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Strategic Behavior of Suppliers in the Face of Production Disruptions

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To mitigate supply disruption risks, some manufacturers consider a flexible sourcing strategy, where they have an option of sourcing from multiple suppliers, including regular unreliable suppliers and backup reliable ones. Our objective is to evaluate the costs and benefits associated with flexible sourcing when suppliers are strategic price setters. We show that when each supplier announces a single (wholesale) price, such a game leads to a conflict of incentives and is not realistic in most practical settings. Therefore, we focus on a contingent-pricing game, with wholesale prices contingent upon the manufacturer's sourcing strategy. We describe the resulting equilibrium outcomes corresponding to the manufacturer's different sourcing and inventory strategies. We show that in equilibrium, inventories are carried either by the manufacturer or the unreliable supplier, but not both. The manufacturer does not necessarily benefit from the existence of a backup supplier and, in fact, is typically worse off. Similarly, supply chain performance may degrade. Thus, an up-front commitment to sole-sourcing may be beneficial. Interestingly, suppliers may benefit from flexible sourcing even though the manufacturer does not. The main results extend to cases when partial backup sourcing is allowed, both suppliers are unreliable, recovery times are non-memoryless, an unreliable supplier may provide a richer set of contingent prices, or when the supplier may be risk averse.

Key words: supply chain disruptions, flexible sourcing, reliability, price competition, supply contracts

1. Introduction

As companies become more integrated and their supply chains more complex, they are exposed to many risks. Examples include natural disasters, economic and political crises, labor strikes, currency devaluation, and pandemics. The number and cost of natural and man-made disasters have dramatically increased over the last decade (Tang 2006). The risk of big losses has led many practitioners and researchers to study how to build more resilient supply chains (Martha and Subbakrishna 2002, Sheffi 2005, Hendricks and Singhal 2005, Tang 2006, Tomlin 2006, Babich et al. 2007). Tang (2006) proposes several mitigation strategies based on his observations of successful business practices, including production postponement, strategic inventories, flexible supply bases, and flexible transportation. Among these, this paper focuses on strategic inventories and flexible supply base (i.e., sourcing strategy).

This work is motivated by firms that contract with multiple suppliers and assign different roles to them–primary versus backup supplier. For example, Kolbus, a German manufacturer of bookbinding machinery sources a majority of its parts from offshore suppliers. In addition, the firm maintains backup suppliers for 70% of its purchased parts using a network of local suppliers, who may be more expensive than the primary suppliers, to hedge against both demand-side and supply-side uncertainties. Kolbus's chief operating officer stated that, "If we actually need the local suppliers as an extended workbench on a full scale, we compensate them for their deliveries generously. And they are prepared, still knowing that they cannot reckon on us for steadily incoming orders" (Sting and Huchzermeier 2010).

Although others have studied the profitability of using more expensive suppliers as backup in the presence of supply disruptions (e.g., Tomlin 2006, Sting and Huchzermeier 2010), existing studies typically assume that the manufacturer is the sole decision maker and that supplier behavior is exogenous. In such an environment, conventional wisdom suggests and many models confirm that a manufacturer cannot be worse off by having backup suppliers. In contrast, we treat suppliers as active decision makers who behave as strategic price setters.

We consider a manufacturer (she) that can source from either (a) a perfectly reliable supplier (he), (b) an unreliable supplier (he), or (c) both. The option of sourcing from more than one supplier (c) is labelled a *flexible sourcing strategy*. The reliable supplier may play one of two roles: serve as primary supplier (option (a)), or provide backup capacity to the manufacturer in the event the unreliable supplier experiences a disruption (option (c)). Because the unreliable supplier faces occasional production disruptions, to mitigate the effects of such disruptions, he may carry inventory. Similarly, if the manufacturer sources from the unreliable supplier (options (b) and (c)), she may also choose to buffer the disruptions with some inventory.

The primary objective of this study is to analyze the strategic behavior of suppliers when they compete for a manufacturer's business. We focus on the suppliers' pricing strategy and the resulting sourcing strategy of the manufacturer in the equilibrium. We seek to answer the following questions: How do the suppliers price under various reliability profiles? What sourcing strategy does the manufacturer adopt? What pricing schemes will prevail in an equilibrium? And, under what circumstances do the manufacturer and the suppliers benefit from a flexible sourcing strategy?

To answer these questions, in our model, the suppliers offer terms of delivery (wholesale prices and inventories) to the manufacturer. The manufacturer then chooses the suppliers and the role that each will play. To evaluate strategic supplier behavior, we describe two pricing games but analyze only the second one. In the first game, called the 'single-wholesale-price' game, each supplier announces a single (wholesale) price. This game leads to a conflict of incentives in terms of the roles suppliers want to play and the size of the business they get, formally confirmed as nonexistence of pure-strategy Nash equilibria in most practical situations. Although single-price contracts are typically considered in the disruptions literature, in reality, the reliable supplier may wish to quote different wholesale prices depending on the role he is assigned. Similarly, the unreliable supplier may offer incentives to win the manufacturer's business if an alternative source of supply is considered. This is the 'contingent-pricing' game, which is the second game and the focus of the present paper.

Specifically, the contingent-pricing game is a simultaneous-move pricing game between the two suppliers, where the reliable supplier offers wholesale prices contingent on whether he serves as the primary supplier, satisfying all the manufacturer's needs, or whether he serves as the backup supplier, used when manufacturer does not have other sources available. The unreliable supplier offers one wholesale price and a penalty for late deliveries in the form of a supplier rebate or a charge-back, which are commonly observed in practice.

The contingent-pricing game may have multiple formats with respect to inventory: (i) no inventory carried by either the unreliable supplier or the manufacturer, (ii) both the manufacturer and the supplier may carry inventory, but either (iia) there is no upfront commitment to carrying inventory, or (iib) the unreliable supplier commits to a certain level of inventory. We analyze case (iib), but the insights are the same and the numerical results are similar for case (iia).

We derive conditions for different sourcing strategies of the manufacturer and corresponding inventory policies. Except for cases with significant cost advantages for one of the suppliers, the manufacturer uses the (less expensive) unreliable supplier as well as the (more expensive) reliable supplier. However, economic benefits are less obvious and possibly surprising. It is commonly believed that the manufacturer should never be worse off by having backup suppliers. However, with endogenously determined wholesale prices, the manufacturer may be worse off due to the existence of a backup supplier and, in fact, is typically worse off. Consequently, an upfront commitment to sole-sourcing may be beneficial rather than opening up the opportunity for multisourcing and more flexible contracts.

Interestingly, suppliers may benefit from flexible sourcing even though the manufacturer does not: the reliable supplier always benefits from offering backup capacity, whereas the unreliable supplier might in some situations benefit from the reliable supplier's backup capacity despite the reduction in business volume. From a system perspective, however, a flexible sourcing strategy may degrade the supply chain performance.

We characterize the sourcing policy by deriving the conditions under which the manufacturer sole sources from the reliable supplier, the conditions under which she sole sources from the unreliable supplier, and the conditions under which she sources primarily from the unreliable supplier, using the reliable supplier as the backup. We show that even when the manufacturer uses both suppliers, it is optimal to maintain safety stock of inventory, because the reliable supplier usually charges a high price for providing backup capacity.

We provide several extensions to this model. Our first extension considers partial backup from the reliable supplier during disruptions. To derive clear insights, we consider the case of no inventory and, using the amount of backup capacity as a control variable, we can intuitively explain the strategic interactions between suppliers and illustrate why flexibility may hurt the manufacturer and benefit the suppliers. Interestingly, if the manufacturer could choose the backup fraction upfront, she always would prefer zero backup (i.e., sole-sourcing). This complements our findings and illustrates how flexible sourcing may be undesirable for the manufacturer. Our second extension considers the case of two unreliable suppliers. Our insights remain unchanged: flexible sourcing may benefit the suppliers, while hurting the manufacturer. In our third extension, we investigate how predictability of disruption recovery times influences the competitive outcomes and equilibrium profits. Although less variability is usually considered favorable in the operations literature, we find that the unreliable supplier may achieve higher profits with more variable disruptions. In our fourth extension, we consider the case where reliable supplier is risk averse. Risk aversion implies that the supplier prefers constant cash flow as the primary supplier, instead of occasional cash flow, with the same expected value, as the backup supplier. While the main findings remain the same, a supplier's risk aversion strengthens the manufacturer's bargaining power and hence her payoff. In our last extension, we provide an extended version of the contingent-pricing game that allows the unreliable supplier to build further contingencies into the contract.

Interestingly, sole sourcing is typically justified by economies of scale, learning, and trust, despite its weakness in case of production disruptions. This model suggests that even in the case of production disruptions, sole sourcing may not be a detriment to the manufacturer.

2. Literature Review

The earliest papers dealing with disruptions concentrate on supply disruptions within one facility or from a single supplier. Meyer et al. (1979) models a production facility with stochastic failures and repairs. Hopp and Spearman (1991) and Berg et al. (1994) consider similar settings, with machine breakdowns and internal disruptions within a facility. Bielecki and Kumar (1988) derives the conditions under which zero-inventory policies are optimal for a manufacturing facility subject to random failures. Parlar and Perry (1995), Parlar (1997), Gupta (1996), and Arreola-Risa and DeCroix (1998) analyze disruptions at the upstream supplier. In principle, the analysis is the same as analyzing the disruptions within a manufacturing facility, provided the downstream buyer has perfect access to the upstream supplier's state. Song and Zipkin (1996) analyzes a single-supplier model with a more general supply process (a generalized version of Kaplan 1970) and concludes that under no-order-crossing assumption, the optimal ordering policy is independent of the state of outstanding orders. Due to the generality of the framework, any single-supplier problem in a multiperiod setting is likely to fit into Song and Zipkin's framework.

An increasing number of papers consider scenarios that are more complex than a single-supplier single-buyer relationship. The benefits of multiple-supplier sourcing have been studied in the context of risks such as price reductions resulting from competition among suppliers (Elmaghraby 2000) and variable supplier lead times (Minner 2003). The first papers to consider multiple suppliers to mitigate disruption risks are Parlar and Perry (1996) and Gurler and Parlar (1997). Both papers consider identical-cost infinite-capacity suppliers who are subject to exponentially distributed failure and repair times with fixed ordering costs. Tomlin (2006) is the most relevant to our work. He assumes that demand is constant and, in a periodic-review setting, two suppliers can serve the manufacturer; one is reliable and the other is unreliable. The unreliable supplier faces no capacity constraints inbetween disruptions but has zero capacity during a disruption. The reliable supplier has a strict capacity constraint and a positive lead-time needed to start production. The major difference between Tomlin's work and this study is that the wholesale prices are exogenously set in his model, whereas we assume that the suppliers are price setters and compete for the manufacturer's business. By modeling suppliers as price setters, we were able to analyze how suppliers' behavior influences the structure of the supply contract and the manufacturer's sourcing strategy. In addition to the strategies analyzed in Tomlin (2006), Tomlin (2009a) also considers demand switching as a potential lever to mitigate supply disruptions.

Another stream of literature related to supply chain disruptions is one that considers supplier yield uncertainty. Yano and Lee (1995) provides a comprehensive review of the yield uncertainty literature. Among the papers in this group, the ones that consider multiple suppliers are Gerchak and Parlar (1990), Yano (1991), Anupindi and Akella (1993), Agrawal and Nahmias (1997), Federgruen and Yang (2009), Gurnani et al. (2000), and Babich et al. (2007). A review of these papers can be found in Tomlin (2006) and Babich et al. (2007). Among these papers, Babich et al. (2007) is closest to our work. It models a single-period procurement problem with multiple uncertain suppliers. The ordering decisions are made before the supply uncertainty is resolved. The supply disruptions are correlated across the suppliers; that is, each of suppliers is able to satisfy the order fully or produce nothing, according to a Bernoulli yield distribution. The suppliers are price setters, as in our model. The paper derives the equilibrium in single wholesale prices for the two-supplier case with deterministic and stochastic demand. Instead of single wholesale-price contracts, we consider a contingent-price framework and allow for different roles that the suppliers can play (which is not considered in their model). Also, our model is a multi-period one with inventories carried across periods. This enables us to evaluate a more realistic and intuitive pricing strategy, as well as to study the efficacy of a broader set of sourcing strategies when inventory is a potential mitigation strategy for disruptions. Tang and Kouvelis (2011) also deals with disruptions that occur in the form of stochastically proportional yield. The paper considers two competing (identical) manufacturers, who have an option to source from two (identical) suppliers in a single-period setting and focuses on how the yield correlation across suppliers influences the desirability of dual-sourcing for the manufacturers. We consider a multiperiod model and a supply process that models random failures and recoveries, with holding inventories as a potential mitigation strategy. Suppliers may differ with respect to production costs and reliability profiles; therefore, we allow suppliers to play different roles by offering contracts contingent on their role. This leads to different insights. Whereas the aforementioned papers assume that supplier yield distribution is known to the buyer, Tomlin (2009b) studies the effect of Bayesian learning on optimal sourcing and inventory decisions.

Some of the papers concentrating on bargaining and principle-agent models with asymmetric supply reliability information are also related to our work. Gurnani and Shi (2006) considers a bargaining setting involving a supplier and a buyer with asymmetric information on supplier reliability. Focusing on asymmetric supply reliability information, Yang et al. (2009) considers a single-period model with one manufacturer and one supplier. The supplier could be of two types, either high-reliability or low-reliability. The supplier may choose to pay a penalty for not being able to deliver or use a backup option. The manufacturer (principal) designs contracts to maximize expected profits, whereas the supplier (agent) truthfully reveals his private information by choosing the contract that maximizes his payoff. The manufacturer, having the full power to design the contract, extracts all the rents in the absence of information asymmetry. In our paper, suppliers offer wholesale prices (rather than the manufacturer offering a menu of contracts), reflecting a different power of suppliers. Also, by focusing on a one-period model, inventory cannot be used in their model to mitigate risk.

Wan and Beil (2009) analyzes a supply base diversification problem to mitigate cost shocks to procurement, where the buyer, due to lack of bargaining power, asks for bids from several suppliers from various geographical regions. The primary focus is to evaluate diversification strategies that minimize the cost of products plus (random) transportation costs. Our focus here is instead on the structure of pricing strategies. Also, we consider complete information games only and allow for inventory to be used as a mitigating factor.

A few recent papers consider insurance as a mitigating factor. However, they consider a single, unreliable supplier (or internal unreliable production), see Dong and Tomlin (2012) and Serpa and Krishnan (2014). A recent classification of supply chain risks can be found in Stecke and Kumar (2009).

3. Model and Assumptions

We consider a manufacturer M who has an option to source from an unreliable supplier U, from a reliable supplier R, or both. U is facing disruptions: at a given moment in time, U is in one of two states, ON or OFF. During the ON state, U can satisfy the manufacturer's order instantaneously, whereas he cannot produce anything during the OFF state. The manufacturer considers three sourcing strategies: solely source from R (labeled as SR), solely source from U (labeled as SU), and finally, flexible sourcing (labeled as FS), where U serves as the primary supplier and R serves as the backup supplier. If M chooses to adopt SU or FS, she has the option of holding inventory to buffer her needs during the OFF periods. Similarly, U can maintain inventory to mitigate the impact of disruptions on the manufacturer.

We describe the sequence of events in two phases.

Phase I: (a) The suppliers simultaneously announce their offers. The reliable supplier announces his wholesale price(s), explained below. The unreliable supplier announces his wholesale price(s) along with inventory commitment for countering disruptions, also explained below.[1]

(b) The manufacturer then determines the roles the suppliers will play; specifically, which supplier will be the primary one and whether any supplier will be chosen as a backup supplier. As a part of this phase, the manufacturer determines her inventory policy.

Phase II: Firms' plans are executed. That is, the manufacturer orders from each supplier, the products are received, if any, and the demand is satisfied subject to the inventory that is available.

We adopt a continuous-time view. Specifically, supplier U's state is governed by a continuous-time Markov chain with two states, ON and OFF. Time (ON), until a disruption, follows an exponential distribution with rate θ_f, and time (OFF), until recovery from a disruption, follows an exponential distribution with rate θ_r. The end-customer demand is deterministic and occurs at a rate of 1.[2] Suppliers do not face any capacity constraints. After recovering from an OFF-state, U catches up with unsatisfied demand instantaneously. Suppliers can supply the products with zero lead-times.

The manufacturer earns a fixed revenue of p per unit of demand. Unsatisfied demand is backlogged. For any backlogged demand, the manufacturer incurs a goodwill penalty π_b per customer

[1] We thank the review team for suggesting contractible inventory. We have also examined the case in which the unreliable supplier's inventory is determined in Phase I(b) and showed that the main results and insights remain the same.

[2] The deterministic demand assumption is appropriate when the long-term supply fluctuations are considered more important compared to short-term demand fluctuations. In addition, our model is appropriate for the situations in which the demand in the short-run is quite predictable. Other disruption papers that make deterministic demand assumptions include Tomlin (2006), Parlar (1997), Parlar and Perry (1995), Parlar and Perry (1996), and partly Babich et al. (2007).

per unit time. If they carry inventories, the manufacturer and the unreliable supplier, respectively, incur h_m and h_u per unit of product per unit of time. We assume that inventory holding costs are linear, and they do not change when wholesale prices change.[3] Production costs are linear with coefficients of c_u and c_r for the unreliable and reliable suppliers, respectively. When R serves only as the backup supplier, he may incur a higher marginal production cost, $c_{rb} \geq c_r$, because producing occasional orders may require a responsive production capability. To isolate the benefits of backup flexibility from cost implications, our analysis mostly assumes $c_{rb} = c_r$.

To evaluate the suppliers' strategic behavior, it is important to specify the contracts that the suppliers offer. The simplest type of supply contract consists of a single wholesale price that the manufacturer needs to pay for each unit of product sourced from each of the suppliers. In the context of our dynamic model, the two suppliers announce their wholesale prices w_r, w_u simultaneously in Phase I(a).

Despite its simplicity, and extensive analysis in literature (in disruption and other settings), as well as broad popularity in practice (in nondisruption settings), we find that the single-wholesale-price contract is not most realistic; indeed, it leads to a conflict of incentives in terms of the role suppliers want to play and the size of the business they get. Consequently, in the most relevant cases, a pure-strategy Nash equilibrium does not exist, where the manufacturer sources from both suppliers. More specifically, the nonexistence of pure-strategy Nash equilibrium is driven by the fact that R wishes to charge different wholesale prices as a primary supplier versus a backup supplier.[4]

The formal lack of equilibrium is consistent with business practice: the aforementioned tension between volume and price plays a crucial role. It would not likely be a stable relationship between supplier and manufacturer if the volume of the business was mis-specified by the manufacturer. For example, when a manufacturer promises a supplier to make him the main provider of parts with presumably low price (due to high volume), but then relegates his role to auxiliary the backup supplier (with a fairly low volume). In practice, one would expect the suppliers' prices to differ based on the supplier's role, the expected volume, and expected predictability of using the supplier's capacity. To account for the possibility that R may be able to price based on his role, throughout the present paper we focus on a contingent-pricing scheme. Specifically, R quotes wholesale prices (w_r, w_{rb}): the wholesale price w_r is for regular orders and w_{rb} is for the emergency (backup) orders.

[3] When the inventory holding cost is mostly attributable to the opportunity cost of money tied up in inventory, it is more appropriate to model the holding cost as a holding cost rate (%). To keep the exposition clear, we use a fixed (physical) holding cost, without necessarily altering the main insights.

[4] If the wholesale price for regular deliveries decreases significantly due to competition for the role of primary supplier, R finds it optimal to raise her price and become the backup supplier. However, in response, U finds it optimal to raise his price to match R's. Consequently, the suppliers do not reach an equilibrium in which the manufacturer exercises his flexible-sourcing option. Similarly, they would not reach equilibrium even if they were allowed to revise prices during the horizon.

U offers a wholesale price, w_u, and in addition, may offer to pay the manufacturer a penalty for any delayed order at a rate of s_u per unit of time. The contingent-pricing scheme is not uncommon in practice. As in the earlier example of Kolbus, firms compensate their backup suppliers generously, implying a premium price for emergency orders. Use of primary and back up suppliers is not limited to manufacturing. In transportation settings, large firms choose a primary and secondary carrier (Boyle 2000). Also, late-delivery rebates are widely applied in various industries. For example, Drewco, a supplier specializing in designing and producing workholding devices, backs its on-time delivery guarantee with a minimum 10% per day rebate for late shipments.[5] Dai et al. (2014) analyze a similar late-delivery rebate adopted in the healthcare industry.

Under the contingent-pricing scheme, if the manufacturer solely sources from R (i.e., adopts SR in Phase I(b)), she sources from R at a rate of 1 per unit time and pays R the wholesale price w_r for each unit of good. There is no need for inventory in this case and Phase II is trivial. Otherwise, if the manufacturer adopts SU or FS, the manufacturer pays w_u (and w_{rb}) per unit for all orders from U (and R) and may choose to carry inventory in each case. Below we describe the inventory decisions before and during a disruption.

Before a disruption: In anticipation of disruptions, both the manufacturer and the unreliable supplier may carry inventories. Denote M's and U's inventory level by κ_m and κ_u, respectively. Both of them are decided in Phase I: κ_u is offered by unreliable supplier U (in Phase I(a)). κ_m is a part of the manufacturer's strategy (Phase I(b)) after the suppliers' offers are in place. Note that due to the exponential distribution assumption, the future looks the same at any time before a disruption; therefore, the inventory levels can be decided at the beginning of the horizon: κ_u in Phase I(a) and κ_m in Phase I(b). After inventory levels are determined, M orders at a rate of 1 to meet the demand, while U produces at a rate of 1, and inventory levels remain unchanged until a disruption occurs.

During a disruption: The manufacturer will sequentially use up to three supply sources to meet demand: rely on U's inventory, rely on her own inventory, and use R's backup capacity. When U faces a disruption, U continues to deliver goods to M until he runs out of inventory. Then M's inventory is used. By an interchange argument, neither U nor later M, has any benefit in delaying the use of inventory. Under FS, the manufacturer starts using R as soon as all stocks (including κ_u and κ_m) run out. However, under SU, after running out of all stocks, M backlogs demand. U pays a penalty s_u for delays, effectively reducing M's backlogging cost to $\pi_b - s_u$.

The firms are risk-neutral and their objective is to maximize their long-run average profits. We aim to characterize the firms' strategies and profits in a subgame-perfect Nash equilibrium. In

[5] http://www.drewco.com/DREWCO_Gaurantee.aspx. Last accessed on June 04, 2015.

addition to subgame perfection, we impose the Pareto-dominance criterion: if multiple equilibria exist, we will focus on the equilibrium that Pareto dominates all the other ones from the two suppliers' perspective, that is, the equilibrium where both suppliers obtain (weakly) higher profits than they do in any other equilibrium.

It is useful to introduce some simplified notation related to the state of the unreliable supplier. The steady-state probabilities are $\pi_{ON} = 1 - \pi_{OFF} = \frac{\theta_r}{\theta_f + \theta_r}$. Let random variable τ be the time until recovery from a disruption, with a cumulative distribution function, $G(t) = 1 - e^{-\theta_r t}$, and probability density function, $g(t) = \theta_r e^{-\theta_r t}$. Let $\bar{G}(t) := 1 - G(t) = \frac{1}{\theta_r} g(t)$. Define $F(t) = \pi_{ON} + \pi_{OFF} G(t)$ as the cumulative distribution function of the long-run average length of a disruption and $\bar{F}(t) = 1 - F(t)$. We note that $F(0) = \pi_{ON}$ describes the proportion of time with no supplier disruption. Finally, we define the inverse function $F^{-1}(x) := \min\{t | F(t) \geq x\}$. Table 1 summarizes the notations used in the present paper.

4. Equilibrium Analysis

We start by analyzing Phase I(b), assuming that the suppliers' offers are already announced in Phase I(a). Then, we move to Phase I(a) and analyze the price competition of the suppliers.

4.1. Phase I(b): Manufacturer's Equilibrium Inventory Policy

Assume that the suppliers have already announced their pricing schemes, (w_u, s_u) and (w_r, w_{rb}), and inventory strategies (κ_u), and the manufacturer has decided her sourcing policy. When the manufacturer solely sources from R, no inventory is needed. When the manufacturer adopts either SU or FS, the unreliable supplier has committed to holding inventory $\kappa_u \geq 0$, and the manufacturer may also decide to hold inventory (κ_m). The following proposition derives the manufacturer's optimal inventory policy and the expected costs M and U incur under each sourcing policy.

Proposition 1. (i) *For any given κ_m and κ_u, the long-run average holding and penalty cost of player $i \in \{m, u\}$ under sourcing plan $sp \in \{SU, FS\}$ is given by $L_i(\kappa_m, \kappa_u | \sigma_i^{sp})$. Consequently, the manufacturer's long-run average profit is $p - w_u - L_m(\kappa_m, \kappa_u | \sigma_m^{sp})$, and U's long-run average profit is $w_u - c_u - L_u(\kappa_m, \kappa_u | \sigma_u^{sp})$.*

(ii) *For sourcing plan $sp \in \{SU, FS\}$ and given κ_u, M's optimal inventory level is $\kappa_m^{sp}(\kappa_u) = (\kappa_m^{sp,0} - \kappa_u)^+$, where $\kappa_m^{sp,0} = F^{-1}(\frac{\theta_r \sigma_m^{sp}}{\theta_r \sigma_m^{sp} + h_m})$ is M's first-best inventory level.*

As shown in Proposition 1 (i) and (ii), the manufacturer's first-best inventory level $\kappa_m^{sp,0}$ is captured by a newsvendor trade-off. Note that σ_m^{sp} is effectively the cost of underage and h_m/θ_r is the cost of overage, that is, expected holding cost for an unused product during a disruption. Taking into account the unreliable supplier's inventory κ_u, the manufacturer stocks additional quantity up to her first-best inventory level $\kappa_m^{sp,0}$. The cost functions presented in Proposition 1(i) imply

Table 1 Notations

Symbol	Meaning
θ_f	rate of ON time
θ_r	rate of OFF time; $\theta_f \leq \theta_r$
c_u	production cost of unreliable supplier
c_r	production cost of reliable supplier
w_u	wholesale price of unreliable supplier
s_u	penalty of unreliable supplier for delayed deliveries due to disruption;
w_{ud}	effective wholesale price of unreliable supplier for delayed deliveries, $w_{ud} = w_u - \frac{s_u}{\theta_r}$;
w_r	wholesale price of reliable supplier for regular orders
w_{rb}	wholesale price of reliable supplier for backup orders
p	selling price of manufacturer
π_b	backlogging cost of manufacturer, per unit per time
h_m	holding cost of manufacturer
h_u	holding cost of unreliable supplier
κ_m	inventory carried by manufacturer
κ_u	inventory carried by unreliable supplier
π_{ON}	steady-state probability that the unreliable supplier is ON; $\pi_{ON} = 1 - \pi_{OFF} = \frac{\theta_r}{\theta_f + \theta_r}$
π_{OFF}	steady-state probability that the unreliable supplier is OFF
$\tau \sim G(\cdot)$	time until recovery from a disruption, $G(t) = 1 - e^{-\theta_r t}$, $g(t) = \theta_r e^{-\theta_r t}$, $\bar{G}(t) = 1 - G(t)$
$F(\cdot)$	distribution of long-run average length of a disruption; $F(t) = \pi_{ON} + \pi_{OFF} G(t)$, $\overline{F}(t) = 1 - F(t)$, $F^{-1}(x) := \min\{t \mid F(t) \geq x\}$
σ_m^{SU}	effective penalty of manufacturer under SU; $\sigma_m^{SU} = \frac{\pi_b - s_u}{\theta_r}$
σ_m^{FS}	effective penalty of manufacturer under FS; $\sigma_m^{FS} = w_{rb} - w_u$
σ_u^{SU}	effective penalty of unreliable supplier under SU; $\sigma_u^{SU} = \frac{s_u}{\theta_r}$
σ_u^{FS}	effective penalty of unreliable supplier under FS; $\sigma_u^{FS} = w_u - c_u$
$L_i(\kappa_m, \kappa_u \mid \sigma)$	player i's long-run average expected holding and penalty cost, for $i \in \{m, u\}$: $L_i(\kappa_m, \kappa_u \mid \sigma) = H_i(\kappa_m, \kappa_u) + \sigma \bar{F}(\kappa_m + \kappa_u)$, where $H_m(\kappa_m, \kappa_u) = h_m \kappa_m + (\frac{h_m}{\theta_r})[\bar{F}(\kappa_m + \kappa_u) - \bar{F}(\kappa_u)]$, $H_u(\kappa_m, \kappa_u) = h_u \kappa_u + (\frac{h_u}{\theta_r})[\bar{F}(\kappa_u) - \bar{F}(0)]$
κ_i^o	$\kappa_i^o = F^{-1}\left(\frac{\pi_b}{\pi_b + h_i}\right)$ for $i \in \{m, u\}$
L_m^o, L_u^o	$L_m^o = L_m(\kappa_m^o, 0 \mid \frac{\pi_b}{\theta_r})$, $L_u^o = L_u(0, \kappa_u^o \mid \frac{\pi_b}{\theta_r})$
$\bar{\kappa}_m^o(\phi)$	$\bar{\kappa}_m^o(s_u) = F^{-1}(\frac{\pi_b - \phi\theta_r}{\pi_b + h_m - s_u})$
Δ	$\Delta = \frac{H_u(\kappa_u^o)}{F(\kappa_u^o)}$ if $h_u \leq h_m$, $\Delta = \frac{H_m(\kappa_m^o)}{F(\kappa_m^o)}$ if $h_u > h_m$

that a similar newsvendor trade-off applies to the unreliable supplier as well. Different from the manufacturer, whose overage and underage costs are dictated by the suppliers' offers, the unreliable supplier can strategically choose his prices and thus influence his own inventory costs and profits. Obviously, the unreliable supplier's decision is not arbitrary, but a result of the competition with the reliable supplier, which we analyze next.

4.2. Phase I(a): Price Competition of Suppliers

In this subsection, we examine the suppliers' pricing competition and inventory decision in Phase I(a). We seek to address the main question of this paper and explore the impact of disruptions on pricing strategies of the suppliers. Specifically, we aim to answer the following questions: How do the suppliers price under various reliability profiles? What sourcing strategy does the manufacturer adopt in the equilibrium, assuming it exists? What pricing schemes will prevail in the equilibrium? Under what circumstances do the manufacturer and the suppliers benefit from a flexible sourcing strategy? We also evaluate the efficacy of the contingent-pricing game using as a centrally-managed supply chain as a benchmark.

To examine the benefits of flexible sourcing, we consider a "No Flexible Sourcing" benchmark, defined as sourcing solely from R or solely from U.

No Flexible Sourcing

Before deriving the equilibrium outcomes, we specify the firms' payoffs in Phase I(a) when the manufacturer chooses between SR and SU. Table 2 summarizes the firms' long-run average profits as functions of the suppliers' offers and the manufacturer's sourcing choice.

Table 2 Firms' long-run average profit functions without the flexible-sourcing option

M's choice	M	U	R
SR	$p-w_r$	0	w_r-c_r
SU	$p-w_u-L_m(\kappa_m^{SU}(\kappa_u),\kappa_u\|\sigma_m^{SU})$	$w_u-c_u-L_u(\kappa_m^{SU}(\kappa_u),\kappa_u\|\sigma_u^{SU})$	0

Proposition 2. *(No-Flexible-Sourcing Equilibrium) When the manufacturer commits to a sole-sourcing strategy, the equilibrium is as follows (with details in Table 3):*

- *if $h_m \geq h_u$,*
  — *if $c_r < c_u + L_u^o$, then R is awarded the whole contract* [Case(SR, $h_m \geq h_u$)];
  — *if $c_r \geq c_u + L_u^o$, then U is awarded the whole contract* [Case(SU, $h_m \geq h_u$)];
- *if $h_m < h_u$,*
  — *if $c_r < c_u + L_m^o$, then R is awarded the whole contract* [Case(SR, $h_m < h_u$)];
  — *if $c_r \geq c_u + L_m^o$, then U is awarded the whole contract* [Case(SU, $h_m < h_u$)].

Table 3 No-FS Equlibrium

Case	w_r^*	w_u^*	s_u^*	κ_u^*	κ_m^*
(SR, $h_m \geq h_u$)	$c_u+L_u^o$	$c_u+L_u^o-(\frac{\pi_b-s_u^*}{\theta_r})\bar{F}(\kappa_u^o)$	$[0,\pi_b]$	κ_u^o	0
(SU, $h_m \geq h_u$)	c_r	$c_r-(\frac{\pi_b-s_u^*}{\theta_r})\bar{F}(\kappa_u^o)$	$[0,\pi_b]$	κ_u^o	0
(SR, $h_m < h_u$)	$c_u+L_m^o$	c_u	0	0	0
(SU, $h_m < h_u$)	c_r	$c_r-L_m^o$	0	0	κ_m^o

Note. M's equilibrium profit is infinitesimally above its profit, evaluated at the losing supplier's break-even price

A pleasing result of Proposition 2 is that, when *SU* is adopted, the inventories are carried by the party having a lower inventory holding cost (unreliable supplier or manufacturer). In these cases, the unreliable supplier bears the full cost of demand backlogging (it manifests itself through the term $-L_m^o$ in w_u^*). Also note that in Proposition 2, when $h_m \geq h_u$, the equilibrium is sustained for any arbitrary s_u^*. This is because U assures M of his κ_u^o units of inventory (by stipulating it in the supply contract), which is higher than M's first-best inventory level. Thus, M does not need to hold any inventory. In this case, any late-delivery penalty becomes an additional compensation to the manufacturer and, as such, it will be fully absorbed in $U's$ wholesale price w_u^*. However, when $h_m < h_u$, the equilibrium penalty, s_u^*, equals zero. Thus, in both cases, the late-delivery penalty does not play any role when the manufacturer does not consider the option of flexible sourcing.

Flexible Sourcing

Now we analyze the main case in which the manufacturer chooses among three alternatives, SU, SR, and FS. Our intent is to characterize and evaluate the equilibrium policies of the suppliers (which include wholesale prices as well as inventory policies). We also characterize the manufacturer's equilibrium strategy in terms of both supplier choice and inventory policy. The detailed analysis is in the supplementary document, whereas we summarize the firm's profit functions and equilibrium outcomes below.

Table 4 Firms' long-run average profit functions with the flexible-sourcing option

M's choice	M	U	R
SR	$p - w_r$	0	$w_r - c_r$
SU	$p - w_u - L_m(\kappa_m^{SU}(\kappa_u), \kappa_u \vert \sigma_m^{SU})$	$w_u - c_u - L_u(\kappa_m^{SU}(\kappa_u), \kappa_u \vert \sigma_u^{SU})$	0
FS	$p - w_u - L_m(\kappa_m^{FS}(\kappa_u), \kappa_u \vert \sigma_m^{FS})$	$w_u - c_u - L_u(\kappa_m^{FS}(\kappa_u), \kappa_u \vert \sigma_u^{FS})$	$(w_{rb} - c_r)\bar{F}(\kappa_m^{FS}(\kappa_u) + \kappa_u)$

PROPOSITION 3. *When the manufacturer has the option of flexible sourcing, equilibrium outcomes are described below with respect to a constant Δ with $0 \leq \Delta < \frac{\pi_b}{\theta_r}$, a threshold $\bar{h}_u \geq h_m$, and two weakly increasing functions, $s_1(.) \leq s_2(.)$, with $s_1(\Delta) = s_2(\Delta) = 0$ and $s_1(\frac{\pi_b}{\theta_r}) \leq s_2(\frac{\pi_b}{\theta_r}) = \pi_b$:*

(SR): *When $c_r - c_u \leq \Delta$, the manufacturer sole-sources from R. If $h_u \leq h_m$, we have case SR-1 and otherwise case SR-2. In both cases $w_{rb}^* \geq w_u^* + \frac{\pi_b - s_u^*}{\theta_r}$.*

(SU): *When $c_r - c_u \geq \frac{\pi_b}{\theta_r}$, the manufacturer sole-sources from U. When $h_u \leq \bar{h}_u$, we have case SU-1 and otherwise case SU-2.*

(FS): *If $\Delta < c_r - c_u < \frac{\pi_b}{\theta_r}$, the manufacturer primarily sources from U and uses R as the backup supplier.*

(i) If $h_u \leq h_m$, we have case FS-1.

(ii) If $h_u \geq \bar{h}_u$, we have case FS-2.

(iii) If $h_m < h_u < \bar{h}_u$, the equilibrium outcomes are further characterized by two thresholds $\bar{c}_1$ and $\bar{c}_2$ with $\Delta \leq \bar{c}_1 \leq \bar{c}_2 \leq \frac{\pi_b}{\theta_r}$ as follows. If $\Delta < c_r - c_u < \bar{c}_1$, we have case FS-2. If $\bar{c}_1 < c_r - c_u < \bar{c}_2$, we have case FS-3. If $\bar{c}_2 < c_r - c_u < \frac{\pi_b}{\theta_r}$, we have case FS-1.

Equilibrium outcomes are shown in Table 5.

Table 5 FS Equlibrium

Case	w_r^*	w_{rb}^*	w_u^*	s_u^*	κ_u^*	κ_m^*
SR-1	$c_u + L_u^o$	∞	$c_u + L_u^o - (\frac{\pi_b - s_u^*}{\theta_r})\bar{F}(\kappa_u^o)$	$[0, \pi_b]$	κ_u^o	0
SR-2	$c_u + L_m^o$	∞	c_u	0	0	0
SU-1	c_r	c_r	c_r	π_b	κ_u^o	0
SU-2	c_r	c_r	$c_r - \frac{\pi_b - s_u^*}{\theta_r}$	$s_1(\frac{\pi_b}{\theta_r})$	0	$\bar{\kappa}_m^o(\frac{s_u^*}{\theta_r})$
FS-1	$c_r + (\frac{\pi_b}{\theta_r} - c_r + c_u)\bar{F}(\kappa_u^o)$	$c_u + \frac{\pi_b}{\theta_r}$	c_r	$(c_r - c_u)\theta_r$	κ_u^o	0
FS-2	$c_r + (\frac{\pi_b}{\theta_r} - c_r + c_u)\bar{F}(\bar{\kappa}_m^o(\frac{s_2(c_r - c_u)}{\theta_r}))$	$c_u + \frac{\pi_b}{\theta_r}$	$c_u + \frac{s_u^*}{\theta_r}$	$s_1(c_r - c_u)$	0	$\bar{\kappa}_m^o(\frac{\pi_b}{\theta_r} - w_{rb}^* + w_u^*)$
FS-3	$c_r + (\frac{\pi_b}{\theta_r} - c_r + c_u)\bar{F}(\bar{\kappa}_m^o(\frac{s_2(\bar{c}_1)}{\theta_r}))$	$c_u + \frac{\pi_b}{\theta_r}$	$c_u + \frac{s_u^*}{\theta_r}$	$s_1(\bar{c}_1)$	0	$\bar{\kappa}_m^o(\frac{\pi_b}{\theta_r} - w_{rb}^* + w_u^*)$

For a clear interpretation of our results, define $w_{ud} := w_u - \frac{s_u}{\theta_r}$, the expected revenue of the unreliable supplier for any order during a disruption that is backlogged. Note that $\frac{1}{\theta_r}$ is the expected time to recover from a disruption. We refer to w_{ud} as the effective wholesale price for delayed deliveries, and represent U's decisions interchangeably by (w_u, s_u) and (w_u, w_{ud}).

It is easiest to interpret Proposition 3 in a special case when the holding costs for both M and U are prohibitively high, making inventory holding an undesirable option for both M and U:

Corollary 1. *Assume that neither M nor U can hold inventory (e.g., when $h_m = h_u = \infty$). Sourcing equilibrium outcomes are as follows. $\kappa_u^* = \kappa_m^* = 0$, and*

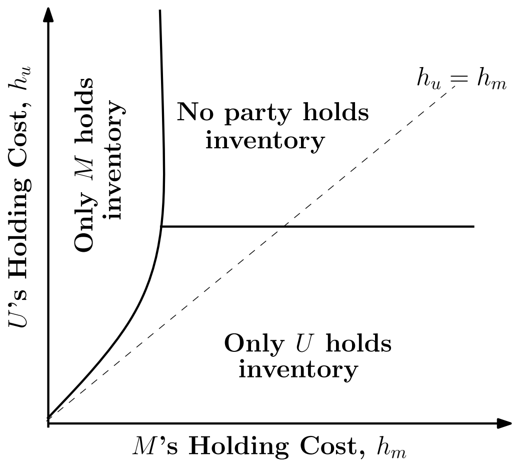
- *if $c_r - c_u \leq 0$, R is the sole supplier and $w_r^* = c_u + \frac{\pi_b}{\theta_r}\pi_{OFF}$, $w_u^* = w_{ud}^* = c_u$, $w_{rb}^* \geq c_u + \frac{\pi_b}{\theta_r}$;*
- *if $c_r - c_u \geq \frac{\pi_b}{\theta_r}$, U is the sole supplier and $w_r^* = c_r$, $w_u^* = c_r$, $w_{ud}^* = c_r - \frac{\pi_b}{\theta_r}$, $w_{rb}^* = c_r$;*
- *if $0 < c_r - c_u < \frac{\pi_b}{\theta_r}$, M adopts flexible sourcing and $w_r^* = c_r + (c_u + \frac{\pi_b}{\theta_r} - c_r)\pi_{OFF}$, $w_u^* = c_r$, $w_{ud}^* = c_u$, $w_{rb}^* = c_u + \frac{\pi_b}{\theta_r}$.*

For the special case, described in Corollary 1, because a zero-inventory policy is optimal in the equilibrium, the manufacturer's orders under SU or FS can be classified into two categories: regular orders that arise with a frequency π_{ON} and emergency (or delayed) orders that arise with a frequency π_{OFF}. With this separation of orders, suppliers effectively engage in two pricing games with the flexibility of quoting different wholesale prices for each game. In the equilibrium, the manufacturer's cost for each type of order (including backlog penalty, if any) is given by his second best option: for regular orders, the manufacturer incurs $\max\{c_r, c_u\}$ and for emergency (or delayed orders), she incurs $\max\left\{c_r, c_u + \frac{\pi_b}{\theta_r}\right\}$, because sourcing from U results in penalty costs for delayed orders. Interestingly, independent of the frequency of failures, for any costs satisfying $0 < c_r - c_u < \frac{\pi_b}{\theta_r}$, the equilibrium results in both suppliers being active.

The potential for holding inventory modifies these thresholds. For general holding costs, although holding inventory could be economical for both M and U, Proposition 3 indicates that, in equilibrium, there is no situation when both M and U hold inventories. Thus, it is either the manufacturer or the unreliable supplier protecting the system against disruptions, but not both.

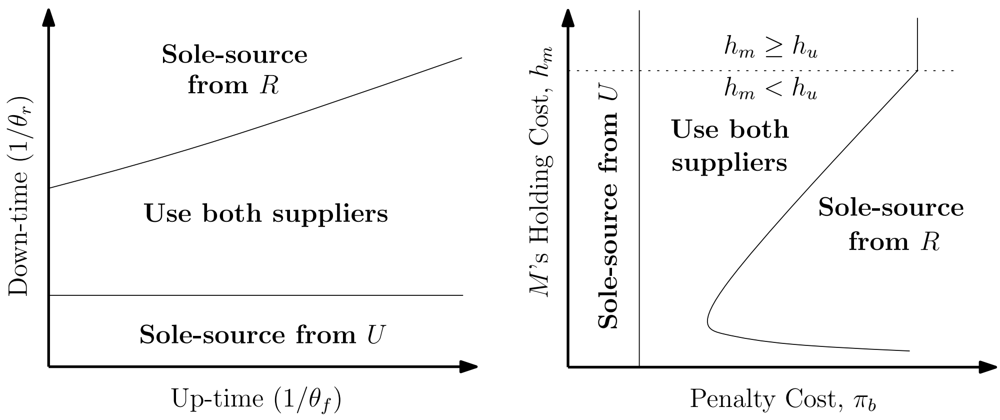
One would expect the firm with a lower holding cost (either U or M) to hold inventory under SU outcome. This is the case when no flexible sourcing is available (see Proposition 2). When flexible sourcing is available as an option, the same intuition holds when $h_u < h_m$, as the supply chain would benefit more when the unreliable supplier (the party with the lower holding cost) carries inventory, not the manufacturer. However, the converse is not necessarily true. When $h_m < h_u$, in order for the unreliable supplier to create the right incentives for M to hold the desired inventory, U needs to choose the appropriate combination of w_u and s_u: (a) U should set the desirable newsvendor ratio for M, and (b) U should ensure that M's total cost does not exceed his other options, SR or FS. Often such a combination exists, but not always. The non-existence of such a contract (in some situations) is due to the dynamics of competition with R. To incentivize (otherwise reluctant) M to hold inventory, U needs to decrease the discount s_u. (Otherwise, with a bigger discount, M prefers to receive the discount and not incur the cost of holding inventory.) However, a lower discount s_u may be impossible, as it allows R to compete for the backup business. When U cannot decrease s_u sufficiently and incentivize M to hold sufficient inventory, the second best option is holding some inventory himself. As illustrated in Figure 1, in some cases, U holds inventory despite having a higher holding cost. In the supplementary document we provide a detailed example for such a situation.

Figure 1 **Inventory Holding in Equilibrium**



The equilibrium sourcing outcomes in Proposition 3 are influenced by the cost advantage of an unreliable supplier, $c_r - c_u$. Except when the cost difference is extremely low or extreme high, the manufacturer uses both the less expensive unreliable supplier and the more expensive reliable supplier (note that the FS region is always nonempty as $\Delta < \frac{\pi_b}{\theta_r}$). When R's production cost is sufficiently low (but not necessarily lower than c_u), $c_r \le c_u + \Delta$, R serves as the sole supplier in equilibrium. When $c_r > c_u + \Delta$, similar to the no-inventory case, the equilibrium sourcing policy is also influenced by the manufacturer's backlogging cost and expected length of disruptions: when $c_r - c_u$ is below the expected penalty cost incurred during a disruption, $\frac{\pi_b}{\theta_r}$, M adopts flexible sourcing in equilibrium, and otherwise, M sole-sources from U. Figure 2 illustrates how the equilibrium sourcing outcome depends on (a) the average uptime and downtime and (b) the manufacturer's inventory holding and penalty costs when $c_r > c_u$.

Figure 2 Equilibrium Sourcing Outcomes



(a) π_b, h_m, h_u, and $c_r > c_u$ are fixed. (b) θ_f, θ_r, h_u, and $c_r > c_u$ are fixed.

Figure 2(a) has an intuitive interpretation. For disruptions with sufficiently short average length (low downtime $1/\theta_r$), U is able to secure the contract as the sole supplier in equilibrium. Otherwise, depending on the average length of disruptions, the manufacturer either sole-sources from R or keeps R as the backup source. The latter case implies lost orders for U whenever he faces disruptions that take longer than the time to use existing inventory.

Figure 2(b), on the other hand, is less intuitiveit reflects the effect of strategic supplier behavior. When the penalty cost is negligible, U is able to secure the contract as the sole supplier; when the penalty cost is moderately high, the manufacturer uses both suppliers. These results are intuitive. However, when the penalty cost becomes higher, manufacturer's sourcing strategy is also influenced by her holding cost, but in a nonmonotonic way. If the holding cost is negligible, the manufacturer can mitigate disruptions by holding a significant amount of inventory; therefore, R cannot compete aggressively to serve as the primary supplier. When the holding cost is very high, the manufacturer is unable to economically hold inventory and has incentive to maintain a backup supplier. In this case, R takes advantage of being reliable and becomes the backup supplier, not because he cannot compete aggressively to be the sole supplier, but because it is more profitable to be a backup. Finally, if the holding cost is in the middle range, it is more profitable for R to compete more aggressively and secure the entire contract as the sole supplier. The dynamics we observe for a high penalty cost is driven purely by strategic supplier behavior in the presence of backup flexibility.

5. Impact of Flexible Sourcing

Exploring the equilibrium outcomes of the contingent-pricing game with and without backup flexibility enables us to address the focal questions of the present paper: Does the manufacturer benefit from flexible sourcing by allowing the reliable supplier to offer flexibility at a higher wholesale price? Which supplier(s) benefit from a flexible sourcing arrangement? In the absence of strategic behavior (i.e., with fixed wholesale prices), the manufacturer would always benefit from flexible sourcing, whereas the supplier U could be hurt, because some of his orders are lost with flexible sourcing. Supplier R may or may not benefit, depending on the original arrangement without flexible sourcing. Below, we show that this intuition does not necessarily carry over when strategic supplier behavior is taken into account. Proposition 4 is formally shown for two cases, when $h_u \leq h_m$ and when h_u is reasonably large, $h_u \geq \bar{h}_u$ (defined in Proposition 3), whereas performance for other values is evaluated numerically.

PROPOSITION 4. *(i) Let $h_u \leq h_m$. With backup flexibility, the profits of both suppliers and the total supply chain profit are higher, whereas the manufacturer's profit is lower, when $\Delta \leq c_r - c_u \leq \frac{\pi_b}{\theta_r}$. Otherwise, profits are not influenced by backup flexibility.*

(ii) Let $h_u \geq \bar{h}_u$. If $c_r - c_u \leq \Delta$, profits are not influenced by backup flexibility. Let $c_r - c_u > \Delta$. R's profit is higher with backup flexibility when $c_r - c_u \leq \frac{\pi_b}{\theta_r}$, and her profit does not depend on flexibility, otherwise. With backup flexibility, there exist $\bar{c}_u$ and $\bar{c}_{sc}$, such that the profits of U and of the supply chain are higher if $c_r - c_u \leq \bar{c}_u$, and $c_r - c_u \leq \bar{c}_{sc}$, respectively, and are lower otherwise. $L_m^o \leq \bar{c}_u, \bar{c}_{sc} \leq \frac{\pi_b}{\theta_r}$. For the manufacturer,

- *if $\frac{\pi_b}{\pi_b + h_m} \leq 1 - \pi_{OFF}^2$, then the manufacturer's profit is lower with backup flexibility when $c_r - c_u < \frac{\pi_b}{\theta_r}$, and does not depend on flexibility otherwise.*
- *if $\frac{\pi_b}{\pi_b + h_m} \geq \frac{4\pi_{ON}}{(1+\pi_{ON})^2}$, then there exists a threshold $\bar{c}_m$ such that the manufacturer's profit is lower with backup flexibility when $c_r - c_u \leq \bar{c}_m$ and is higher when $c_r - c_u \geq \bar{c}_m$.*
- *if $1 - \pi_{OFF}^2 < \frac{\pi_b}{\pi_b + h_m} < \frac{4\pi_{ON}}{(1+\pi_{ON})^2}$, then there exist two thresholds, $\bar{c}'_m$ and $\tilde{c}$, such that the manufacturer's profit is lower with backup flexibility when $c_r - c_u \leq \bar{c}'_m$, is higher if $\bar{c}'_m < c_r - c_u \leq \tilde{c}$, and is lower if $\tilde{c} < c_r - c_u \leq \frac{\pi_b}{\theta_r}$. The manufacturer's profit does not depend on flexibility if $c_r - c_u \geq \frac{\pi_b}{\theta_r}$.*

Proposition 4 shows that R always (weakly) benefits from offering backup flexibility in two special cases. An extensive numerical study indicates that this remains the case for other values of h_u. Surprisingly, U and the manufacturer may or may not benefit from backup capacity, which is a major departure from our intuition for the case of nonstrategic suppliers. Even more surprisingly, there is no case when all supply chain players improve their profits with backup flexibility simultaneously and, in some of those situations, the supply chain performance degrades.

Figure 3 Sourcing Outcomes and Benefits of Backup Flexibility with $(U): h_u \leq h_m$

Sourcing outcome	Regions with respect to $c_r - c_u$		
with no FS	R		U
with FS	R	Use both suppliers R and U	U
Benefits of Backup Flexibility			
Reliable Supplier	**0**	+ + + + + + + + +	**0**
Unreliable Supplier	**0**	+ + + + + + + + +	**0**
Manufacturer	**0**	− − − − − − − − −	**0**
Supply Chain	**0**	+ + + + + + + + +	**0**

Note. "+": benefits, "−": does not benefit, "**0**": is indifferent

The findings of Proposition 4 point (i) are illustrated in Figure 3 and point (ii) in Figure 4. When inventory holding cost is high for M (Proposition 4(i) and Figure 3), M does not hold inventory and both suppliers benefit from existence of backup flexibility, whereas M is worse off. In the competitive range, when both suppliers could be used economically, the equilibrium wholesale prices are driven by the following dynamics.

- To be competitive for the orders with delayed deliveries, the unreliable supplier needs to offer a lower discounted price w_{ud} compared to regular orders. With a discount equal to the expected backlogging penalty, w_{ud} is easily below U's cost, and U loses money on delayed orders. U is better off charging at cost, $w_{ud} = c_u$ and allowing R to serve as the backup supplier.

- The reliable supplier, interested in the backup business, can charge a premium corresponding to the expected backlogging penalty, $w_{rb} = c_u + \frac{\pi_b}{\theta_r}$. Alternatively, R can serve as the primary (and only) supplier and charge a price that makes the manufacturer indifferent to the cost of buying from an unreliable supplier (at w_u) plus the cost of backup delivery from R.

- w_u is critical for the role R plays. The competition drives w_u down until suppliers reach a point where R benefits more from serving as the backup supplier. When this happens, both suppliers make a larger profit than if they competed as sole suppliers. See supplementary document SA for a numerical example.

The contingent-pricing game allows the suppliers to quote prices based on their strengths and weaknesses. For example, when U's strength is low cost and his weakness is long disruptions, then it is in his interest to be the primary supplier and give up on orders during disruptions. The logic above highlights that when the manufacturer seeks flexible sourcing, suppliers are able to segment the demand and compete less aggressively, making the manufacturer worse off.

Figure 4 Sourcing Outcomes and Benefits of Backup Flexibility with $(M): h_u = \infty$

Sourcing outcome	**Regions with respect to** $c_r - c_u$			
with no FS		R	U	
with FS	R	Use both suppliers R and U		U
Benefits of Backup Flexibility				
Reliable Supplier	0	+ + + + + + + + + +		0
Unreliable Supplier	0	+ + + + + + + + +		− − −
Manufacturer	0	− − − − − − − − −		+ +
Supply Chain	0	+ + + + + + + + +		− − −

Note. "+": benefits, "−" : does not benefit, "**0**" : is indifferent. Numerical results show that the threshold of the supply chain $\bar{c}_{sc}$ is lower than the threshold of the manufacturer $\bar{c}_m$, whereas it can be higher or lower than the threshold of the unreliable supplier $\bar{c}_u$.

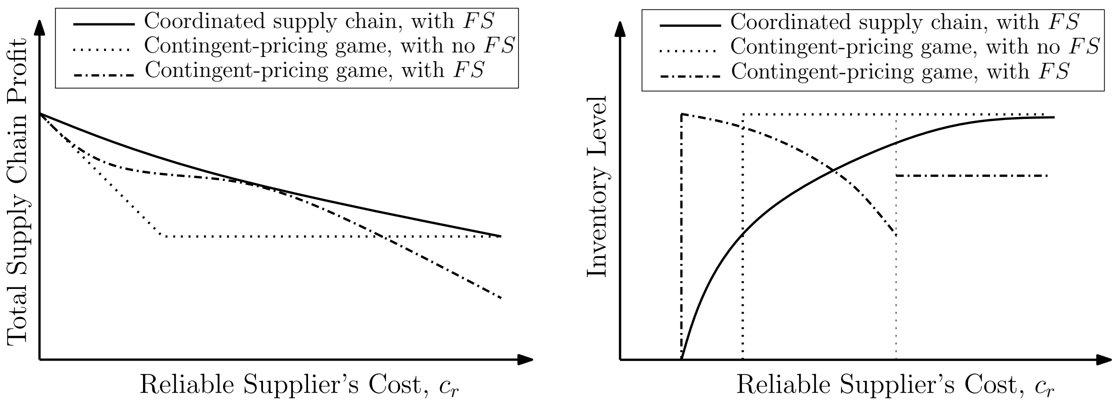
The situation may be slightly different when holding inventory is expensive for U (Proposition 4(ii)). The difference between Figures 3 and 4 illustrates how the benefits of flexible sourcing shift when h_u increases. As shown in Figure 4, the manufacturer, in some cases, may benefit from flexible sourcing. However, when the manufacturer benefits from a flexible sourcing strategy, the supplier U is worse off, because U can no longer depend on inventories during the disruption. Moreover, in these cases, the supply chain performance is poorer, compared to the case when flexible sourcing is not allowed.

Although the supply chain performance often improves, typically a coordinated outcome is not achieved. The coordinated outcome for this supply chain is described in the supplementary document. Figure 5 illustrates the total supply chain profit and inventory level under three scenarios (assuming $c_u = 0$, $\Delta < c_r < \frac{\pi_b}{\theta_r}$ and $h_m < h_u < \bar{h}_u$): coordinated outcome, contingent-pricing game with FS and with no FS.

Although the inventory decision is not distorted when flexible sourcing is not allowed, it is distorted in the contingent-pricing game when flexible sourcing is allowed. To illustrate why distortion takes place in the latter case, note that in the equilibrium (Proposition 3) U charges his cost for delayed orders, $w^*_{ud} = c_u$. In response, the equilibrium wholesale price of the (reliable) backup supplier is $w^*_{rb} = c_u + \frac{\pi_b}{\theta_r}$, which does not depend on c_r. However, U's equilibrium wholesale price,

w_u^*, is (weakly) increasing in c_r. Thus, the manufacturer faces an increasing (as a function of c_r) wholesale price for regular orders and a constant wholesale price for emergency (backup) orders and has less incentive to carry inventory. Instead, the manufacturer has more incentive to rely on the backup supplier. This is opposite to forces in a coordinated supply chain where inventory would increase. Thus, the competitive dynamics between U and R, rather than the economics of holding inventory, determines inventory levels.

Figure 5 Supply Chain Performance



(a) Total supply chain profit in equilibrium (b) Inventory Level

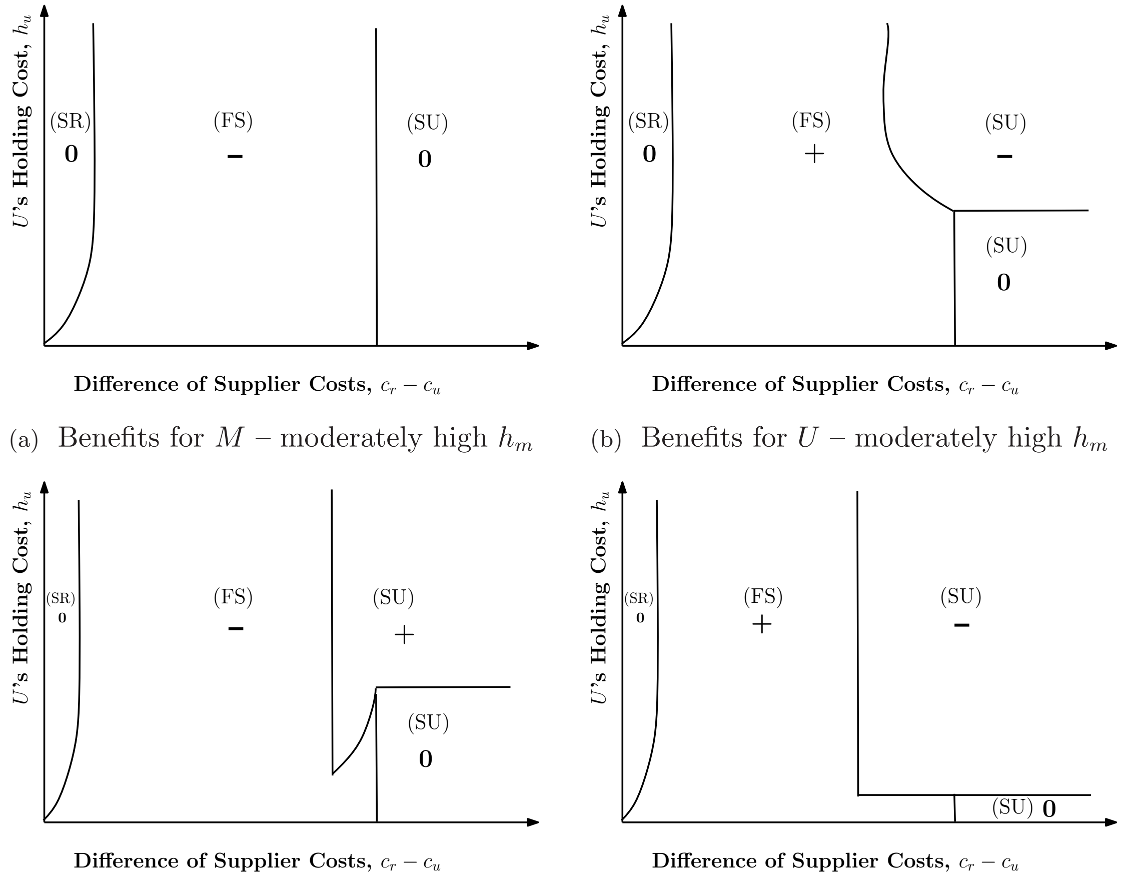
Through numerical study, we next illustrate how the theoretical results derived above and the corresponding intuition apply to more general cases. We also describe the benefits and/or cost of flexible sourcing for the manufacturer and the suppliers as a function of the system parameters (holding costs, uptime, and downtime).

We first consider the distribution of benefits for M and U as a function of a holding cost, h_u.

Figures 6 (a) and (b) correspond to the case where M's holding cost is moderately high, whereas (c) and (d) correspond to the case where M's holding cost is low. Note that low and high values of h_u confirm lessons from Popositions 3 and 4.

While U benefits from flexibility in most of the cases, this is not the case for the manufacturer. When h_m is not very low (panel (a)), U has fairly significant control when making his offer and captures the benefits, leaving the manufacturer indifferent or worse off. M may only benefit from flexibility when the supplier cost difference is high and also the manufacturer's holding cost is sufficiently low, as shown in Figure (c). Even though holding inventory is not expensive, backup flexibility will decrease M's incentives to hold inventory, which will lead to either (i) reduction in U's sales or (ii) U carrying inventories, even if he has a higher holding cost, both of which benefit the manufacturer.

Figure 6 Benefits/Costs of Flexibility – Numerical Study



(a) Benefits for M – moderately high h_m (b) Benefits for U – moderately high h_m

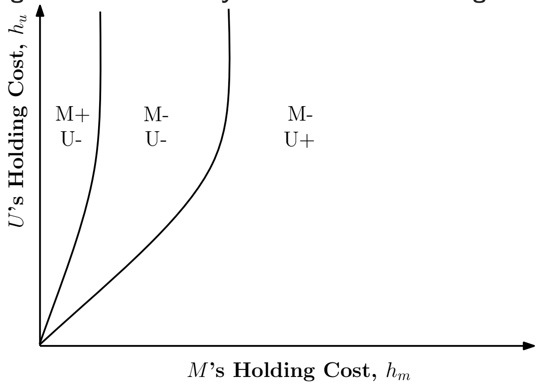
(c) Benefits for M – low h_m (d) Benefits for U – low h_m

Although the cases when the manufacturer may benefit from flexibility are fairly rare, looking at them (Figures 7 and 8) allows us to highlight the effects of holding costs and of disruption frequency. Figure 7 assumes a high cost difference, $c_r - c_u$, and illustrates the distribution of benefits as a function both h_m and h_u. M is better off with flexibility only when h_m is much smaller than h_u, whereas U is worse off in this range. For an intermediate range of h_m, both M and U are worse off, whereas for higher values of h_m, only U (along with R) is better off.

To evaluate the distribution of benefits with respect to disruption parameters, probabilities of failure, and recovery, θ_f and θ_r, we continue to assume a high supplier cost difference and a low holding cost for the manufacturer, see Figure 8.

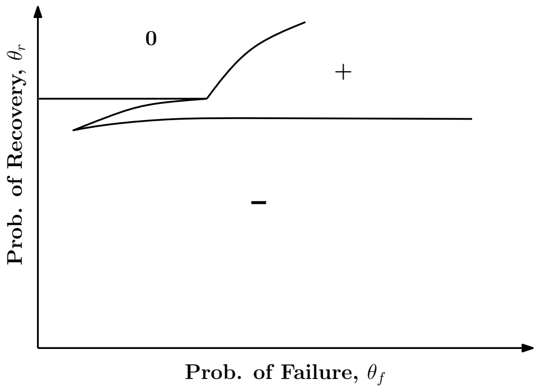
Facing a long recovery from disruption (low recovery rate, θ_r), the manufacturer invests in inventory and uses a backup supplier. Whereas the unreliable supplier loses some business when M runs out of inventories, the reduction in R's incentive to compete aggressively benefits U, while hurting M. When recovery is faster, M protects against disruptions only by using inventory without using flexible sourcing. But in this case, M's inventory is lower than for the no-FS case, due to

Figure 7 Sensitivity of Benefits to Holding Costs

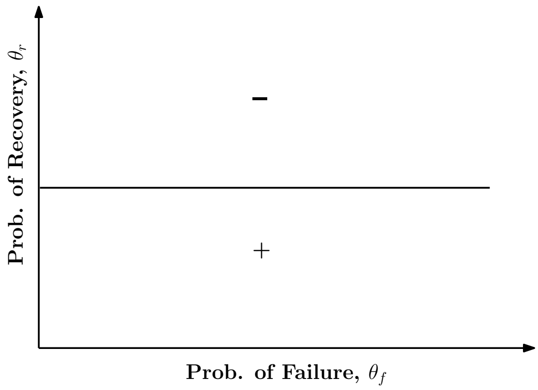


the discount that U offers for delayed orders and, in some cases, U holds inventory rather than M. Short recovery implies a smaller earning potential for the reliable supplier and more aggressive competition, leaving the unreliable supplier worse off. With frequent disruptions, M holds some inventory under FS and benefits from flexibility, due to more intense competition. On the other hand, when U faces infrequent disruptions, U will hold inventory under FS and set prices that leave M indifferent between sourcing from U versus R.

Figure 8 Sensitivity of Benefits to Disruption Parameters



(a) Benefits for M



(b) Benefits for U

In the range of the cost parameters that we considered, which have the potential for M to be better off with flexibility, infrequent failures and slow recovery makes M worse off with flexibility. Meanwhile, frequent failure and quick recovery makes M better off, allowing the manufacturer to benefit from flexible sourcing. This is consistent with the variability reduction literature, where short, frequent disruptions are easier to buffer. Although the cases we used above are not necessarily common, the same forces play a role in all areas; that is, even though the manufacturer is worse off with flexible sourcing, she is *less* worse off (or even better off with flexibility) when the disruptions are short and frequent.

Our analysis has assumed equal production costs for regular and emergency orders for the reliable supplier ($c_{rb} = c_r$). When the reliable supplier incurs a higher production cost for emergency orders ($c_{rb} > c_r$), our results remain structurally unchanged. However, with a higher production cost, R has more incentive to compete aggressively to win the contract as the sole supplier. This reduces the disadvantage that the manufacturer faces, and, in fact, the manufacturer may be better off. The case of higher production cost for emergency orders is addressed formally in the extended version of the contingent-pricing game in Section 6.

Incorporating strategic supplier behavior shows that opening opportunities for more flexibility typically hurts the manufacturer. Consequently, the manufacturer may not adopt a flexible sourcing strategy, even when it is beneficial for the supply chain, and may ask the suppliers to quote single wholesale prices with an upfront commitment to a sole-sourcing strategy.

6. Extensions

In this section, we discuss extensions of our model, which characterize when the main conclusions continue to hold. These include partial (i.e., $< 100\%$) backup from the reliable supplier during disruption, the case when both suppliers are unreliable, the possibility of non-memoryless recovery times, risk aversion, and an extended version of the contingent-pricing game, which allows the unreliable supplier to build further contingencies into the contract. For each extension, we summarize the main results and provide detailed analysis in the supplementary document.

Partial Backup during Disruption

Our base model assumes that if the manufacturer adopts flexible sourcing, she sources (satisfies) her entire need from the reliable supplier when all inventory in the system is exhausted. In this situation, we showed that the manufacturer M may be worse off. An intriguing question is whether M may be better off, if she only sources a portion of her needs from reliable supplier R. To answer this question, we extend the model by allowing the manufacturer to only source a fraction, β, of its need from the reliable supplier after all the stock is exhausted. It can be shown easily that if flexible sourcing is profitable and the manufacturer chooses β *for given supply offers* $(w_u, s_u, \kappa_u, w_r, w_{rb})$, then it is optimal for the manufacturer to source her entire need from the backup, reliable supplier (i.e., $\beta^* = 1$).

Interesting and more relevant from a practical perspective is the case where β is given or determined *before* the suppliers decide the contractual terms and is fixed throughout the horizon. That is, assume that the manufacturer can commit to a fractional backup sourcing plan.[6] The fraction

[6] This may be a natural commitment for a reliable supplier who has a certain slack capacity and would not invest in more capacity without becoming a primary supplier.

β affects the suppliers' pricing competition and, thus, also the manufacturer's profit. We note that the partial-backup problem can be formulated in the same way as for the base model, except that the effective underage costs under the FS model become $\sigma_m^{FS} = \beta(w_{rb} - w_u) + (1-\beta)\frac{\pi_b - s_u}{\theta_r}$ and $\sigma_u^{FS} = \beta(w_u - c_u) + (1-\beta)\frac{s_u}{\theta_r}$.

Assuming a special case with zero inventories, the following proposition considers the continuum of backup capacities and allows for a clear interpretation of the role of backup capacity. It first describes equilibrium outcomes, and then, derives the manufacturer's profit as a function of backup fraction. It shows that the manufacturer is always better off committing to sole sourcing.

Proposition 5. *Assume that neither M nor U can hold inventory.*

- *The equilibrium sourcing outcomes and the wholesale prices are:*

(i) If $c_r \geq c_u + \frac{\pi_b}{\theta_r}$, U is the sole supplier and $w_u^* = c_r$, $s_u^* = \pi_b$, $w_r^* = w_{rb}^* = c_r$.

(ii) If $c_r \leq c_u + \frac{(1-\beta)\pi_{OFF}}{1-\beta\pi_{OFF}}\frac{\pi_b}{\theta_r}$, R is the sole supplier and $w_u^* = c_u$, $s_u^* = 0$, $w_r^* = c_u + \frac{\pi_b}{\theta_r}\pi_{OFF}$, $w_{rb}^* \geq c_u + \frac{\pi_b}{\theta_r}$.

(iii) Otherwise, M adopts flexible sourcing in equilibrium and $w_u^* = \frac{1-\beta\pi_{OFF}}{\pi_{ON}}c_r - \frac{(1-\beta)\pi_{OFF}}{\pi_{ON}}(\frac{\pi_b}{\theta_r} + c_u)$, $s_u^* = \theta_r(w_u^* - c_u)$, $w_r^* = \pi_{ON}w_u^* + \pi_{OFF}(\frac{\pi_b}{\theta_r} + c_u)$, $w_{rb}^* = c_u + \frac{\pi_b}{\theta_r}$.

- *The suppliers' profits increase in β, whereas the manufacturer's profit decreases in β.*
- *If the manufacturer could choose the backup fraction β, then the optimal backup option β^* is as follows. If $c_r \geq c_u + \frac{\pi_b}{\theta_r}\pi_{OFF}$, then $\beta^* = 0$ and U serves as the sole supplier. If $c_r < c_u + \frac{\pi_b}{\theta_r}\pi_{OFF}$, then $\beta^* = 0$ and R serves as the sole supplier.*

Proposition 5 complements our findings and shows that the suppliers prefer flexible sourcing, whereas the manufacturer does not. It illustrates well how increasing availability of the backup option makes the manufacturer gradually worse off, while benefitting suppliers. As such, it provides a link between two extreme cases of no flexibility and full flexibility. With flexible sourcing, suppliers may reduce the intensity of the competition for regular orders. Consequently, as the backup fraction increases, the unreliable supplier can charge a higher wholesale price for ontime deliveries (w_u^* increases in β, as in Proposition 5 (iii)), which in turn hurts the manufacturer.

Both Suppliers are Unreliable

When both suppliers are unreliable, the suppliers' strategy space expands, because both suppliers can play the role of the primary supplier or the backup supplier, and each of them (the primary and the backup supplier) may experience disruptions during production. The optimal inventory policy becomes state-dependent; consequently, supplier payoffs in the pricing games cannot be expressed in closed form. While this limits the analysis we can perform, the equilibrium outcomes can be derived *when inventory holding costs are prohibitively high.* Specifically, we index suppliers by $i = 1, 2$, with the production costs of the suppliers, $c_1 \leq c_2$. We consider a periodic-review version of the model and assume that disruptions across suppliers are independent. Let θ_{fi} and θ_{ri} be the probabilities that supplier i faces a disruption and recovers from a disruption in the next period, respectively, and $F(t) := 1 - \left(\frac{\theta_{fi}}{\theta_{fi}+\theta_{ri}}\right)(1-\theta_{ri})^t$. Because either supplier can serve as the primary source, whereas the other one serves as backup, we allow each supplier to quote three wholesale prices: wholesale price for regular deliveries, w_i, wholesale price for backup availability, w_i^b, and wholesale price for delayed deliveries, provided that an order is not placed with the other supplier who is operational, w_i^d. We refer to supplier i's opponent as supplier $-i$. Since both suppliers are unreliable, it is possible that after disruption at the primary supplier, back-up supplier is activated and also faces a disruption. When flexible sourcing is used, there are no charges for the delayed deliveries.

Proposition 6. *Assume that neither M nor U can hold inventory.*
(i) *When suppliers do not offer backup availability:*
Let $i = \arg\min_{i=1,2}\left\{c_i + \frac{\pi_b}{\theta_{ri}}\pi^i_{OFF}\right\}$. *Then, supplier i serves as the sole supplier and charges a wholesale price,* $w_i = c_{-i} + \frac{\pi_b}{\theta_{r,-i}}\pi^{-i}_{OFF} - \frac{\pi_b}{\theta_{ri}}\pi^i_{OFF}$.
(ii) *When suppliers offer backup availability:*
Let $\rho_i = \pi^i_{OFF} - \pi^1_{OFF}\pi^2_{OFF}\left(\frac{\theta_{ri}}{\theta_{r1}+\theta_{r2}-\theta_{r1}\theta_{r2}}\right)$. *If* $c_2 > c_1 + \frac{\pi_b}{\theta_{r1}}$, *supplier 1 serves as the sole supplier in equilibrium with* $w_1 = c_2 + \left(\frac{\pi_b}{\theta_{r2}(1-\rho_1)}\right)\pi^2_{OFF}$ *and* $w^1_d = c_2 - \frac{\pi_b}{\theta_{r1}}$. *Otherwise, if* $c_1 \leq c_2 \leq c_1 + \frac{\pi_b}{\theta_{r1}}$, *then supplier 1 serves as the primary supplier and supplier 2 serves as the backup supplier, with* $w_1 = c_2 + \frac{\pi_b}{\theta_{r2}}\left(\frac{\rho_2}{1-\rho_1}\right)$ *and* $w^2_b = c_1 + \frac{\pi_b}{\theta_{r1}}$.
(iii) *With backup availability, the profits of both suppliers are higher, whereas the manufacturer's profit is lower.*

With two unreliable suppliers, flexible sourcing still leads to larger profits for the suppliers and lower profit for the manufacturer. An extensive numerical study shows that similar conclusions would apply, when both suppliers are unreliable and inventory is allowed.

Non-memoryless Recovery Times

Our model assumes exponential uptimes and downtimes, which is commonly assumed in the supply disruptions literature. This assumption not only provides us with a simpler analytical framework with which to work, but it is also appropriate if the disruptions are very unpredictable. To understand the effect of lower variability in the recovery times, we examine the boundary case with deterministic recovery times, where a disruption (i.e., downtime) lasts for D time units.

The condition for the optimality of a zero inventory policy is the same as for exponential disruptions. However, the details in a deterministic disruptions case are slightly modified as the manufacturer may stop sourcing from R toward the end of a disruption, unlike the case with exponential disruptions. Based on numerical experiments, Figures 3 and 4 remain structurally unchanged for the case when disruptions are deterministic. However, the thresholds and the profits are obviously influenced.

We compare the effect of variability on both the suppliers' and manufacture's profits. Reducing variability is usually considered favorable for operational efficiency. In the context of disruptions, we expect that in competitive settings, more variable disruptions hurt the manufacturer and also the supplier U, whereas they benefit R, as R holds the competitive advantage due to being reliable. It is natural, therefore, to expect that R prefers exponential disruptions, whereas U and the manufacturer prefer deterministic ones. These indeed hold when R does not offer backup flexibility. When backup flexibility is available, the manufacturer remains worse off, and R is always better off with memoryless disruptions. Contrary to the intuition, however, U may be better off with more variability. This is because higher variability can dampen the competition between the suppliers. We find that this counterintuitive phenomenon (U prefers exponential disruptions) occurs only if the difference of supplier costs, $c_r - c_u$, is sufficiently small.

Extended Contingent-Pricing Game

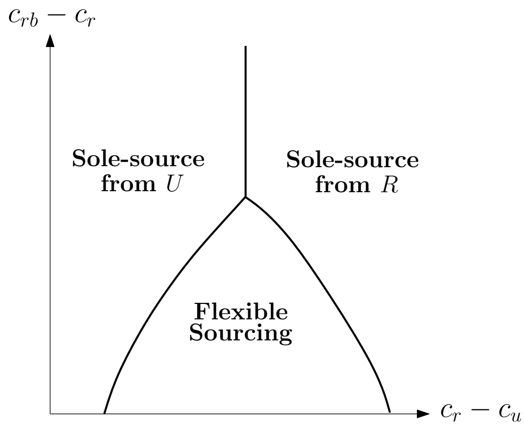
The contingent-pricing game considered in this paper allows the reliable supplier to offer a wholesale price based on his role, whereas the unreliable supplier offers only one wholesale price and a subsidy. It is easy to justify that this combination of contractual terms is sufficient for the case of no inventories. However, it is not the case when manufacturer can hold inventory. U may end up offering high subsidies to be able to serve as the sole supplier, distorting the manufacturer's incentive to hold inventory and potentially leading to losses for himself. To avoid this outcome, U may also offer two wholesale prices based on his role (in addition to the subsidy), assuming that he has sufficient bargaining power to do so.

If U serves as the sole supplier, he satisfies all demand, possibly with a delay, but when serving as the primary supplier along with R as the backup, the portion of demand he cannot immediately satisfy may be lost to R. Consequently, he charges a wholesale price, w_u^s, as sole supplier, while charging w_u^p as the primary supplier in FS (in the extended contingent-pricing game). U continues to offer a penalty for delays, s_u, provided that he serves as the sole supplier. R continues to quote (w_r, w_{rb}), as before. The equilibrium outcomes are derived below.

Proposition 7. *Let $\delta \geq 0$ be such that $c_{rb} = c_r + \delta$. There exist a threshold $\bar{\delta}$ and two thresholds $\Delta_1(\delta)$ (an increasing function of δ) and $\Delta_2(\delta)$ (a decreasing function of δ) that characterize the equilibrium sourcing strategy of the manufacturer as follows. If $\delta \geq \bar{\delta}$, the manufacturer never adopts flexible sourcing in equilibrium. If $\delta < \bar{\delta}$, the equilibrium sourcing policy of the manufacturer is SR, if $c_r - c_u \leq \Delta_1(\delta)$, FS if $\Delta_1(\delta) < c_r - c_u < \Delta_2(\delta)$, and SU if $c_r - c_u \geq \Delta_2(\delta)$. Whenever a* *sole-sourcing outcome emerges in equilibrium, the equilibrium wholesale prices are the same as in Proposition 2.*

The equilibrium outcomes are clearly influenced by the cost advantage of the unreliable supplier, $c_r - c_u$, and the efficiency of backup production, $c_{rb} - c_r$. When the additional cost that R incurs for backup production is prohibitively high, only a sole-sourcing outcome emerges in equilibrium. Otherwise, the manufacturer uses the less expensive, unreliable supplier as well as the more expensive reliable supplier (except when cost of U is extremely low or extremely high). Figure 9 illustrates the equilibrium sourcing policy of the manufacturer as a function of the cost differences, $c_r - c_u$ and $c_{rb} - c_r$. In the following proposition, we characterize the distribution of benefits with the extended-contingent pricing game.

Figure 9 **Equilibrium Sourcing Policies**



PROPOSITION 8. *(i) Let $\delta \le \bar{\delta}$ and $\Delta_1(\delta) < c_r - c_u < \Delta_2(\delta)$, leading to FS in equilibrium. With backup flexibility, the profits of both suppliers are higher, whereas the manufacturer's profit is lower. Otherwise, profits are not influenced by flexibility.*

(ii) The equilibrium profits of both suppliers are weakly decreasing in c_{rb}, whereas the manufacturer's profit is weakly increasing in c_{rb}.

Proposition 8 shows that R and U always (weakly) benefit from flexible sourcing in the extended contingent-pricing game, whereas M may not benefit from flexible sourcing. Thus, allowing the unreliable supplier to set prices based on his role further enhances his profit, whereas it hurts the manufacturer. The spirit of this observation is that the more sophisticated the contracts are that suppliers offer, the easier it is for the suppliers to differentiate their roles and earn additional rents.

Proposition 8 provides further qualitative insight describing the effect of c_{rb} on the benefits of flexibility. In the absence of strategic supplier behavior, the manufacturer and the reliable supplier would suffer from inefficient backup production, whereas U would benefit. Proposition 8 shows that in the presence of strategic behavior, this intuition holds only for the reliable supplier. Interestingly, the manufacturer is better off with a more inefficient backup production system. To see why, note that when c_{rb} is increased, R's profit as a backup supplier is lower; therefore, he chooses to compete more aggressively to serve as the sole supplier. As a result, both suppliers' profits decrease, whereas the manufacturer's profit increases.

Risk Aversion

Our analysis so far has assumed risk-neutral decision makers. While we show that the reliable supplier may choose to serve as a backup supplier, his revenue becomes unpredictable, as opposed to a constant stream of revenue when he serves as the primary source. To account for the fact that R may prefer a constant stream of revenue over an uncertain one with the same expected value, we model R's behavior as risk averse. To capture the key effects of risk aversion, we simplify the analysis and assume that inventories are too costly to be considered. To analyze this case, we introduce a notion of risk aversion for renewal processes.

The reliable supplier's long-run average profit is $(w_{rb}-c_r)\pi_{OFF}$. Recall that the long-run probability of the system in the ON state (or alternatively, the long-run proportion of time that the system stays in the ON state) is π_{ON} and π_{OFF} for the OFF state. Under FS, R makes zero profit with probability π_{ON}, and $w_{rb}-c_r$ with probability π_{OFF}. The standard deviation of the profit per unit time is $(w_{rb}-c_r)\sqrt{\pi_{ON}\pi_{OFF}}$. To represent R's risk preference, we penalize variability (standard deviation in profits) by a constant $\gamma \geq 0$. Consequently, R's payoff is expressed as

$$(w_{rb}-c_r)(\pi_{OFF}-\gamma\sqrt{\pi_{ON}\pi_{OFF}})$$

Clearly, γ should be sufficiently small for R's payoff to be meaningful. In particular, we assume $\gamma << \sqrt{\frac{\pi_{OFF}}{\pi_{ON}}}$. With R's risk-aversion modeled in this fashion, the equilibrium outcomes are expressed as follows.

PROPOSITION 9. *Assume that R is risk-averse and that neither M nor U holds inventory.*

- *The equilibrium sourcing outcomes and the wholesale prices are:*

(i) If $c_r \geq c_u + \frac{\pi_b}{\theta_r}$, *U is the sole supplier and* $w_u^* = c_r$, $\phi^* = \frac{\pi_b}{\theta_r}$, $w_r^* = w_{rb}^* = c_r$.

(ii) If $c_r \leq c_u$, *R is the sole supplier and* $w_u^* = c_u$, $\phi^* = 0$, $w_r^* = c_u + \frac{\pi_b}{\theta_r}\pi_{OFF}$, $w_{rb}^* \geq c_u + \frac{\pi_b}{\theta_r}$.

(iii) Otherwise, M adopts flexible sourcing in equilibrium. The equilibrium contractual terms are $w_{rb}^* = \min\left(\frac{\pi_b}{\theta_r} + c_u, (c_r - c_u)\frac{\sqrt{\pi_{ON}}}{\gamma\sqrt{\pi_{OFF}}} + c_r\right)$, $w_u^* = \frac{c_r(\pi_{ON}+\gamma\sqrt{\pi_{ON}\pi_{OFF}})-w_{rb}^*\gamma\sqrt{\pi_{ON}\pi_{OFF}}}{\pi_{ON}}$, $w_r^* = w_{rb}^*\pi_{OFF} + w_u^*\pi_{ON}$, *and* $\phi^* = w_u^* + \frac{\pi_b}{\theta_r} - w_{rb}^*$.

- *(Effects of risk aversion) The suppliers' profits decrease in* γ, *whereas the manufacturer's profit increases in* γ. *That is, the risk aversion of the reliable supplier makes the backup option more profitable to the manufacturer.*

• *(Comparison with no flexible sourcing) When $\gamma = 0$, both suppliers are better off by the backup flexibility, whereas the manufacturer is worse off. When γ becomes sufficiently large, one of the suppliers may get worse off by the backup flexibility, whereas the manufacturer may become better off.*

As demonstrated, risk-aversion weakens R's position, and requires him to compete more aggressively. This hurts both suppliers and favors the manufacturer.

In addition to the suppliers' risk aversion that helps manufacturers benefit from flexible sourcing, several other dimensions outside of the model may help the manufacturer. Most importantly, the manufacturer's buying power may curtail the effects described in this paper. In practice, multiple sourcing contracts are based on comparing the price to internal cost of production and imposing mandatory price reductions. Sufficiently powerful manufacturers are able to impose such additional controls, which effectively limits the suppliers' pricing power and their "strategic-ness."

7. Summary and Conclusions

Our objective in the present study was to evaluate the costs and benefits associated with flexible sourcing when the suppliers are strategic. We have considered a manufacturer choosing to source from either a perfectly reliable supplier, an unreliable supplier, or both, where suppliers are active decision makers and who decide on their pricing strategies.

We argued that the single-wholesale price game, where each supplier quotes one wholesale price, leads to a conflict of incentives in terms of the roles suppliers want to play and the size of the business they get, formally confirmed as the non-existence of pure-strategy Nash equilibria in most practical situations. Therefore, to evaluate the effect of strategic supplier behavior on the benefits of flexible sourcing, we considered a contingent-pricing game, where the reliable supplier is allowed to offer wholesale prices contingent on his role, whereas the unreliable supplier is allowed to offer one wholesale price and a penalty for delayed deliveries, in the form of a supplier rebate or a charge-back. The contingent-pricing game reflects a more intuitive practical relationship and formally leads to pure-strategy Nash equilibria. We showed that with contingent pricing, only one party, either an unreliable supplier or the manufacturer holds inventory. Except for cases with significant cost advantages for one of the suppliers, the manufacturer uses the less expensive, unreliable supplier, as well as the more expensive, reliable supplier.

We show that with endogenously determined wholesale prices, the manufacturer does not necessarily benefit from the existence of a backup supplier and, in fact, is typically worse off. Thus, an upfront commitment to sole-sourcing may actually be beneficial, as opposed to opening up the opportunity for one supplier to serve as a backup, through more flexible contracts. Interestingly, suppliers may benefit from flexible sourcing even though the manufacturer does not: the reliable supplier always benefits from maintaining backup capacity, whereas the unreliable supplier might in some situations benefit from the reliable supplier's backup capacity despite the reduced business volume. From a system perspective, a flexible sourcing strategy may degrade the supply chain's performance.

We extended our results in various dimensions. We consider partial backup sourcing during disruptions. We show that both suppliers may be better off with a high backup fraction, whereas the manufacturer could be worse off, consistent with our original findings, where additional flexibility benefits suppliers rather than the manufacturer. In the case of two unreliable suppliers, assuming zero inventories, we showed that our primary insights hold: suppliers benefit from backup flexibility, but the manufacturer does not. Although reducing variability is usually considered favorable in the operations literature, we find that the unreliable supplier may achieve higher profits with unpredictable (more variable) disruptions, resulting from a dampening of competition due to the availability of a backup supplier.

We also provide illustrations that the contingent-pricing game can be extended in several directions (further contingencies in the pricing or different costs of production) without changing the model's insights.

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