption.[2] As an alternative to the penalty clause, one could use a canonical, two-part tariff (fixed plus variable payment) contract and obtain the same equilibrium outcome as in our contract with penalty clause. Either the variable payment or the penalty provides an incentive to the supplier to look for alternative means of satisfying its obligations.

In our model, we call such alternatives *backup production*. Backup production could take many forms. For the Menu Foods Corp. example, on disruption a supplier like ChemNutra might re-source its wheat gluten from a different second-tier supplier (not Xuzhou Anying, which was the culprit of the disruption), install different quality controls, produce the wheat gluten itself, or perhaps use a combination thereof. Backup production sometimes involves heroic efforts by the supplier. For example, in 1997, when a fire at one of Toyota's suppliers—Aisin Seiki—threatened to halt production at many Toyota plants, Aisin Seiki averted disruption by shifting production to its own suppliers and other firms (including some outside the automotive industry; see Nishiguchi and Beaudet 1998). Where backup production is infeasible or implausible, our paper captures this by including in its model the possibility that backup production is prohibitively expensive and hence never used. In addition, we extend our analysis to the case where the manufacturer has access to its own backup production option.

We use a single-period, single-supplier, single-manufacturer model where the supplier is subject to a random production disruption, the likelihood of which is the supplier's private information. There are two supplier types, classified according to their reliability: high and low. In case of a production disruption, the supplier has two choices: use a perfectly reliable (but costly) backup production option to fulfill the manufacturer's order or pay the manufacturer a penalty. Using mechanism design theory, we find the optimal menu of contracts offered by the manufacturer to the supplier and obtain answers to our research questions. We emphasize a few of our results below.

Because backup production at the supplier improves the chances of products being delivered to the

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[1] What we call penalties in this paper are known, in precise legal terms, as "liquidated damages." To be court-enforceable, liquidated damages must not exceed damages that the buyer reasonably expects to suffer as a result of supplier nonperformance (Corbin 2007). The penalties studied in this paper satisfy this requirement. For more on nonperformance remedies and contract law, see Plambeck and Taylor (2007) and references therein.

[2] An example of this is the suit brought by medical device manufacturer Beckman Coulter against its circuit board supplier Flextronics, after Flextronics exited the medical device circuit board business without delivering the units promised to Beckman Coulter (*Beckman Coulter v. Flextronics*, OCSC Case No. 01CC08395, September 24, 2003, Orange County Superior Court), described at http://www.callahan-law.com/verdicts-settlements/fraud-beckman-coulter/index.html.

manufacturer, one might intuitively expect that the manufacturer is more likely to encourage the use of this tool when working with a less reliable supplier. However, under information asymmetry, we observe that this need not be true, addressing *research question* 1. In an effort to correctly set incentives for a more reliable supplier, the manufacturer may force a less reliable supplier to pay penalties in case of a disruption, while asking a more reliable supplier to use backup production.

Addressing *research question* 2, the value of perfect information for the manufacturer depends on the cost of the supplier's backup production option. Where backup production is cheap, the value of information is small. The value of information is the greatest for moderately costly backup production, where the manufacturer, in an attempt to control the incentives of a more reliable supplier, decides to deviate from the risk-management strategy that is optimal under symmetric information. Furthermore, jumping to *research question* 4, as the reliability gap between the two supplier types increases, the value of information for the manufacturer increases as well. Interestingly, the value of information may also increase as supplier types become uniformly more reliable. Thus, higher reliability need not be a substitute for better information.

Intuitively, the better the manufacturer's information about the supplier's reliability, the more precisely it can execute risk-management actions such as ensuring the supplier would exercise its backup production option, and the more valuable the presence of such an option is for the manufacturer. In contrast to this intuition, we find that the supplier's backup production option may become less valuable if better information about the supplier becomes available, addressing *research question* 3.

The paper is organized as follows. In §2, we briefly review related literature. The model is described in §3. In §4, we present the optimal contracts under symmetric information as a benchmark for our study of asymmetric information. The optimal menu of contracts under asymmetric information is presented in §5. Value of information, value of backup production, and the interaction between them are explored in §6. We conduct a sensitivity analysis in §7. In §8, we extend our model to allow for the manufacturer's backup production option. In §9, we summarize managerial implications, discuss model limitations, and suggest future research directions. Proofs and tables with technical results can be found in the e-companion.[3]

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[3] An electronic campanion to this paper is available as part of the online version that can be found at http://mansci.journal.informs. org/.

2. Literature Review

Supply chain risk management has attracted interest from both researchers and practitioners of operations management. Chopra and Sodhi (2004) and Sheffi (2005) provide a diverse set of supply disruption examples. Various operational tools that deal with supply disruptions have been studied: multisourcing (e.g., Anupindi and Akella 1993; Tomlin 2005; Babich et al. 2005, 2007), alternative supply sources and backup production options (e.g., Serel et al. 2001, Kouvelis and Milner 2002, Babich 2006), flexibility (e.g., Van Mieghem 2003, Tomlin and Wang 2005), and supplier selection (e.g., Deng and Elmaghraby 2005). For a recent review of supply-risk literature, see Tang (2006).

These and the majority of other papers in the supply-risk literature assume that the distribution (likelihood) of supply disruptions is known to both the suppliers and the manufacturer. In contrast, we assume that the supplier is better informed about the likelihood of disruption. There are few papers that consider the issue of the manufacturer not knowing the supplier reliability distribution. For instance, Tomlin (2008) studies a model where the manufacturer faces two suppliers, one with known and the other with unknown reliability. The manufacturer learns about the latter supplier's reliability through Bayesian updating. In our model, information is also revealed, but through a contract choice rather than through repeated interactions. In Gurnani and Shi (2006), a buyer and supplier have differing estimates of the supplier's reliability. Unlike our setting, the buyer's beliefs about reliability are not affected by knowing the supplier's self-estimate. Depending on whose estimate is larger, the authors employ contract terms incorporating either downpayment or non-delivery penalty.

Disruptions in supply chains could be caused by quality problems, and several papers have examined information asymmetry in quality control. For instance, Baiman et al. (2000) study a moral hazard issue surrounding the fact that both the supplier and the manufacturer can exert costly effort to prevent (requiring supplier effort) or weed out defective items. Lim (2001) examines a problem where the manufacturer can inspect incoming units at a cost to identify defects. If inspection is not done and a defective unit is passed on to the consumer, the channel incurs warranty costs. The central theme in this literature is how to allocate quality-related costs among the channel partners and/or how to motivate several parties to exert costly quality improvement efforts.

In the operations contracting literature, prior work has examined situations in which cost information is

private, be it the manufacturer's cost (Corbett et al. 2004) or the supplier's cost (Corbett 2001). In addition, the latter is extensively studied in the literature on procurement auctions under asymmetric information (Rob 1986, Dasgupta and Spulber 1990, Che 1993, Beil and Wein 2003, Elmaghraby 2004, Chen et al. 2005, Kostamis et al. 2006, Wan and Beil 2009). However, as discussed in the introduction, there is a crucial difference between asymmetric information about suppliers' costs (studied in those papers) and asymmetric information about supply disruptions (studied here).

3. Model

We model a stylized supply chain in which a manufacturer purchases a product from a supplier to satisfy market demand. The supplier is unreliable in that its regular production is subject to a random disruption. We assume there are two types of suppliers in the market: high reliability and low reliability. These types differ from each other in the likelihood that they will suffer a disruption and in their cost of regular production. Let the fraction of high-reliability suppliers in the market be $\alpha \in (0, 1)$. We hereafter refer to high- and low-reliability suppliers as high type and low type and distinguish them with labels H and L. For a type-i supplier, $i \in \{H, L\}$, we represent the random yield of its regular production as a Bernoulli random variable ρ_i having success probability θ_i; that is,

$$\rho_i = \begin{cases} 1 & \text{with probability } \theta_i, \\ 0 & \text{with probability } 1 - \theta_i, \end{cases} \quad (1)$$

where probability θ_i can be interpreted as a measure of the supplier's reliability. The success probabilities are $\theta_H = h$ and $\theta_L = l$, where $1 > h > l > 0$. We assume that it costs a type-i supplier c_i (per unit) to run regular production, regardless of whether the run is disrupted. Although we allow c_H and c_L to be different, the high type is assumed to be the more cost-efficient supplier; that is, the expected cost of successfully producing one unit using regular production is smaller for the high-type supplier:[4]

ASSUMPTION 1. $c_L/l > c_H/h$.

In addition to a regular production run, the supplier has access to a backup production option in case of disruption. We assume that backup production is perfectly reliable, with unit cost b.[5] We make the following assumption on b:

ASSUMPTION 2. $b > c_H/h$.

In other words, the cost of backup production is greater than the high-type supplier's expected cost of successfully producing one unit using regular production. As explained in §3.1, this assumption avoids the situation in which neither type of supplier uses regular production before running backup production.

To focus on the effects of supply risk without additional complications from demand uncertainty, we assume the manufacturer faces a deterministic demand, D, for the product. In other words, demand is known at the time the manufacturer places its order. The demand is infinitely divisible, and without loss of generality, we normalize it to $D = 1$. The manufacturer collects a revenue of r per unit sold. We restrict r as follows:

ASSUMPTION 3. $r > c_H/h$.

If this assumption does not hold, the manufacturer would not order from either supplier type, because the unit revenue would be less than the expected cost of producing one unit.

To capture the manufacturer's lack of visibility into the supplier's reliability and cost, we assume that the supplier's type is its private information. All other information is common knowledge. The manufacturer designs a contract menu without knowing the type of the supplier, who can act strategically and take advantage of its private information. We find the manufacturer's optimal menu of contracts using mechanism design theory. This approach dates back to the seminal work by Myerson (1981). Invoking the revelation principle (Dasgupta et al. 1979, Myerson 1979), the mechanism design problem can be solved by focusing on incentive compatible, direct revelation mechanisms. Therefore, the manufacturer offers two contracts, one for each type of supplier, and the supplier truthfully reports its type. In our model, a contract consists of three terms: an upfront transfer payment, $X_i \geq 0$; an order quantity, $q_i \geq 0$; and, because of the possibility of supplier nondelivery, a unit penalty, $p_i \geq 0$, for delivery shortfall, where $i \in \{H, L\}$.

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[4] Note that, for one unit of input going into regular production, the expected output of a type-i supplier is θ_i. Hence, were repeated regular production attempts allowed, the expected cost of successfully producing one unit using regular production would be c_i/θ_i.

[5] The analysis would go through if one assumed that the unit cost of backup production were a random variable whose value is realized after the supplier commits to using it. In such a case, the parameter b would represent the expected value of the random unit backup production cost.

Figure 1   Timing of Events
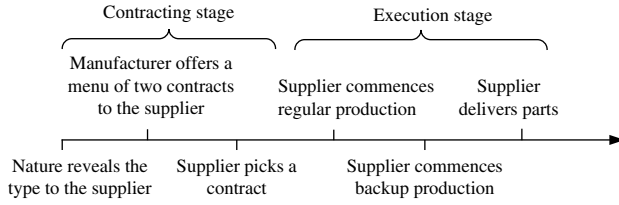
The timing of events is shown in Figure 1. The problem can be divided into two stages: contracting and execution. At the beginning of the contracting stage, nature reveals the supplier type to the supplier but not to the manufacturer. Then the manufacturer designs a menu of two contracts, (X_i, q_i, p_i), $i \in \{H, L\}$. The supplier then selects a contract (signals its type), concluding the contracting stage. In the execution stage, the supplier receives its transfer payment from the manufacturer, runs regular and/or backup production, makes delivery, and pays a penalty, if necessary.

We solve the problem by working backward from the execution stage. The next subsection presents the analysis of the supplier's execution stage decisions.

3.1. Supplier's Production Decisions

For notational convenience, in this subsection we suppress the supplier's subscript i from the parameters ρ_i, c_i, θ_i, X_i, q_i, and p_i. In the execution stage, given a contract (X, q, p) offered by the manufacturer, the supplier chooses its regular production size and delivery quantity to maximize its expected profit. The supplier first decides on z, the size of its regular production run. After the completion of regular production, which has yielded ρz, the supplier decides the total quantity to be delivered to the manufacturer, y. Subsequently, the supplier engages backup production to make up the difference, $(y - \rho z)^+$, and/or pays a penalty for the shortfall $(q - y)^+$. The $^+$ operator is defined such that $x^+ = x$ if $x > 0$ and $x^+ = 0$ if $x \le 0$. The following is the optimization problem of the supplier whose probability of successful regular production is θ:

$$\pi_S(X, q, p \mid \theta) = \max_{z \ge 0} \Big\{ X - cz - E\Big\{ \min_{y \ge 0}[b(y - \rho z)^+ + p(q - y)^+] \Big\} \Big\}. \quad (2)$$

Let z^* and y^* denote the optimal decisions. Solving this problem, we observe that, when deciding how much to deliver, the supplier either uses backup production (i.e., $y^* = q$) if $b < p$ or pays a penalty (i.e., $y^* = \rho z^*$) if $b \ge p$. When choosing z^*, the

supplier trades off the cost of regular production, cz, against the cost of recourse (backup production cost or penalty). The supplier will run regular production only if its expected cost of successfully producing one unit using regular production, c/θ, is lower than both the backup production cost, b, and the unit penalty, p. The following proposition formalizes the above discussion.

PROPOSITION 1. *For a given contract (X, q, p), the size of the supplier's optimal regular production run, z^*, the delivery quantity, y^*, and the supplier's expected profit, π_S, are as follows:*

Case	z^*	y^*	$\pi_S(X, q, p \mid \theta)$
(1) $p > b$, $b < c/\theta$	0	q	$X - bq$
(2) $p > b$, $b \ge c/\theta$	q	q	$X - cq - (1 - \theta)bq$
(3) $b \ge p$, $p < c/\theta$	0	0	$X - pq$
(4) $b \ge p$, $p \ge c/\theta$	q	ρq	$X - cq - (1 - \theta)pq$

Notice that in case (3) of Proposition 1 the supplier makes no effort to produce. As we will see later, this situation never arises under the manufacturer's optimal contracts. In case (1) of Proposition 1 the supplier does not use regular production, instead finding it more economical to use backup production to produce and deliver q units. Note that, per Assumption 2, this situation does not arise with the high-type supplier, which will always give regular production a try. However, Assumption 2 does not rule out the possibility that $b \le c_L/l$, in which case the low-type supplier would bypass regular production.

Proposition 1 shows that the supplier's profit is increasing in its reliability, θ. (In this paper, we use increasing and decreasing in the weak sense.) We extend this observation and show that, given the same contract, a high-type supplier would earn a larger profit in expectation than a low-type supplier. We denote the difference between the high and low types' optimal profits, given the manufacturer's contract, by Γ.

DEFINITION 1. $\Gamma(q, p) \triangleq \pi_S(X, q, p \mid h) - \pi_S(X, q, p \mid l)$ is the benefit of being a high-type supplier over a low-type supplier, given the manufacturer's contract, (X, q, p).

Notice that Γ is not a function of the transfer payment, X, because the transfer payment term cancels out in the calculation. Applying Proposition 1 to the definition yields the expression for $\Gamma(q, p)$.

COROLLARY 1. *For given q and p, the expression for $\Gamma(q, p)$ is given by the following table and illustrated*

in the accompanying figure. Moreover, $\Gamma(q, p)$ is always nonnegative.

Case	$\Gamma(q, p)$
$p > b$	
$\quad b < c_L/l$	$(hb - c_H)q$
$\quad b \geq c_L/l$	$[(h - l)b + (c_L - c_H)]q$
$b \geq p$	
$\quad p < c_H/h$	0
$\quad c_L/l > p \geq c_H/h$	$(hp - c_H)q$
$\quad p \geq c_L/l$	$[(h - l)p + (c_L - c_H)]q$

Cost of backup production
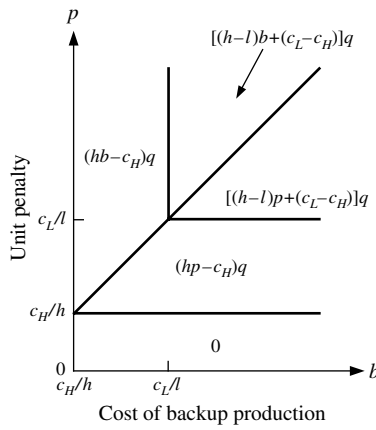
$\Gamma(q, p)$ reflects the high-type supplier's reliability advantage over the low-type supplier. We will carefully consider this advantage when solving the manufacturer's contract design problem, as described in the next subsection. With Corollary 1, $\Gamma(q, p)$ can be shown to be increasing in b, p, q, and h and decreasing in l. These properties of $\Gamma(q, p)$ will be instrumental in developing insights about the effects of asymmetric information on the manufacturer's optimal contract.

3.2. Manufacturer's Contract Design Problem

Recall that we model the manufacturer's decisions as a mechanism design problem, using a standard information-economics approach (e.g., see Laffont and Martimort 2002), and, by the revelation principle, we focus on incentive-compatible, direct revelation contracts.

For shorthand, we define $\pi_H(X, q, p) \triangleq \pi_S(X, q, p \mid h)$ and $\pi_L(X, q, p) \triangleq \pi_S(X, q, p \mid l)$. In addition, given contract (X_i, q_i, p_i), we denote the optimal delivery of the type-i supplier by $y_i^*(X_i, q_i, p_i)$, $i \in \{H, L\}$. Where convenient, we suppress the explicit dependence of y_i^* on the contract terms. The expressions of π_H, π_L, and y_i^* can be obtained from Proposition 1.

Using these definitions, we present the manufacturer's contract design problem as the following optimization program:

$$\max_{\substack{(X_H, q_H, p_H) \\ (X_L, q_L, p_L)}} \{\alpha[rE\min(y_H^*, D) - X_H + p_H E(q_H - y_H^*)^+]$$

$$+ (1 - \alpha)[rE\min(y_L^*, D) - X_L$$

$$+ p_L E(q_L - y_L^*)^+]\} \qquad (3a)$$

subject to

$$(\text{I.C. H}) \quad \pi_H(X_H, q_H, p_H) \geq \pi_H(X_L, q_L, p_L), \qquad (3b)$$

$$(\text{I.C. L}) \quad \pi_L(X_L, q_L, p_L) \geq \pi_L(X_H, q_H, p_H), \qquad (3c)$$

$$(\text{I.R. H}) \quad \pi_H(X_H, q_H, p_H) \geq 0, \qquad (3d)$$

$$(\text{I.R. L}) \quad \pi_L(X_L, q_L, p_L) \geq 0, \qquad (3e)$$

$$X_H \geq 0, \quad X_L \geq 0, \quad q_H \geq 0,$$
$$q_L \geq 0, \quad p_H \geq 0, \quad p_L \geq 0. \qquad (3f)$$

The objective function (3a) of this problem is the sum of the manufacturer's expected profits from the high and low supplier types, each weighted by the probability of drawing that type of supplier. Constraints (I.C. H) are (I.C. L) are *incentive compatibility* constraints, which ensure that a supplier does not benefit from lying about its type to the manufacturer. Constraints (I.R. H) and (I.R. L) are *individual rationality* constraints, which reflect the fact that a supplier accepts the contract only if its reservation profit is met. We assume that both supplier types have the same reservation profit, normalized to zero. This assumption is common in mechanism design problems and has been used in both the economics literature (e.g., Myerson 1981, Che 1993) and the operations management literature (e.g., Lim 2001, Corbett et al. 2004).

4. Optimal Contracts Under Symmetric Information

To explore the influence of asymmetric information, as a benchmark we first derive the optimal menu of contracts when the manufacturer knows perfectly the reliability type of the supplier. We refer to this case as *symmetric information*.

Under symmetric information, nature reveals the supplier type to the supplier and the manufacturer simultaneously. Thus, the incentive compatibility constraints (3b) and (3c) in the manufacturer's problem (3) are no longer required, and the manufacturer's choice of the contract for one supplier type does not interfere with the choice for the other type. At optimality, the individual rationality constraints in the manufacturer's optimization problem will be binding, and either type of supplier earns

zero profit. This is formalized in Proposition 2 below, which describes the optimal menu of contracts and resulting profits.[6] Let $\check{\pi}_{M|i}(X_i, q_i, p_i)$ and $\check{\pi}_i(X_i, q_i, p_i)$ denote the manufacturer's and supplier's profits, respectively, given that nature draws a supplier of type i, $i \in \{H, L\}$, and the manufacturer offers contract (X_i, q_i, p_i) to the supplier of type i. Thus, $\alpha\check{\pi}_{M|H} + (1-\alpha)\check{\pi}_{M|L}$ is the manufacturer's expected profit prior to nature drawing the supplier type, where we have suppressed the contract terms. Let $\check{\pi}^*_{M|i}$ and $\check{\pi}^*_i$ denote the manufacturer's and supplier's profits, respectively, under the manufacturer's optimal contract. Figure 2 illustrates the following proposition.

PROPOSITION 2. *The manufacturer's optimal contract under symmetric information is*

Region	Penalty	Quantity	Transfer payment
(i) $r > b$	any $p_H \in (b, r)$	$q_H = 1$	$X_H = c_H + (1-h)b$
	any $p_L \in (b, r)$	$q_L = 1$	$X_L = \begin{cases} b & b < c_L/l \\ c_L + (1-l)b & \\ & b \geq c_L/l \end{cases}$
(ii) $b \geq r > c_L/l$	any $p_H \in [c_H/h, b]$	$q_H = 1$	$X_H = c_H + (1-h)p_H$
	any $p_L \in [c_L/l, b]$	$q_L = 1$	$X_L = c_L + (1-l)p_L$
(iii) $b \geq r$,	any $p_H \in [c_H/h, b]$	$q_H = 1$	$X_H = c_H + (1-h)p_H$
$c_L/l \geq r$	any $p_L \in [0, r)$	$q_L = 0$	$X_L = 0$

Furthermore, the supplier's profit is zero—that is, $\check{\pi}^*_H = \check{\pi}^*_L = 0$—and the manufacturer extracts the entire channel profit ($\check{\pi}_{M|i}$ is the manufacturer's profit if the supplier is of type i, $i \in \{H, L\}$), given in Table EC.1 *(see the e-companion).*

From Proposition 2, in region (i), backup production is cheap relative to the product's market revenue, so the manufacturer uses backup production with both types of suppliers. In the sequel, if the manufacturer's contract induces the supplier to use backup production in case of disruption, we will refer to this by the shorthand term "using backup production." In region (ii), backup production is costly, and the manufacturer induces both types to pay a penalty in case of disruption. In the sequel, if the manufacturer's contract induces the supplier to pay penalties, we will refer to this by the shorthand term "paying penalty." In region (iii), the unit revenue, r, is too low to justify ordering from the low-type supplier.

Per Proposition 2, under symmetric information, the manufacturer extracts all channel profit. Let $\pi_{C|i}(X_i, q_i, p_i)$, $i \in \{H, L\}$ denote the channel's profit

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[6] The legal requirement that penalties (or liquidated damages) do not exceed a reasonable estimate of the buyer's damages translates to $p \leq r$ in our model. This condition is satisfied by the buyer's optimal contracts derived in this paper.

Figure 2 Supplier's Actions Induced by the Manufacturer's Optimal Menu of Contracts Under Symmetric Information
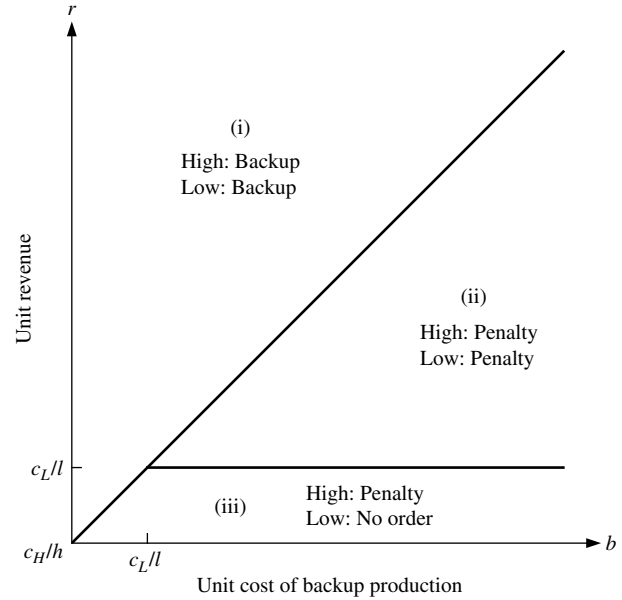
Notes. "High" and "Low" refer to the supplier's type. "Penalty" and "Backup" refer to the manufacturer's choice of inducing the supplier to pay a penalty or use backup production in case of disruption. "No order" indicates that the manufacturer does not order from the supplier.

when nature draws a supplier of type i and the manufacturer offers this supplier contract (X_i, q_i, p_i), and let $\pi^*_{C|i}$ denote the channel's optimal profit. Hence, $\pi^*_{C|i}$ is given by $\check{\pi}^*_{M|i}$, and the optimal contract under symmetric information also maximizes the channel's profit. It will be of interest in the following section to examine the channel's profit loss when the manufacturer offers a contract different from the contract in Proposition 2. In particular, we define the following.

DEFINITION 2. $\Delta(X, q, p) \triangleq \pi^*_{C|L} - \pi_{C|L}(X, q, p)$ is the channel loss, given that nature draws a low-type supplier and the manufacturer offers this supplier contract (X, q, p).

5. Optimal Contracts Under Asymmetric Information

In this section, we first overview the procedure of solving the manufacturer's problem (3) by describing the tradeoffs involved in the solution. The solution is presented in Proposition 3 below. We then compare the optimal contract with that under symmetric information.

5.1. The Fundamental Trade-Off

We first notice from rearranging Equation (2) that $-X_i + p_i E(q_i - y^*_i)^+ = -\pi_i(X_i, q_i, p_i) - c_i z^*_i - bE(y^*_i - \rho_i z^*_i)^+$ for $i \in \{H, L\}$, where z^*_i is the optimal size of the regular production run for the type-i supplier. We suppress the dependence of z^*_i on the contract terms

(X_i, q_i, p_i) for notational convenience. Using this, we rewrite the manufacturer's objective (3a) as

$$\max_{\substack{(X_H, q_H, p_H) \\ (X_L, q_L, p_L)}} \{\alpha[rE\min(y_H^*, D) - \pi_H(X_H, q_H, p_H)$$
$$- c_H z_H^* - bE(y_H^* - \rho_H z_H^*)^+]$$
$$+ (1-\alpha)[rE\min(y_L^*, D) - \pi_L(X_L, q_L, p_L)$$
$$- c_L z_L^* - bE(y_L^* - \rho_L z_L^*)^+]\}. \quad (4)$$

Second, as an outcome of the mechanism design problem (see the proof of Proposition 3 in the e-companion), at the optimal solution, the high-type supplier's incentive compatibility constraint is binding; that is $\pi_H(X_H, q_H, p_H) = \pi_H(X_L, q_L, p_L)$. Combining this observation with the definition of $\Gamma(q, p)$ (Definition 1), we have $\pi_H(X_H, q_H, p_H) = \pi_L(X_L, q_L, p_L) + \Gamma(q_L, p_L)$. At the same time, the low-type supplier's individual rationality constraint (3c) is also binding; that is, $\pi_L(X_L, q_L, p_L) = 0$. Therefore, at optimality, the profit of the high-type supplier, $\pi_H(X_H, q_H, p_H)$, equals $\Gamma(q_L, p_L)$, which is a function of the contract terms offered to the low-type supplier. In addition, at the optimal solution, the individual rationality constraint for the high-type supplier (3d) and the incentive compatibility constraint for the low-type supplier (3c) turn out to be nonbinding. Hence, we can roll binding constraints (3b) and (3e) into the objective function (4) by substituting $\pi_H(X_H, q_H, p_H) = \Gamma(q_L, p_L)$ and $\pi_L(X_L, q_L, p_L) = 0$ into (4) and separating terms that depend on (X_H, q_H, p_H) and (X_L, q_L, p_L) to obtain

$$\max_{(X_H, q_H, p_H)} \{\alpha[rE\min(y_H^*, D) - c_H z_H^*$$
$$- bE(y_H^* - \rho_H z_H^*)^+]\} \quad (5a)$$
$$+ \max_{(X_L, q_L, p_L)} \{(1-\alpha)[rE\min(y_L^*, D) - c_L z_L^*$$
$$- bE(y_L^* - \rho_L z_L^*)^+] - \alpha\Gamma(q_L, p_L)\}. \quad (5b)$$

Third, we observe that the bracketed expressions in (5a) and (5b) are the same as the profit of the channel with a high-type and low-type supplier, respectively. Therefore, when the manufacturer chooses (X_H, q_H, p_H) to maximize (5a), the resulting profit equals $\pi_{C|H}^*$. Furthermore, applying the definition of Δ (Definition 2), we can rewrite the manufacturer's objective function (5) as

$$\alpha\pi_{C|H}^* + (1-\alpha)\pi_{C|L}^*$$
$$- \min_{(X_L, q_L, p_L)} \{\alpha\Gamma(q_L, p_L) + (1-\alpha)\Delta(X_L, q_L, p_L)\}. \quad (6)$$

Observe from (6) that the manufacturer's profit is the optimal channel profit under symmetric information minus two types of losses from asymmetric information: $\Gamma(q_L, p_L)$, which can be interpreted as

the incentive payment to the high-type supplier to represent itself truthfully; and $\Delta(X_L, q_L, p_L)$, the loss in the channel profit. Thus, the manufacturer's decision boils down to selecting a contract, (X_L, q_L, p_L), offered to the low-type supplier, to minimize the sum of these two losses. To mitigate the loss from the incentive payment, the manufacturer deviates from the contract that is optimal with the low-type supplier under symmetric information, causing channel loss (per Definition 2). This trade-off between $\Gamma(q_L, p_L)$ and $\Delta(X_L, q_L, p_L)$ is the *fundamental trade-off* in our analysis.

## 5.2. Optimal Contracts Under Asymmetric Information

Following the steps outlined above, we derive the optimal solution to problem (3). We divide the (b, r) plane into five regions using five lines, as illustrated on the right panel of Figure 3. See Lemma EC.1 in the e-companion for a formal definition of these five regions.

The right panel of Figure 3 shows the salient features of the menu of optimal contracts under asymmetric information. The optimal contract terms vary by region, and details are provided in the following proposition.

PROPOSITION 3. *Under asymmetric information, the optimal unit penalties, p_H and p_L, order quantities, q_H and q_L, and transfer payments, X_H and X_L, offered to the high- and low-type suppliers are as follows:*

Region	Penalty	Quantity	Transfer payment
(I)	*any $p_H \in (b, r)$*	$q_H = 1$	$X_H = X_L$
	any $p_L \in (b, r)$	$q_L = 1$	$= \begin{cases} b & b < c_L/l \\ c_L + (1-l)b \\ & b \geq c_L/l \end{cases}$
(II)	*any $p_H \in (b, r)$*	$q_H = 1$	$X_H = h(c_L/l) + (1-h)b$
	$p_L = c_L/l$	$q_L = 1$	$X_L = c_L/l$
(III)	*any $p_H \in [c_L/l, b]$*	$q_H = 1$	$X_H = h(c_L/l) + (1-h)p_H$
	$p_L = c_L/l$	$q_L = 1$	$X_L = c_L/l$
(IV)	*any $p_H \in (b, r)$*	$q_H = 1$	$X_H = c_H + (1-h)b$
	any $p_L \in [0, r)$	$q_L = 0$	$X_L = 0$
(V)	*any $p_H \in [c_H/h, b]$*	$q_H = 1$	$X_H = c_H + (1-h)p_H$
	any $p_L \in [0, r)$	$q_L = 0$	$X_L = 0$

Furthermore, the low-type supplier's profit is zero, $\pi_L^* = 0$. The high-type supplier's profit, π_H^*, and the manufacturer's expected profits of sourcing from the high- and low-type suppliers, $\pi_{M|H}^*$ and $\pi_{M|L}^*$, are provided in Table EC.2 (see the e-companion).

Figure 3 Supplier's Actions Induced by Manufacturer's Optimal Menu of Contracts Under Symmetric Information (Left Panel) and Asymmetric Information (Right Panel)
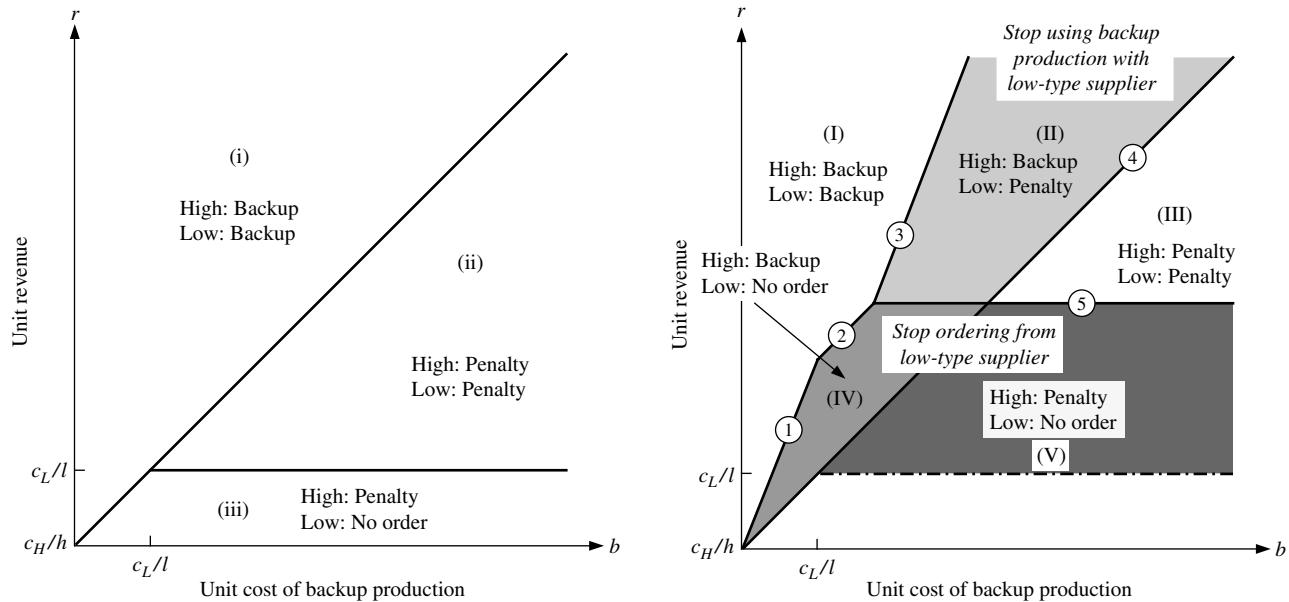
Notes. The effects of asymmetric information are indicated on the right panel. Region (i) is the union of regions (I), (II), and (IV); region (ii) is the union of region (III) and the shaded portion of region (V); and region (iii) is the unshaded portion of region (V).

5.3. Effect of Asymmetric Information on the Optimal Contract

Using Propositions 2 and 3, we compare the manufacturer's optimal risk-management policies under symmetric and asymmetric information and highlight the difference in Figure 3, addressing *research question* 1. Specifically, in region (II), under asymmetric information, the manufacturer induces the high-type supplier to use backup production in case of disruption but (unlike the optimal contract under symmetric information) makes the low-type supplier pay a penalty. This is, perhaps, counterintuitive, because the manufacturer uses backup production as a quantity-risk management tool. Therefore, one might expect that the less reliable the supplier is, the more the manufacturer prefers that the supplier use backup production. In regions (IV) and (V), as in the symmetric-information case, the manufacturer orders from the high-type supplier. However, in region (IV) and the shaded portion of region (V), information asymmetry causes the manufacturer to stop ordering from the low-type supplier.

To gain intuition for this behavior, note that the manufacturer deviates from the symmetric-information risk-management policies to reduce the incentive payment to the high-type supplier. Specifically, in region (II), if the low-type supplier had used backup production, the resulting transfer payment to the low-type supplier would have been large, because backup production is relatively expensive. Consequently, the incentive payment to the high-type supplier would have been large as well. Therefore, the manufacturer

curtails this large incentive payment by forcing the low-type supplier to pay a penalty (less than the cost of backup production). Similarly, in region (IV) and the shaded portion of region (V), the incentive payment is avoided by simply not ordering from the low-type supplier.

As a consequence of the deviation from the symmetric-information contract, we have the following result.

COROLLARY 2. *The quantity received by the manufacturer from the supplier under symmetric information is stochastically larger than the quantity received under asymmetric information.*

The manufacturer deviates from the symmetric-information risk-management policies to reduce incentive payments. In doing so, it incurs channel loss, as captured by the fundamental trade-off in Equation (6).

5.4. Informational Rent and Channel Loss

Using the optimal contract terms from Proposition 3, we can evaluate the incentive payment to the high-type supplier, $\Gamma(q_L, p_L)$, and channel loss, $\Delta(X_L, q_L, p_L)$, at the optimal contract (X_L, q_L, p_L) offered to the low-type supplier. Hereafter, we denote the incentive payment at the optimal contracts by γ and refer to it as informational rent, as is customary in information economics. In addition, let δ denote the channel loss under the optimal contracts. The expressions of γ and δ are provided in Table EC.3 (see the e-companion).

Table EC.3 reveals that under the optimal contract, in all regions except region (II), the manufacturer incurs either informational rent or channel loss, but not both. Intuitively, the manufacturer chooses the less onerous type of loss. For example, in regions (IV) and (V), revenue is so low that the channel loss from not ordering from the low-type supplier is small. In return for this sacrifice, the manufacturer avoids paying what would have been relatively high informational rent. In region (I), backup production is so cheap that the channel loss from not using backup production with the low-type supplier is large. But in region (III), backup production is so costly that it would not be used with symmetric or asymmetric information, while high unit revenue entices the manufacturer to order from either supplier type. Therefore, there is no channel loss incurred in regions (I) and (III). In region (II) the manufacturer incurs a mixture of informational rent and channel loss.

6. Values of Information and Backup Production

In this section, we address *research questions* 2 and 3, examining how the value of information and the value of backup production depend on important problem parameters: backup production cost b and unit revenue r. As in the previous sections, all the figures in this section represent analytically derived results.

Value of information for an entity of the supply chain is the difference between its optimal expected profits under symmetric and asymmetric information.

The manufacturer earns the entire channel profit under symmetric information. However, under asymmetric information, it loses informational rent, γ, if the supplier is of high-type and suffers a channel loss, δ, if the supplier is of low-type (see the fundamental trade-off in Equation (6)). Therefore, the value of information for the manufacturer equals $\alpha\gamma + (1-\alpha)\delta$ (where expressions for γ and δ are provided in Table EC.3 in the e-companion).

The supplier makes no profit under symmetric information, regardless of its type. Under asymmetric information, the low-type supplier continues to make zero profit. Therefore, the value of information is zero for the low-type supplier. In contrast, the high-type supplier earns an informational rent, γ, under asymmetric information. Hence, the value of information for the high-type supplier is $-\gamma$.

The channel loses a profit, δ, under asymmetric information, when the manufacturer offers the low-type supplier a contract that differs from what an integrated channel would offer, as discussed earlier. The value of information for the channel (prior to nature choosing supplier type) is $(1-\alpha)\delta$, where $1-\alpha$ is the probability of drawing a low-type supplier.

6.1. Value of Information and the Cost of Backup Production

We first study how the value of information for the manufacturer, channel, and supplier change in the unit backup production cost, b. The results are shown on the left panel of Figure 4, which follows from Table EC.3 (see the e-companion) with unit revenue fixed at $r = r_0$ above line 5 (marked on the right panel of Figure 4). The behavior for smaller values of r (below line 5) is similar.

For the manufacturer, the channel, and the supplier, the effect of information is most pronounced for moderate values of b. To gain intuition for this,

Figure 4 Value of Information Reaches Its Peak at the Rightmost Border of Region (I), Given a Fixed r; $\hat{b}(r)$ Is the Union of Line Segments 1, 2, and 3
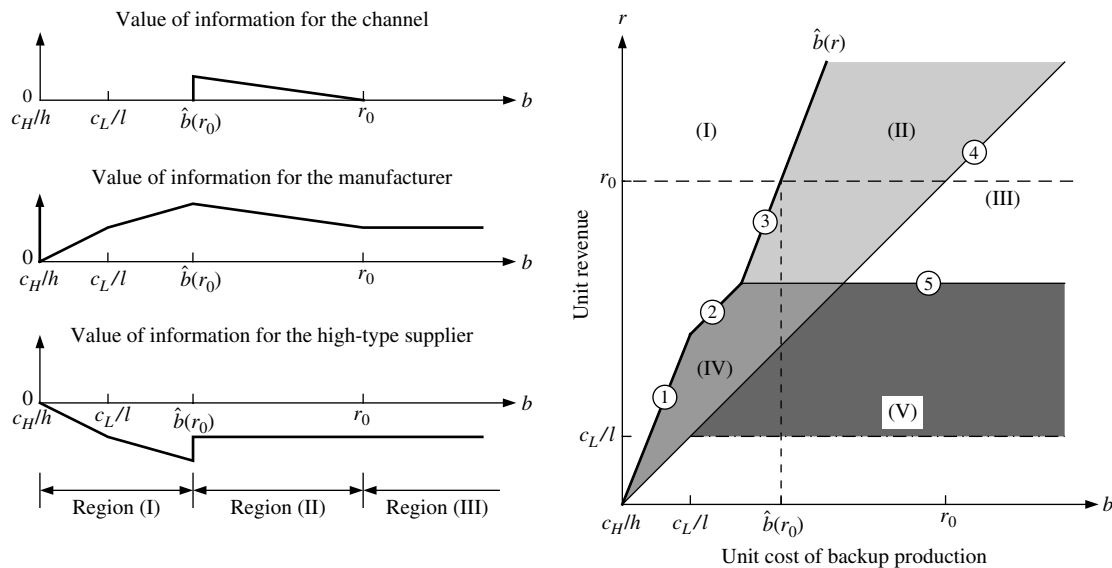
consider a large r (above line 5). For small values of b, backup production is so cheap that the manufacturer would like both supplier types to use it. Similarly, if b is very expensive, the manufacturer does not want either type of supplier to use it. At these extreme values of b, the manufacturer does not care to distinguish between supplier types and can offer them the same contract, as formalized in the following corollary.

COROLLARY 3. *Per Proposition* 3, *under asymmetric information, in regions* (I) *and* (III) *the manufacturer can offer the same optimal contract to the two supplier types by letting* $p_H = p_L$.

In contrast, at medium values of b, the trade-offs are more intricate and the manufacturer may choose to stop using backup production with the low-type supplier. Therefore, this is the region where the manufacturer benefits the most from knowing the supplier's type.

6.2. Value of Information and the Unit Revenue
We now study how the value of information for the manufacturer, channel, and supplier changes in the unit revenue, r. The results are shown on the left panel of Figure 5, leveraging Table EC.3 (see the e-companion). We examine the value of information at a fixed backup production cost $b = b_0$, where b_0 is marked on the right panel of Figure 5. The behavior for other values of b is similar.

From Figure 5, observe that the value of information for the channel and the high-type supplier is nonmonotone, with jumps at $\bar{r}$ and $\hat{r}$, where $\bar{r}$ corresponds to line 5 and $\hat{b}(\hat{r}) = b_0$. Each discontinuity coincides with a strategic decision by the manufacturer to change whether it incurs informational rent,

channel loss, or both, as captured by Table EC.3. For example, for $r \leq \bar{r}$ the manufacturer avoids paying an informational rent by not ordering from the low-type supplier, but once $r > \bar{r}$ the low-type receives an order and informational rent is incurred (along with channel loss). Finally, observe that the value of information is always increasing for the manufacturer and is increasing within each region for the channel. From Corollary 2, the quantity received by the manufacturer and hence the quantity sold are stochastically smaller under asymmetric information. The larger the unit revenue, the larger loss the manufacturer would suffer from the reduction of sales. Similar reasoning applies for the channel, within each region.

6.3. Value of Backup Production
For the manufacturer, supplier and channel, we examine the *value of the backup production option*, defined to be the difference between profits with and without backup production (where the latter can be computed by setting $b = r$, making backup production economically unattractive). The expressions for the value of backup production in Table EC.4 (see the e-companion) are derived from Proposition 3. Using Table EC.4, it can be verified that the value of backup production for the manufacturer and the value for the channel are decreasing in the backup production cost b, increasing in the revenue r, and nonnegative under asymmetric information.

As shown in Figure 6, the value of backup production for the high-type supplier is nonmonotone in backup production cost, b, and could be negative. Recall that the profit of the high-type supplier comes from informational rent. For small r (i.e., $r \leq \bar{r}$) the high-type supplier earns zero informational rent in

Figure 5 Value of Information vs. Unit Revenue, r; $\hat{b}(r)$ Is the Union of Line Segments 1, 2, and 3
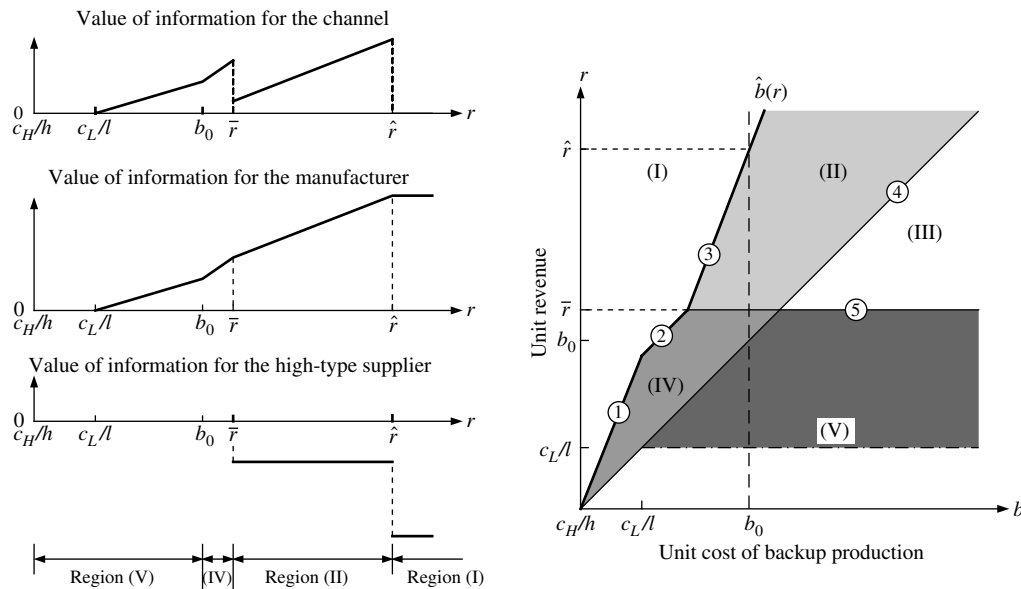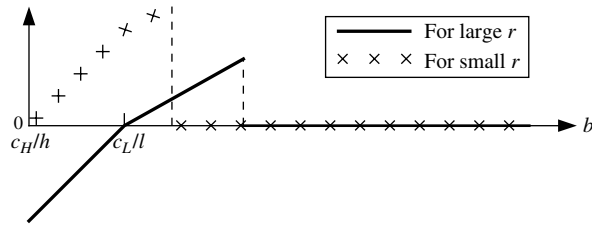
Figure 6   Value of Backup Production for the High-Type Supplier

Note. Value of backup production for the high-type supplier is negative for large r (i.e., $r > \bar{r}$) and small b ($b < c_L/l$), but is always nonnegative for small r (i.e., $r \leq \bar{r}$).

the absence of backup production, because the low-type supplier receives no orders. Therefore, for such r the value of adding backup production can only be positive. In contrast, for large r (i.e., $r > \bar{r}$) the high-type supplier earns informational rent even in the absence of a backup production option. Introducing a cheap backup production option of unit cost $b < c_L/l$ reduces the economic advantage of being a high-type supplier by allowing disruptions to be cheaply remedied. This diminishes the high-type supplier's informational rent. Therefore, for small b and large r, the value of backup production is negative for the high-type supplier.

6.4.   Effect of Information on the Value of Backup Production
Intuition might suggest that if information asymmetry regarding supplier reliability is eliminated, then the manufacturer will make better use of the backup production option to manage the supply risk. Hence, one may expect the value of backup production to be larger under symmetric information. However, as shown on the left panel of Figure 7, the value of

backup production may be larger or smaller under symmetric information. Under information asymmetry, the presence of a backup option with a small unit cost, b, results in a decrease in the informational rent paid to the high-type supplier. This additional benefit of backup production does not exist under symmetric information. As a result, under small b the value of backup production is greater under asymmetric information. In contrast, when b is moderate, under asymmetric information the backup option increases the informational rent paid to the high-type supplier, thus diminishing the value of backup production.

7.   Sensitivity Analysis
In this section, we address *research question* 4 by investigating the sensitivity of our earlier results to changes in the underlying business setting, including reliability parameters, h and l, the fraction of high-type suppliers in the market, α, and the manufacturer's contracting flexibility.

7.1.   Sensitivity to Supplier Reliabilities
Suppose we increase supplier reliabilities h and l simultaneously, fixing the difference, $h - l$. This corresponds to the case in which all suppliers in the market become more reliable while the reliability gap between the two supplier types remains constant. One might expect that the value of information should always decrease as suppliers become more reliable, but the following corollary shows that when unit revenue is relatively small or backup production is relatively cheap, the value of information for the manufacturer can actually increase with supplier reliability.

Figure 7   Value of Backup Production Under Symmetric and Asymmetric Information
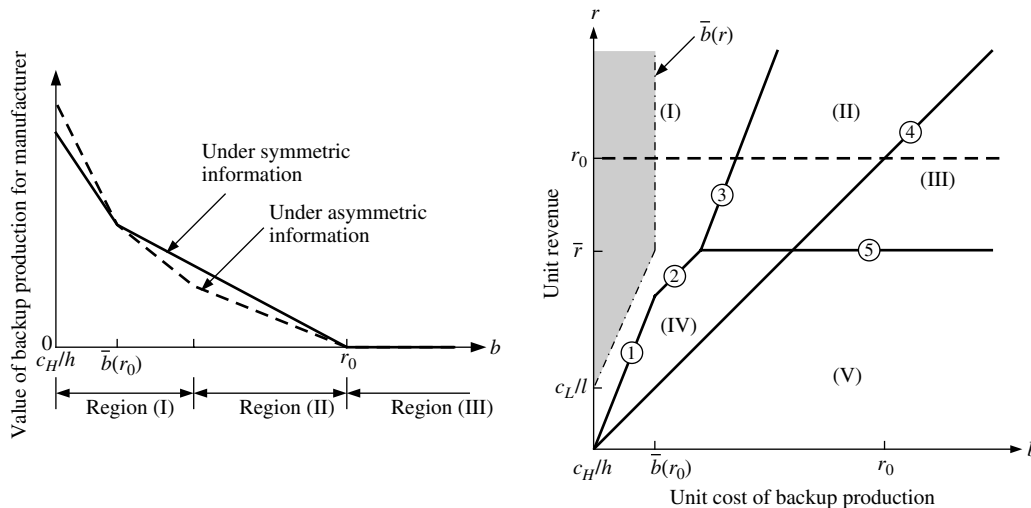
Notes. The left panel plots the values of backup production for $r = r_0$ (marked on the right panel). On the right panel the shaded portion of region (I) indicates (b, r) pairs for which the value of backup production is greater under asymmetric information. The right panel also shows the line $\bar{b}(r)$ used on the left panel and defined as follows: for $r > \bar{r}$, $\bar{b}(r) = c_L/l$; for $r \in (c_L/l, \bar{r}]$, $\bar{b}(r) = ((1 - \alpha)l/(\alpha h))(r - c_L/l) + c_H/h$.

Corollary 4 (Sensitivity of Value of Information to Supplier Reliability). *Per Table EC.3 (see the e-companion), if the supplier reliabilities l and h increase to $l + \epsilon$ and $h + \epsilon$, respectively (while $h - l$ remains constant), then in the interior of regions* (I), (IV), *and* (V) *the value of information for the manufacturer increases, and in the interiors of regions* (II) *and* (III) *the value of information for the manufacturer decreases.*

The intuition for the behavior in regions (I), (IV), and (V) can be gleaned from Table EC.3. In regions (IV) and (V), only channel loss is incurred because of the manufacturer not ordering from the low-type supplier. The more reliable the low-type supplier becomes, the larger this channel loss is and, hence, the larger the value of information. But in region (I), only informational rent is incurred. In the part of region (I) where backup production is very cheap ($b < c_L/l$), the low-type supplier does not utilize regular production at all, and its unit production cost is fixed at the cost of backup production. As the high-type supplier's reliability, h, increases, its reliability advantage also increases, which drives up the informational rent and, hence, the value of information.

Using Table EC.4 (see the e-companion), we next examine how the value of backup production changes. The next corollary follows from the fact that the manufacturer's need for backup production diminishes as suppliers become more reliable.

Corollary 5 (Sensitivity of Value of Backup Production to Supplier Reliability). *Per Table EC.4, if the supplier's reliabilities h and l increase to $h + \epsilon$ and $l + \epsilon$, respectively (while $h - l$ remains constant), then the value of backup production for the manufacturer decreases.*

7.2. Sensitivity to Reliability Gap
Here, we fix the low type's reliability, l, and increase the high type's reliability, h. This corresponds to an increase in the reliability gap $h - l$, with the high-type supplier becoming more reliable. The following corollary describes how the value of information and value of backup production depend on the reliability gap.

Corollary 6 (Sensitivity to Supplier Reliability Gap). *Per Proposition 3 and Table EC.3 (see the e-companion), if h increases and l is fixed, then*
(i) *the value of information for the manufacturer increases; and*
(ii) *the value of backup production for the manufacturer decreases, and the absolute value of backup production for the high-type supplier increases.*

Intuitively, as the two supplier types become increasingly different, information about the supplier's type becomes more critical. In addition, as the high-type supplier becomes even more reliable, the probability that backup production is used to fulfill the order decreases. Consequently, the value of backup production for the manufacturer diminishes.

7.3. Sensitivity to the Fraction of High-Type Suppliers in the Market
Recall that the value of information for the manufacturer is $\alpha\gamma + (1 - \alpha)\delta$, where informational rent γ and channel loss δ do not depend on α, the probability of drawing a high-type supplier (see Table EC.3 in the e-companion). In regions (I) and (III), where only informational rent is incurred (channel loss is zero), the effect of informational rent is magnified because of an increase in α, and the value of information becomes larger. In regions (IV) and (V), where only channel loss is incurred (informational rent is zero), the effect of channel loss is diminished because of a decrease in $1 - \alpha$, and the value of information decreases. In region (II) value of information can move either way in α, depending on whether channel loss or informational rent is larger. These observations are formalized in the following corollary.

Corollary 7 (Sensitivity of Value of Information to α). *Per Table EC.3, if α increases to $\alpha + \epsilon$, then in the interior of regions* (I) *and* (III) *the value of information for the manufacturer increases, and in the interiors of regions* (IV) *and* (V) *the value of information for the manufacturer decreases. In region* (II) *the value of information increases if $(h - l)(c_L/l) + (c_L - c_H) > (1 - l)(r - b)$ and decreases otherwise.*

Using Table EC.4 (see the e-companion), we examine how the value of backup production changes with α. One may expect that, if the fraction of more reliable suppliers in the market increases, disruptions will become less likely and, hence, the value of backup production will decrease. This intuition holds under symmetric information, but not necessarily under asymmetric information, as Corollary 8 illustrates.

Corollary 8 (Sensitivity of Value of Backup Production to α). *Per Table EC.4, as α increases to $\alpha + \epsilon$, the value of backup production for the manufacturer decreases in region* (I) *and increases in regions* (II) *and* (IV).

To understand why the value of backup production increases in the fraction of high-type suppliers when the cost of backup production is moderate (in regions (II) and (IV)), recall that the manufacturer asks only the high-type supplier to use backup production in these regions. Therefore, in these regions, the benefit of backup production is realized only if a high-type supplier is drawn, and an increase in the fraction of high-type suppliers, α, enhances the value of backup production for the manufacturer.

7.4. Sensitivity to Manufacturer's Contracting Flexibility
We now discuss the effects of the manufacturer's contracting flexibility on its contracting decisions and its profit, using three types of manufacturers:

1. *Informed* manufacturer, which knows the supplier's type prior to contracting. The informed man-

ufacturer's problem is the symmetric-information problem (discussed in §4).

2. *Partially informed and discriminating* manufacturer, which does not know the supplier's type prior to contracting, but knows that there are two supplier types and has the flexibility of offering a menu of contracts. This manufacturer's problem is the asymmetric-information problem (discussed in §5).

3. *Partially informed and nondiscriminating* manufacturer, which is identical to the *partially informed and discriminating* manufacturer, except that it is constrained to offer a single contract. The manufacturer could either be legally bound to offer a single contract or limited by its procurement department's resources to monitor and enforce multiple supplier-specific contacts.

As shorthand, we will refer to the latter two manufacturer types as discriminating and nondiscriminating, respectively. We have already defined mathematical models for the informed and discriminating manufacturer types. The nondiscriminating manufacturer's problem is

$$\max_{\substack{(X, q, p): \\ X \geq 0, q \geq 0, p \geq 0}} \left\{ \alpha E[r \min(y_H^*, D) - X + p(q - y_H^*)^+] \mathbf{1}_{\{\pi_H(X, q, p) \geq 0\}} \right.$$

$$+ (1 - \alpha) E[r \min(y_L^*, D)$$

$$\left. - X + p(q - y_L^*)^+] \mathbf{1}_{\{\pi_L(X, q, p) \geq 0\}} \right\}. \quad (7)$$

In the above expression, $\mathbf{1}_{\{A\}}$ is the indicator of an event A. The manufacturer offers a single contract (X, q, p). A type-i supplier, $i \in \{H, L\}$, chooses to participate if $\pi_i(X, q, p) \geq 0$. The optimal contract is stated in Proposition 4 and is characterized on the left panel of Figure 8.

PROPOSITION 4. *The optimal contract offered by the nondiscriminating manufacturer is summarized in the following table*:

Region	Penalty	Quantity	Transfer payment
(I) *and* (IIa)	*any* $p \in (b, r)$	$q = 1$	$X = \begin{cases} b & b < c_L/l \\ c_L + (1-l)b \\ & b \geq c_L/l \end{cases}$
(III) *and* (IIb)	$p = c_L/l$	$q = 1$	$X = c_L/l$
(IV) *and* (IIc)	*any* $p \in (b, r)$	$q = 1$	$X = c_H + (1-h)b$
(V)	*any* $p \in [c_H/h, b]$	$q = 1$	$X = c_H + (1-h)p$

By comparing Propositions 3 and 4 and using Corollary 3, we notice that the optimal contracts offered by the discriminating and nondiscriminating manufacturers coincide in regions (I) and (III). Furthermore, the contracts offered by the two manufacturer types coincide for the high-type supplier in regions (IV) and (V). In these two regions, the low-type supplier does not participate with either manufacturer type. In region (II), where the discriminating manufacturer does use its power to discriminate between the two supplier types, the nondiscriminating manufacturer does not have that option and falls back on one of three kinds of contracts: the contracts in subregions (IIa), (IIb), and (IIc) coincide, respectively, with the contracts offered by the discriminating manufacturer in regions (I), (III), and (IV).

The right panel of Figure 8 shows the expected profits of the three manufacturer types. The difference between the profits of the discriminating and informed manufacturer types equals the value of information for the manufacturer, discussed in §6.

Figure 8 **(Left Panel) Optimal Contract Offered by the Nondiscriminating Manufacturer; (Right Panel) Expected Profits of the Three Manufacturer Types (r Is Fixed to Be r_0, Marked on the Left Panel)**
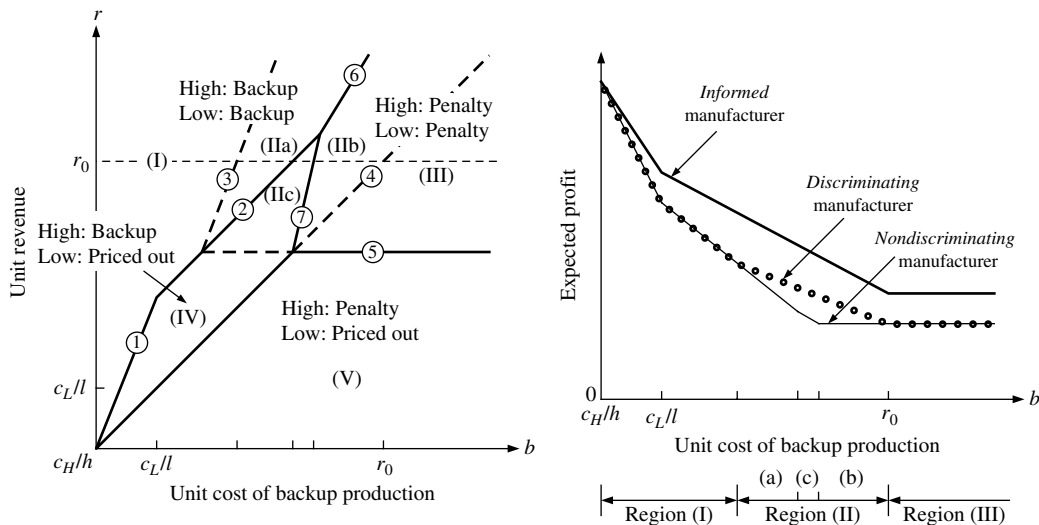
Note. The nondiscriminating manufacturer earns a smaller profit than the discriminating manufacturer only when b is moderate (i.e., (b, r) is in region (II)).

Interestingly, the profits of the discriminating and nondiscriminating manufacturer types are different only in region (II). This happens because only in region (II) the discriminating and nondiscriminating manufacturers induce suppliers to take different actions. It follows that, in our model, the ability to discriminate pays off for the manufacturer only if the backup production option is moderately expensive. The reasoning for this is akin to that provided after Figure 4 to explain why information is most valuable when backup production is moderately expensive.

8. Extension: Manufacturer's Backup Production Option

So far, we have assumed that only the supplier has access to backup production capacity. It is also possible that the manufacturer has its own backup production option, the implications of which we investigate in this section.[7]

To the model we have been using so far, we add the ability of the manufacturer to use its own backup production at unit cost b_M. If both the supplier and the manufacturer have access to the same third-party backup source, then the manufacturer's cost of accessing this source, b_M, may be higher or lower than the supplier's cost, b, depending, for example, on the relative bargaining powers of the supplier and the manufacturer versus the third party. For example, if the manufacturer has more bargaining power than the supplier when negotiating the contract for the alternative supply source, it can secure a lower price, resulting in $b_M < b$. It is also possible that, instead of having its own backup production option, the manufacturer asks the supplier to run the supplier's backup production even if the original contract did not call for it. For instance, in region (II), if the low-type supplier experiences a disruption and according to the contract would not deliver, perhaps the manufacturer could simply pay the supplier b and ask it to run backup production. In such a case, b_M could be equal to b, but it is more likely that $b_M > b$ because of administrative costs, for instance, the cost of verifying that a disruption indeed occurred. Verification prevents the supplier from claiming to have had a disruption and consequently demanding the b payment from the manufacturer for backup production, regardless of whether there was actually a disruption.

As before, we assume that the cost of backup production exceeds the effective cost of regular production for the high-type supplier, $b_M \geq c_H/h$. To

the contracting and execution stages of the original problem (see the timeline in Figure 1), we append a *manufacturer recourse* stage in which the manufacturer may run its backup production. In the recourse stage, the manufacturer chooses s_i, $i = H, L$, the total product supply that will be available to it at the stage's conclusion. In the execution stage, given a contract from the manufacturer, (X_i, q_i, p_i) $i = H, L$, the supplier's production decisions, y_i^* and z_i^*, are unaffected by the manufacturer's backup production option and are the same as those described in Proposition 1. In the contracting stage the manufacturer designs the contract menu (X_i, q_i, p_i), $i = H, L$, and offers it to the supplier.

To find the optimal contract menu we invoke the following intuitive observations. Suppose the unit revenue for the product is fixed at some $r = r_0$. First, if the manufacturer's backup production cost is greater than the revenue, $b_M > r_0$, the manufacturer's backup production option is economically infeasible and none of this paper's previous results change. Second, if $b_M \leq r_0$, the optimal contracts under symmetric and asymmetric information are given by Propositions 2 and 3, respectively, where r is replaced by b_M. Consequently, all of the subsequent analysis (value of information, value of supplier backup production, etc.) goes through with b_M playing the role of r. To understand why, we observe that if the quantity delivered by the supplier, y, is less than demand, D, the manufacturer pays $b_M(D - y)^+$ when its backup production option is available and "pays" $r(D - y)^+$ (via lost revenue) when such an option is absent. Thus, mathematically, b_M plays the same role in this model that r played in Equations (3a) and (4). (Proposition EC.1 in the e-companion formalizes this argument.)

Addressing *research question* 1, we notice from Corollary 2 that asymmetric information increases the risk of nondelivery from the supplier. This effect increases the manufacturer's reliance on its own backup production option.

Addressing *research question* 2, we examine how introducing the manufacturer's backup production option affects the manufacturer's value of information. Recall from Figure 5 that the value of information increases in r, the unit shortfall cost in the absence of the manufacturer's backup production option. As pointed out earlier, the presence of the manufacturer's backup production option reduces the manufacturer's unit shortfall cost from r to $b_M < r$. By making the manufacturer less sensitive to shortfall, the manufacturer's backup production option reduces the value of information. Thus, addressing *research question* 3, the manufacturer's backup production option is a substitute for information. In particular, this means that the value of the manufacturer's backup production option is greater under

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[7] For example, in the *Beckman Coulter v. Flextronics* example we cited earlier, after Flextronics failed to deliver the promised units, Beckman Coulter was able to convert one of its existing prototype production lines for full-scale production.

asymmetric information. This is in contrast to the supplier's backup production option, which can be either a substitute or a complement for information. Intuitively, the supplier's backup production option can increase the high-type supplier's reliability advantage, thus increasing the informational rent, whereas the manufacturer's backup production option has no such effect.

Similarly, the manufacturer's backup production option is a substitute for the supplier's backup production option. This is because the value of the supplier's backup production option increases in the unit shortfall cost (see Table EC.4 in the e-companion, where the shortfall cost equals r). The introduction of the manufacturer's backup production option reduces this shortfall cost from r to $b_M < r$, thereby reducing the value of the supplier's backup production option.

9. Concluding Remarks

In a supply chain, lack of visibility into supplier reliability impedes the manufacturer's ability to manage supply risk effectively. This paper examines a situation where the supplier's reliability is either high or low and is its private information, and the supplier has two options to respond to a disruption: use backup production or pay a penalty to the manufacturer for nondelivery. When designing a procurement contract, the manufacturer must anticipate which of these options the supplier would choose and how this would affect the manufacturer's expected procurement costs, use of its own backup production option, and sales revenues. To our knowledge, this paper is among the first in operational risk management to consider asymmetric information about supplier reliability.

We model the manufacturer's contracting decisions as a mechanism design problem and derive closed-form expressions for the optimal menu of contracts that elicits the supplier's private information. We observe that the manufacturer faces a key trade-off when designing the contract for the low-type supplier: pay high informational rent to the high-type supplier, or suffer channel loss. Informational rent comes from the high-type supplier's incentive to exploit its reliability advantage over the low-type supplier, and it depends on the low-type supplier's actions in response to a disruption. In controlling this incentive, the manufacturer offers to the low-type supplier a contract that would be suboptimal under symmetric information, resulting in the channel loss. This trade-off between informational rent and channel loss determines how the manufacturer manages its supply risk.

We answered four main research questions in this paper. Addressing *research question* 1 (*How do a manufacturer's risk-management strategies change in the presence of asymmetric information about supply reliability?*), we found that asymmetric information can have a pronounced effect on the manufacturer's risk-management strategy. Although information asymmetry encourages the use of the manufacturer's backup production option, it discourages the use of the supplier's backup production option. In particular, information asymmetry may cause the manufacturer to stop using the backup production of a less reliable supplier, while continuing to use the backup production of a more reliable supplier. Additionally, the manufacturer may stop ordering from the less reliable supplier altogether.

Addressing *research question* 2 (*How much would the manufacturer be willing to pay to eliminate this information asymmetry?*), we obtained a closed-form expression for the value of information. We found that the manufacturer would be willing to pay the most for information—that is, asymmetric information is of the greatest concern for managers—when the supplier's backup production is moderately expensive. In this case, the manufacturer predicates the supplier's use of backup production on the supplier's type. In contrast, when the supplier's backup production is cheap or expensive, the manufacturer's decision to induce the use of backup production does not depend on the supplier's type.

Addressing *research question* 3 (*Are risk-management tools more or less valuable when there is information asymmetry?*), we found that asymmetric information enhances the benefits the manufacturer derives from its own backup production option. The effect of information on the value of the supplier's backup production option is more intricate. For the manufacturer, information asymmetry makes the supplier's backup production option more valuable, provided it is moderately expensive, and less valuable when it is cheap, but the value is always positive. On the flip side, for the supplier, under symmetric information, the value of its backup production option is always zero. However, under asymmetric information, the value of the backup production option for the high-type supplier is positive, provided backup production is moderately expensive, but negative when it is cheap. Cheap backup production for the supplier erodes the high-type supplier's reliability advantage over the low-type supplier's by reducing the cost of remedying supply disruptions. Therefore, an already reliable supplier may be reluctant to embrace the addition of cheap backup production into the supply base.

Addressing *research question* 4 (*How do answers to the above questions depend on changes in the underlying business environment, such as supply base heterogeneity, or the*

manufacturer's contracting flexibility?), we found that, as the reliability gap between the two supplier types increases because of an improvement in the reliability of the high-type supplier, information becomes more valuable for the manufacturer. Interestingly, the value of information may increase even as both supplier types simultaneously become more reliable. Therefore, higher reliability need not be a substitute for better information. The high-type supplier's benefit (or disbenefit) from its backup production option is magnified as its reliability improves. In particular, an improvement in the reliability of the high-type supplier may actually enhance its benefit from backup production. Finally, we find that the flexibility to offer a menu of two contracts to the supplier benefits the manufacturer only if the supplier's backup production is moderately expensive. Thus, a manufacturer that does not want to exert the effort to offer a menu of contracts need not do so if supplier backup production is cheap or very expensive.

The above findings were derived through closed-form analysis, facilitated by several simplifying assumptions. We assumed the manufacturer's demand, D, is common knowledge. Maskin and Tirole (1990, §4, Proposition 11) proved that if (i) the principal (the manufacturer) also has private information, (ii) the principal's information cannot directly affect the agent's payoffs, and (iii) the agent's and principal's payoffs are quasilinear in the transfer payment, then the principal derives no benefit from its private information. In other words, without loss of optimality one can focus on the situation in which the information about the principal is public. Applied to our paper, this means that when the manufacturer has private information about its demand, it can do no better than when this information is public.

Another assumption about demand is that it is deterministic. We conjecture that the main trade-offs identified in this paper would remain if demand were stochastic; however, the details of how these trade-offs play out would change. This analysis would be far more complicated because of the *monotonicity* condition and bunching (Laffont and Martimort 2002, pp. 39, 140), meaning the contract design problem cannot be separated into independent subproblems for the high and low types.

We expect that increasing the number of discrete supplier types would also not substantially change the main qualitative insights documented in answers one through four above, although it would make the analysis more tedious. Having more than two supplier types or allowing a continuum of types may again create problems with *monotonicity* conditions. For an illustration of principal-agent problems with three agent types, please refer to Laffont and

Martimort (2002). For a general treatment of mechanism design with N agent types, see Lovejoy (2006). For a discussion of detailed *monotonicity* conditions under a continuum of types, see Fudenberg and Tirole (1991, pp. 266–268).

We also assume linear backup production costs and restrict the manufacturer to offer linear penalty schedules to the supplier. As a result, the supplier would either run backup production or pay a penalty, but not both simultaneously. We can show that under general concave backup production costs and concave penalty schedules for shortfall, the supplier's production decisions are unchanged and, consequently, all our results hold. An example of a concave penalty schedule (backup production cost) is a fee-plus schedule, whereby the supplier pays a fixed fee plus an additional fee per unit of shortage (backup production quantity). Convex backup production costs are also possible in practice; however, incorporating them into the model makes the analysis significantly more difficult.

We modeled supply risk using a random yield framework. One could also model supply risk arising from supplier lead time uncertainty. Under certain conditions the two approaches are equivalent: For example, for a manufacturer with a selling season that is short relative to the variability in supply lead times, a delay is tantamount to a disruption, and the backup option corresponds to the ability of the supplier to expedite the production (and the delivery). A more general model would have to introduce the manufacturer's sensitivity to delivery delays and the ability of the supplier to speed up (at a cost), depending on the forecast of the remaining production time. One might also wish to model the supplier's decision to slow down production (at a cost savings). With such features, the supplier's problem becomes a rather intricate stochastic control problem, compounding the difficulty of finding the manufacturer's optimal menu of contracts. We leave this interesting and challenging topic for future research.

In this paper, we assume that the cost of regular production is perfectly correlated with the supplier type and the expected backup production cost is public information. Allowing imperfect correlation between supplier reliability and its cost, or extending information asymmetry to backup production, would require solving a multidimensional screening problem. Such problems have been solved for rather few, special cases (see Kostamis and Duenyas 2007). We leave the study of this problem to future research as well.

10. Electronic Companion

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

Acknowledgments

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