Forewarned Is Forearmed? Contingent Sourcing, Shipment Information and Supplier Competition

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Problem definition: Dual sourcing and contingent (or emergency) sourcing are important risk-mitigation strategies adopted by buying firms to manage supply-chain risks including transportation-related losses of inbound orders from suppliers. Contingent sourcing as a means of managing transportation risk is made possible by shipment information realized at discrete in-transit inspection points or through shipment monitoring technologies. We examine the impact of contingent sourcing and shipment information in a setting where a buyer can source from two competing suppliers. One supplier (unreliable) has a long transportation lead time and is prone to in-transit yield loss; the other supplier (reliable) has a short, but nonzero, lead time and is not prone to yield loss. **Methodology/results:** We analyze a multistage game-theoretical model in which the two suppliers compete on wholesale prices and then the buyer determines its initial order quantities. Later, the buyer can place an emergency order with the reliable supplier based on shipment information which reveals (possibly imperfectly) the status of the in-transit order from the unreliable supplier. We show that the buyer will adopt one of four possible sourcing strategies: (1) initially source only from the unreliable supplier but resort to the reliable supplier contingent on the updated shipment information, (2) diversify its initial order across the two suppliers but resort to the reliable supplier if needed, (3) diversify its initial order and not engage in contingent sourcing, or (4) sole source from the reliable supplier. Interestingly, contingent sourcing may or may *not* benefit the buyer because it may soften the competition between suppliers. Moreover, the buyer's profit may not be monotonic in the accuracy of shipment information. **Managerial implications:** The buyer must design its supply base so that the unreliable supplier is particularly cost efficient if the buyer is to benefit from the possibility of contingent sourcing. The buyer may not always benefit from operational improvements that enhance shipment information accuracy because they may soften supplier competition. A corrective-action capability to possibly resolve yield loss does benefit the buyer.

Key words: Contingent sourcing, supply risk, supplier competition, shipment information

1. Introduction

Supply-chain risk continues to be a major concern for senior executives: according to a McKinsey survey in 2020, "93% of global supply chain leaders [were] planning to increase resilience" (Lund et al. 2020). A firm's sourcing strategy is critical to its resilience. Multi-sourcing and contingent sourcing have long been viewed as key pillars of a resiliency strategy (Yossi 2005, Tomlin 2006, Simchi-Levi 2010), and they remain a key focus in practice (Lund et al. 2020). Multi-sourcing hedges the buying firm against issues that might arise during a supplier's production or transportation. Contingent (also called backup) sourcing enables the firm in theory to "dynamically reallocate volumes across suppliers based on anticipated delivery risk" (Deloitte 2020, p.7). In practice, that requires the firm to be able to monitor evolving risk and to have a responsive supplier that can quickly react to a new or increased order.

Yield losses associated with detrimental conditions during transportation and storage pose a significant challenge for drugs, fresh fruit and vegetables, seafood, and other perishable products. It has been estimated that losses due to in-freight temperature deviations cost the pharmaceutical industry approximately $15 billion a year (Haag 2019). The yield challenge is not limited to perishable products: fragile industrial electronic devices can be easily damaged during transportation as a result of jostled movement, mishandling, or adverse environmental conditions. If a buying firm discovers transportation-related loss (spoilage, damage, etc.) only upon order arrival then contingent sourcing is not a viable remedy unless the responsive supplier can fulfill a reactive order almost-instantaneously or customers are willing to wait for an extended period. Therefore, a buying firm must ensure access to some level of updated shipment-risk information during transportation if it is to pursue a contingent sourcing strategy.

Inspections can be used to evaluate the condition of goods between departure from the supplier and arrival at the buyer site, but such inspections are traditionally limited to particular in-transit points such as ports or cross-docking locations (White III and Cheong 2012). Developments in shipment-monitoring technologies (e.g., temperature and impact senors deployed on perishable or fragile shipments) have made contingent sourcing more attractive. For example, shipment sensors "can send an immediate alert if a shipment of fragile automotive parts experiences harmful handling or if sensitive components experience a temperature excursion. Instead of waiting until goods arrive to discover such problems, the supply chain manager knows as soon as they occur, giving them time to reroute a replacement shipment" (Dukach 2018, paragraph 6). Some buying firms dictate the use of shipment monitoring devices by their suppliers: Walmart, for example, mandates that "all fresh produce, meat, seafood, and floral suppliers ... utilize Emerson GO wireless temperature recorders on all pre-cooled inbound shipments to our food distribution centers, food import centers, fresh solution centers and food cross docks"(Walmart Stores, Inc. 2022, page 283).

In-transit inspections and shipment monitoring technologies enable contingent sourcing by providing the buying firm with updated (i.e., post-departure) information on damage, spoilage and related yield losses, but they may not perfectly predict actual losses because inspection and monitoring technologies may be imperfect or because losses might occur after the last actionable update is received. Multi-sourcing and contingent sourcing increase a buying firm's resilience, and a more accurate in-transit detection of yield losses will enhance the operational value of contingent sourcing. However, in strategically evaluating different sourcing policies, the buying firm should account for a policy's impact on supplier behavior. Enabling contingent sourcing might alter how suppliers compete, as might an improvement in the accuracy of in-transit loss detection. When supplier competition is considered, does contingent sourcing add value to the buyer? Does the buyer benefit from a more accurate in-transit shipment prediction?

To answer these questions, in this paper we analyze a supply chain consisting of a buyer and two competing suppliers. The buyer sources a product for sale over a short season with a quantity-dependent selling price. One supplier has a long lead time and is prone to all-or-nothing yield loss in transportation, e.g., an overseas supplier requiring a long transportation distance. The other supplier has a short lead time and is not prone to yield loss, e.g., a local or near-shore supplier with little transportation distance. The buyer orders the product from one or both suppliers to arrive in time for the season. At a later point in time, based on updated information about the unreliable supplier's shipment, the buyer can place a contingent order with the reliable supplier. The two suppliers compete in wholesale prices, anticipating the buyer's possible sourcing strategies.

We first show that for any given wholesale prices, the buyer will adopt one of four sourcing strategies: (1) initially source only from the unreliable supplier but resort to the reliable supplier later contingent on the updated shipment information, (2) diversify its initial order across the two suppliers but also resort to the reliable supplier later if needed, (3) diversify its initial order and not engage in contingent sourcing, or (4) sole source from the reliable supplier to remove all risk. The second strategy, which combines diversification and contingent sourcing, is not optimal if the updated shipment information perfectly predicts the yield loss. This combined strategy can be optimal when the updated shipment information imperfectly predicts yield loss.

Next, in analyzing the supplier-competition equilibrium, we prove that the existence of the contingent-sourcing option always benefits both suppliers (at least weakly) but it can harm the buyer. Although contingent sourcing enables the buyer to respond to yield loss, it may soften the price competition between suppliers and thus increase the buyer's purchase costs in equilibrium. Furthermore, we establish that the buyer's expected profit is *not* monotone in the accuracy of shipment information. We examine several model extensions that explore the impact of improvements in supplier reliability, the effect of a corrective-action ability to resolve yield loss, the effect of incomplete information, and alternative models of emergency contracting.

From a managerial perspective, our results have implications for buyers and suppliers. To ensure that the operational benefits of contingent sourcing outweigh the competition-dampening disadvantage, a buying firm must design its supply base so that the distant supplier is particularly cost-efficient. Furthermore, the buyer may not benefit from operational improvements that enhance shipment information accuracy (such as superior inspection technology, continuous monitoring, or a shorter contingent lead time) because such improvements can soften supplier competition. However, a corrective-action capability that can potentially resolve yield loss does benefit the buyer. For the unreliable supplier, a marginal improvement in its transportation reliability is not necessarily to its advantage, even if such an improvement is costless.

The remainder of the paper is organized as follows. We review the relevant literature in §2. The model is described in §3 and the results are presented in §4. Various extensions are discussed in §5. We conclude in §6. Technical proofs and additional results are relegated to the Online Appendices. The Supplementary Materials can be found in the unabridged version of the paper available from the authors upon request.

2. Literature Review

Our paper is primarily related to the operations management literature on sourcing strategies to manage supply risk. The multi-sourcing model developed in our paper is also related to the literature on quick-response strategies. We discuss each stream of literature in turn.

There is an extensive literature on supply risk management. One stream studies random yield models in which the delivered quantity is randomly proportional to the quantity ordered, with the proportion sometimes being modeled as all-or-nothing in which delivery occurs in full or not at all; see Yano and Lee (1995) for a review of the literature on order sizing in the presence of random yield. Our work is more closely related to the literature that explore sourcing strategies in the presence of yield risk, where this includes single-period, supply-disruption models that are in effect all-or-nothing random-yield models because the buyer places an order before the disruption possibility is realized.

Diversification, in which a buyer simultaneously orders from multiple suppliers, is an important sourcing strategy for managing yield risk, and it has been widely studied in the literature. For example, dual sourcing, i.e., splitting orders across two suppliers, in single-period models is examined by Tomlin and Wang (2005), Tomlin (2009b), Wang et al. (2010), Tang and Kouvelis (2011), Hu and Kostamis (2015), Ang et al. (2017), and references therein. Multi-sourcing, i.e., allowing for a general number of suppliers, is explored in Dada et al. (2007), Federgruen and Yang (2008, 2009), Dong et al. (2022) (single-period models) and Federgruen and Yang (2011, 2014) (multi-period models). Additionally, in a context of transportation procurement, Lu et al. (2017) examine a supplier portfolio selection problem in the presence of delivery time uncertainties.

Contingent sourcing, in which the buyer places an emergency order after yield uncertainty is resolved, is another important strategy for managing supply risk. Chopra et al. (2007) consider a model in which a buyer, sourcing from a random-yield supplier, can manage its risk by placing an emergency order from a perfectly-reliable, more expensive, responsive supplier if the buyer reserves some capacity upfront. Tomlin (2009a) studies the use of contingent sourcing alongside other supply-risk strategies such as diversification and demand switching to explore when a particular strategy is preferred and when there is value to adopting multiple strategies. Wang and Yu (2020) examine the interplay between a buyer's sourcing and pricing strategies in the presence of an unreliable supplier and a reliable supplier as a contingent option. They show that contingent sourcing and responsive pricing (i.e., pricing after uncertainty resolution) can be either substitutable or complementary risk-mitigation measures.

Several papers have examined the choice of contingent sourcing by multiple *buyers* competing in an end market. Gupta et al. (2015) consider a model with one reliable supplier, one unreliable supplier, and two competing buyers. The buyers can source solely from the reliable supplier, or first place an order with the unreliable supplier and contingently source from the reliable supplier in case of a disruption. Based on a similar supply chain setting, He et al. (2016) further consider the two competing buyers' choices between contingent sourcing and allocating the initial order to two suppliers.

Focused on the different context of lead time uncertainty, Kouvelis and Li (2008) consider a constant demand rate environment in which a single buyer sources initially from a stochastic lead-time supplier and, after knowing the accurate lead-time information, can place an emergency order with a deterministic lead-time backup supplier.

The above contingent-sourcing papers endow the buyer with the contingent option, whereas Yang et al. (2009) and Farahani et al. (2021) both, in a single-supplier, single-buyer setting, endow the supplier (not the buyer) with the contingent production option. Yang et al. (2009) examine the role of a supplier's contingent production option when a buyer offers a screening purchase contract under asymmetric information about the supplier's reliability. Farahani et al. (2021) explore a supply-flexibility contract in which the random-yield supplier offers a wholesale price and promises to fulfill a minimum fraction of the buyer's order.

Our work differs from all the above diversification and contingent sourcing papers in that we explore *supplier competition* and its impact on sourcing strategies. The prices charged by suppliers are exogenous in all the papers above with the exception of the single-supplier papers of Yang et al. (2009) and Farahani et al. (2021). Moreover, different to the contingent-strategy papers, our work allows for incomplete resolution of supply uncertainty at the time of contingent ordering.

Only a few papers in the literature on supply-risk management have examined supplier competition. Babich et al. (2007) considers supplier diversification and competition in the context of a single-period, all-or-nothing random supply setting. The suppliers first compete on wholesale prices, and then the buyer decides on the order quantities from each supplier. The paper shows that the buyer can benefit from highly correlated disruption risks (although the diversification benefit is weakened) because low correlation dampens supplier competition and thus increase the equilibrium wholesale prices. Shan et al. (2022) generalize the model in Babich et al. (2007) by considering a buyer who can responsively determine the selling price of the product after supply disruptions are realized. They find that due to supplier competition and the buyer's responsive pricing, a supplier may not benefit from a high reliability but can possibly benefit from a high disruption correlation. We also allow the buyer to control the selling price through the quantity released to the market. Among a number of differences between our work and these two papers is that, unlike these papers, in our model both diversification and contingent sourcing are possible buyer strategies for given wholesale prices, and this influences how suppliers compete.[1] More distant to our work, Gümüş et al. (2012) study two competing suppliers with one supplier's reliability level is private information, and they focus on the signaling role of supply contracts under information asymmetry.

Another relevant supplier-competition paper is Demirel et al. (2018) in which a buyer facing a constant demand rate over an infinite horizon can source from a reliable supplier or an unreliable supplier that alternates between being available (on) and unavailable (off). The current state is always known to the buyer and so there is no uncertainty at the time of order placement about the quantity that will be delivered. Lead times are instantaneous. The buyer can single source from the reliable or unreliable supplier or it can source from the unreliable supplier and only use the reliable one as a backup when the unreliable one is off. Order splitting between suppliers is not allowed. Suppliers compete on price and the paper explores the value to the buyer of pre-committing to single-sourcing, where the value arises from the fact that allowing the reliable supplier to play a backup role can influence competition in an adverse manner for the buyer. Our research question and therefore our model differ significantly from Demirel et al. (2018). We are interested in exploring the value of contingent sourcing and shipment information in the context of transportation yield-loss risk during non-instantaneous order delivery. In our problem, the buyer can split the order and may not necessarily have full knowledge about the risk realization at the time of contingent sourcing; these distinct features substantially change the dynamics of supplier competition.

The impact of supplier competition on a firm's sourcing strategies is also discussed in Lu et al. (2020), where the authors consider a deterministic model with quality sensitive customers and

[1] To focus on the impact of contingent sourcing, we consider one reliable and one unreliable supplier whereas Babich et al. (2007) and Shan et al. (2022) allow for more than two suppliers. Chakraborty et al. (2020) also adopt a two-supplier model to explore supplier competition and cooperation in a single-period, all-or-nothing random supply setting. They allow for a *passive* contingent-production option for the buyer, that is, the contingent price is exogenous and the contingent order is not filled by either supplier.

show that using a combination of a fast and a slow supplier enables quality differentiation in the end market but this benefit may be more than offset by reduced supplier competition. Again, our context and research question differs significantly, as does our model.

We now turn our attention to the quick-response literature that examines how a fast-supply option can be used by a buyer to help manage demand uncertainty for short-season products. In particular, after placing an initial order with a slow-supply option, a buyer can respond to updated demand information by placing a later order with the fast option (e.g., Fisher and Raman 1996, Iyer and Bergen 1997). This enables the buyer to better match supply with demand. In the context of a single supplier providing both the slow and fast options, a number of papers examine the contracting problem between the buyer and the supplier (Donohue 2000, Özer et al. 2007, Zhang et al. 2021).

A number of papers have examined quick-response models with two competing buyers (also called retailers). Li and Ha (2008) examine the procurement quantities of competing buyers that both have a quick response option. Lin and Parlaktürk (2012) investigate whether a single supplier should offer a quick response option when selling to two competing retailers. Wang et al. (2014) explore whether competing buyers should choose to have slow or fast (i.e, responsive) supply. Calvo and Martínez-de Albéniz (2016) examine supplier competition in a quick-response model in which a single buyer can source from a slow supplier and a fast supplier. The buyer chooses between single sourcing (use only one of the suppliers) or dual sourcing in which an initial order is placed only with the slow supplier but a quick-response order can be placed later with the fast supplier based on updated demand information. They find that dual sourcing may hurt the buyer when the two suppliers compete on wholesale prices.

A major difference of our work compared to the quick-response literature is that we focus on sourcing strategies to mitigate supply risk not demand risk, and therefore the buyer might want to adopt supply diversification (i.e., splitting the initial order across suppliers), contingent sourcing, or a mix of the two strategies. In the quick-response literature focused on demand uncertainty, the buyer never diversifies the initial order because order splitting is not relevant to managing demand risk. As a result, supplier competition in our model has vastly different dynamics.[2]

Finally, the role of shipment information discussed in our paper is loosely related to the literatures on inventory tracking and asset condition monitoring in various areas of operations management such as spare parts inventory management (Li and Ryan 2011), after-sales contracting (Li

[2] For example, in Calvo and Martínez-de Albéniz (2016) the suppliers are forced into a winner-take-all competition when quick response (i.e., contingent sourcing) is ruled out because order splitting is not relevant. However, in our setting, whether contingent sourcing is ruled out or not, the supplier competition is not winner-take-all because the buyer can mitigate supply risk by diversifying the initial order. Additionally, under the dual sourcing strategy considered in Calvo and Martínez-de Albéniz (2016), the fast supplier is used exclusively as a quick response option and not for the initial order, whereas in our problem supplier R can always compete for the initial order.

and Tomlin 2022), improvement of inventory record accuracy with radio-frequency identification technologies (Lee and Özer 2007, Heese 2007), and communication among autonomous sensors (Saghafian et al. 2022). Different from these papers, our work explores how contingent sourcing (and enhanced shipment information) influences the strategic interactions among a sourcing firm and two competing suppliers.

3. The Model

We consider a firm (the "buyer") purchasing a product for sale in a short season. The selling price of the product is determined by an inverse linear demand function $p(q) = m - q$, where m is the market potential and q represents the sales volume. For any available-to-sell quantity Q, the buyer's revenue function can be written as $R(Q) = \max_{q \le Q}(m-q)q$, or equivalently,

$$R(Q) = \begin{cases} mQ - Q^2 \text{ if } Q \le m/2 \\ m^2/4 \text{ otherwise.} \end{cases} \tag{1}$$

That is, we allow the buyer to hold back some quantity from the market. We will establish later, however, that the buyer will not do so in equilibrium.

Prior to the selling season, the product can be purchased from two potential suppliers: supplier U and supplier R. Supplier U has a long lead time such that the buyer has only one ordering opportunity before the selling season begins. Supplier U's transportation process is subject to random all-or-nothing yield loss. Yield is modeled by a Bernoulli random variable ϵ, where $\epsilon = 1$ if the order is delivered successfully and $\epsilon = 0$ otherwise. The probability of a successful delivery is given by P_1, i.e., $\Pr(\epsilon = 1) = P_1$ and $\Pr(\epsilon = 0) = P_0 = 1 - P_1$ where $0 < P_1 < 1$. Supplier U has a unit production cost of c_U. Supplier U can be thought of as a long-distance supplier such that potential environmental and other disturbances during transportation present a material risk of product spoilage or damage prior to arrival at the buyer. We assume all-or-nothing yield loss for tractability but note that it is a reasonable approximation to settings of interest to this paper, e.g., a full load of temperature-sensitive products can be spoiled if temperature deviates from the required range during transportation, or a container-load of fragile electronics can be damaged if the container is mishandled. The assumption of all-or-nothing yield loss enables us to explicitly characterize the equilibrium of the supplier competition; such an assumption is commonly adopted in the literature with competing unreliable suppliers (e.g., Babich et al. 2007, Shan et al. 2022). Supplier R has a shorter but nonzero lead time and its transportation process is reliable: it can successfully deliver the buyer's order with probability one. The unit production cost of Supplier R is given by c_R. One can think of supplier R as a closer supplier with negligible risk of detrimental disturbances during transportation because the delivery time is shorter. At Time 0, the buyer can order from supplier U, supplier R, or both, based on the wholesale prices quoted by suppliers U and R, denoted by w_U and w_R, respectively. Orders placed at Time 0 will be delivered at the beginning of the selling season.

Contingent Sourcing and Shipment Information Because supplier R has a shorter lead time than supplier U, the buyer can place an emergency order with supplier R at a later time if the shipment from supplier U is found to be damaged.[3] Let Time 1 represent the latest time at which an emergency order can be placed with supplier R yet still arrive in time for the season. The buyer's contingent sourcing decision depends on the shipment information available by Time 1. We model this information as a binary signal $s \in \{G, B\}$ realized to the buyer at Time 1, where $s = G$ represents a good signal indicating that no damage was detected and $s = B$ represents a bad signal indicating that damage was detected.[4] In practice, this information can be collected by traditional inspections conducted at particular in-transit locations (White III and Cheong 2012) prior to Time 1 or by continuous shipment monitoring devices (Walmart Stores, Inc. 2022).

We allow for inaccurate shipment information as follows. If the order is damaged during transportation, then the signal obtained at Time 1 is bad with probability ρ, i.e., $\Pr(s = B|\epsilon = 0) = \rho$, and is (mistakenly) good with probability $\Pr(s = G|\epsilon = 0) = 1 - \rho$. If no damage occurs then the signal at Time 1 is good with probability one, i.e., $\Pr(s = G|\epsilon = 1) = 1$. As a result, the order might arrive damaged even if the signal is good. If the signal is bad, however, then the order will arrive damaged. The higher the value of ρ, the more accurate is the shipment information available to the buyer at the time of contingent sourcing. Signal inaccuracy can arise because the inspection or monitoring technology may overlook damage that has already occurred or because damage may occur after the last viable inspection point (in the case of transit-point inspections) or after Time 1 (in the case of continuous shipment monitoring) even if no damage occurred by the time of the contingent sourcing decision. More accurate shipment information (i.e., a higher ρ) would be associated with superior monitoring/inspection technologies (which reduces the chance of overlooking damage), with a shorter supplier R lead time (which delays the contingent sourcing decision and thus reduces the probability of subsequent damage), or with the adoption of continuous monitoring instead of transit-point inspection (because the signal is obtained later, i.e., at Time 1). In §S.1 of the Supplementary Materials of the paper, we present and analyze a continuous-time, adverse-event, damage model and develop a closed form expression for ρ in terms of the damage-model

[3] For expositional ease we mostly adopt the term "damage" hereafter, and may use "damage" and "spoilage" interchangeably to connote any failure in successful order arrival.

[4] Although not the focus of this paper, transportation delay such that the order arrives too late for the selling season can also be captured by our model if one views delay as order failure and the updated information as a prediction of delay or no delay. We note that shipment-delay risk is a key driver of the apparel industry's acceleration towards both dual sourcing (to hedge risk) and near sourcing (to enable reactive or contingent sourcing) (Hedrich et al. 2021).

primitives and lead times. We show how the above three factors influence ρ. We do not require that particular underlying damage model, and our binary signal model is quite general. However, as discussed in Supplementary Material §S.1, our binary signal model does not reflect all possible damage models (e.g., damage resulting from an accumulation of unfavorable operating conditions).

Sequence of Events. To incorporate the buyer's initial ordering and contingent sourcing decisions, we consider the following sequence of events.

- At Time 0, suppliers U and R simultaneously offer their wholesale prices to the buyer. That is, supplier U announces its wholesale price w_U, while supplier R announces a regular wholesale price w_R along with an emergency-order wholesale price w_E. Note that w_R and w_E can be different.[5] Given these wholesale prices, the buyer determines the initial order quantities Q_U and Q_R to be placed with suppliers U and R, respectively.
- At Time 1, signal s is realized to the buyer, based on which the buyer updates its belief on supplier U's shipment status and decides on an emergency order quantity $Q_E(s)$ placed with supplier R.
- At Time 2, $Q_R + Q_E(s)$ units of the product ordered from supplier R are received with certainty, while Q_U units ordered from supplier U are delivered if no spoilage occurs, i.e., $\epsilon = 1$. Suppliers are paid according to the actual delivered quantities. The selling season begins and the buyer earns a revenue $R(\epsilon Q_U + Q_R + Q_E(s))$.

Both suppliers know when the buyer's selling season begins and so they are aware of the existence of each other and the buyer's second ordering opportunity. This is a reasonable assumption for many products with a fixed selling season. To focus on the primary insights, we assume that supplier R's production cost c_R to be time-invariant. We do not explicitly consider transportation costs because they can be regarded as a part of supplier costs c_U and c_R when costs include delivery. To focus on the strategic interactions among the sourcing firm and suppliers, we do not model competition in freight transport markets and assume the choice of transportation service providers is given (and thus suppressed in the model). Suppliers U and R are located in different regions (hence the difference in lead times) and so transportation-provider competition across different transportation lanes is unlikely to be a first-order driver of supplier choice in the types of situations our model seeks to reflect.

In the above sequence of events, we have assumed that supplier R needs to determine both wholesale prices w_R and w_E at Time 0. It is common that two different wholesale prices are specified in the same contract for different ordering times; see, for example, Özer et al. (2007) and Donohue

[5] Suppliers often know the time frame of a buyer's selling season especially for perishable products and so a time-dependent price schedule can easily be implemented: w_R is the price for orders placed at Time 0 but the price will change to w_E for orders placed at a later time.

(2000). Furthermore, in §5.3, we analyze two alternative settings, one in which supplier R sets w_E at Time 1 and another in which it offers a menu of screening contracts at Time 1 to elicit the buyer's privately observed signal s. Our model also assumes that the costs c_U, c_R, the damage probability P_0, and the shipment information accuracy ρ are common knowledge.[6] In some settings, buyers can effectively estimate supplier production costs (and suppliers can estimate their competitors' costs), and so common cost knowledge is a reasonable approximation. In practice, the value of ρ depends on the buyer's shipment monitoring requirements or inspection policies and these are often specified in publicly accessible supplier guidance. For instance, temperature recording devices for perishable shipments are specified in Walmart's cold chain compliance requirements; see page 283 of Walmart Stores, Inc. (2022). Moreover, assuming production costs and disruption probabilities are common knowledge among competing suppliers is standard in the literature (Babich et al. 2007, Shan et al. 2022).[7] In §5.2, however, we discuss cases in which the common-knowledge assumption is relaxed and so suppliers engage in an incomplete information game at Time 0.

In what follows, we formulate the buyer and the suppliers' problems in a backward fashion.

Buyer's Problem. We use Q_U and Q_R to denote the buyer's initial order quantities from supplier U and supplier R at time 0, respectively, and $Q_E(s)$ to denote the emergency order quantity from supplier R. Note that $Q_E(s)$ is contingent on the realized signal s. Based on the aforementioned information structure, the probability of signal s being bad (good) is given by $P_B = P_0\rho$ $(P_G = 1 - P_0\rho)$. Define shorthand notation $P_{0s} = \Pr(\epsilon = 0|s)$ $(P_{1s} = \Pr(\epsilon = 1|s))$ to represent the conditional probability that the shipment is spoiled (not spoiled) given signal s. By Bayes' rule, we have $P_{1G} = 1 - P_{0G} = \frac{P_1}{P_1 + P_0(1-\rho)}, P_{0B} = 1$ and $P_{1B} = 0$.

Given wholesale prices w_U and (w_R, w_E), the buyer's sourcing problem can then be written as a two-stage stochastic program:

$$\max \sum_{s\in\{B,G\}} P_s \left(\sum_{\epsilon\in\{0,1\}} P_{\epsilon s} R(\epsilon Q_U + Q_R + Q_E(s)) - w_E Q_E(s) - w_R Q_R - w_U \epsilon Q_U \right) \tag{2}$$
$$\text{s.t. } Q_R, Q_U, Q_E(s) \geq 0 \text{ for all } s \in \{B, G\}$$

where the initial order quantities Q_U and Q_R are the first-stage decision variables, where $Q_E(G)$ and $Q_E(B)$ are wait-and-see variables. It is worth noting that in practice either the buyer or the

[6] The buyer does not need to know the suppliers' production costs when deciding on order quantities.

[7] For the context considered in our paper, the damage probability P_0 depends mostly on the transportation process for supplier U's goods. A buying firm's packaging and transportation standards for perishable goods are often specified in public supplier guidance (Walmart Stores, Inc. 2022). Thus, the buyer, as the receiver of the goods, should have the same information about P_0 as supplier U. Supplier R can also infer P_0 from the buyer's cold chain standards and the possible transportation means being used. For example, only a few seaports can be used to import perishable goods to the United States, and so the transportation route being used by a supply chain is not secretive; see Hutchins (2017) for a report on Walmart's perishable shipment.

supplier can be responsible for losses during transportation depending on the specific trade terms. In the above formulation we have assumed that the buyer pays supplier U only if the order is successfully delivered; however, it is easy to show that our results continue to hold if supplier U is paid regardless of the delivery outcome.

Supplier Pricing Game. Anticipating that the buyer optimizes (2) to determine its sourcing strategy, the two suppliers at Time 0 simultaneously determine the wholesale prices w_U, w_R and w_E to maximize their own expected profits. Let $Q_U^*(w_U, w_R, w_E)$, $Q_R^*(w_U, w_R, w_E)$, $Q_E^*(s, w_U, w_R, w_E)$ represent the optimal order quantities maximizing (2). Supplier R chooses w_R and w_E to maximize its expected profit

$$\pi_R(w_R, w_E|w_U) = (w_R - c_R)Q_R^*(w_U, w_R, w_E) + \sum_{s\in\{B,G\}} P_s(w_E - c_R)Q_E^*(s, w_U, w_R, w_E) \quad (3)$$

while supplier U chooses w_U to maximize its expected profit

$$\pi_U(w_U|w_R, w_E) = (P_1 w_U - c_U)Q_U^*(w_U, w_R, w_E). \quad (4)$$

Without loss of generality, we will assume that supplier R sets its regular wholesale price not greater than the emergency wholesale price, i.e., $w_R \le w_E$. It is easy to show that for supplier R, any amount of revenue under $w_R > w_E$ can be induced by $w_R = w_E$, so supplier R's strategy space can be restricted to $w_R \le w_E$ without loss of generality.[8] To rule out uninteresting cases, we assume $c_R \le m$ and $c_U \le P_1 m$; if the former (latter) inequality does not hold, supplier R (supplier U) will not be able to make a positive profit from the buyer even if it is the only supplier available.

Before presenting our main results, we first establish the following lemma which helps simplify the exposition in the rest of the paper.

LEMMA 1. *For any $w_R \le w_E$, there exists an optimal solution to the buyer's problem in which $Q_E^*(G) = 0$ and $Q_E^*(B) \ge 0$.*

Lemma 1 implies that without loss of optimality we can assume that the buyer never places an emergency order with supplier R if it receives a good signal.[9] Per Lemma 1, we will hereafter write the emergency order quantity $Q_E^*(B)$ simply as Q_E^* with the understanding that $Q_E^*(G) = 0$.

[8] If $w_R > w_E$, the buyer will set $Q_R^* = 0$, in which case supplier R's revenue is $w_E(Q_E^*(G) + Q_E^*(B))$. By letting $w_R = w_E$, supplier R can always obtain the same amount of revenue (even though the buyer has multiple optimal solutions under $w_R = w_E$).

[9] The intuition is as follows. If a positive emergency order quantity is optimal given a good signal, i.e., $Q_E^*(G) > 0$, then one can show that a (weakly) larger emergency order quantity must be optimal given a bad signal, i.e., $Q_E^*(B) \ge Q_E^*(G)$. Whenever $Q_E^*(G) > 0$, the buyer will be (weakly) better off shifting the $Q_E^*(G)$ units to the regular order while placing an emergency order of $Q_E^*(B) - Q_E^*(G)$ units only if receiving a bad signal.

4. Results

4.1. Buyer's Optimal Order Quantities

We start by determining the buyer's optimal order quantities Q_U^*, Q_R^* and Q_E^* that solve problem (2) for any given w_U and $w_R \le w_E$. It is clear that if a wholesale price exceeds the buyer's market potential m, the corresponding order quantity will be zero. Hence, we can restrict attention to $w_U \le m$ and $w_R \le w_E \le m$.

As characterized in the following proposition, the buyer will engage in one of four sourcing strategies: (i) *contingent sourcing* in which the buyer sources from only supplier U at Time 0 but sources from supplier R at Time 1 depending on the realized shipment signal; (ii) *mixed sourcing* in which the buyer sources from both U and R at Time 0 but sources from R again at Time 1 depending on the signal; (iii) *diversification* in which the buyer sources from both U and R at Time 0 but does not source again at Time 1 regardless of the signal; and (iv) *sole sourcing* from R in which the buyer sources from only R at Time 0 and therefore removes all shipment risk. We note the mixed strategy combines diversification with contingent sourcing, hence the name. The optimal strategy (and resulting sourcing quantities) will depend on the three wholesale prices. Define shorthand notation $\eta_1(w_U, w_E) = P_1 w_U + P_B w_E + P_G P_{0G} m$ and $\eta_2(w_U, w_E) = P_1 w_U + P_0 w_E$, and note that $\eta_1(w_U, w_E) \ge \eta_2(w_U, w_E)$.

Proposition 1. *Given any $w_U \le m$ and $w_R \le w_E \le m$, the buyer's optimal order quantities are characterized by one of the following cases.*

(i) If $\eta_1(w_U, w_E) < w_R$, then $Q_U^* = Q_U^i$, $Q_R^* = 0$, and $Q_E^* = Q_E^i$. ["contingent"]

(ii) If $\eta_2(w_U, w_E) < w_R \le \eta_1(w_U, w_E)$, then $Q_U^* = Q_U^{ii}$, $Q_R^* = Q_R^{ii}$ and $Q_E^* = Q_E^{ii}$. ["mixed"]

(iii) If $w_U < w_R \le \eta_2(w_U, w_E)$, then $Q_U^* = Q_U^{iii}$, $Q_R^* = Q_R^{iii}$ and $Q_E^* = 0$. ["diversification"]

(iv) If $w_R \le w_U$, then $Q_U^* = Q_E^* = 0$ and $Q_R^* = Q_R^{iv}$. ["sole"]

The closed-form expressions of order quantities are given in Table 1.

Table 1 Closed-form expressions of the buyer's optimal order quantities in Proposition 1

Case number n	Q_U^n	Q_R^n	Q_E^n
i	$\frac{m-w_U}{2}$	0	$\frac{m-w_E}{2}$
ii	$\frac{w_R-P_G w_U-P_B w_E}{2P_G P_{0G}}$	$\frac{P_G P_{0G} m-w_R+P_B w_E+P_1 w_U}{2P_G P_{0G}}$	$\frac{w_R-P_1 w_U-P_0 w_E}{2P_G P_{0G}}$
iii	$\frac{w_R-w_U}{2P_0}$	$\frac{P_0 m-w_R+P_1 w_U}{2P_0}$	0
iv	0	$\frac{m-w_R}{2}$	0

Figure 1 illustrates the optimal conditions in Proposition 1 in which each of the four strategies is optimal. If supplier R's regular price w_R is sufficiently low, i.e., lower than supplier U's wholesale

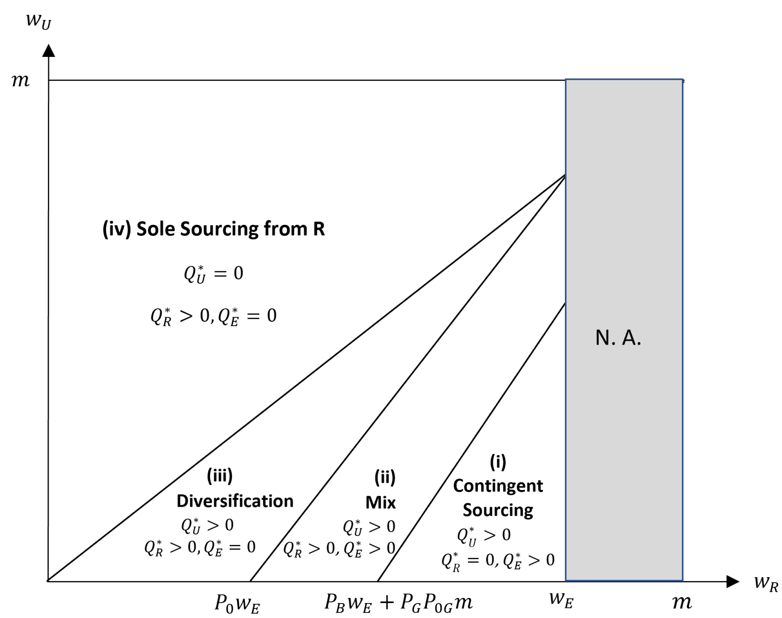

Figure 1 **Structure of the buyer's optimal order quantities with imperfect IoT.**

price w_U [Case (iv)], then sole sourcing from supplier R is clearly optimal because it is cheaper and eliminates all shipment risk. At the opposite end, if w_R is very high, i.e., exceeds $\eta_1(w_U, w_E)$ [Case (i)], then contingent sourcing is optimal because it is unattractive from a cost perspective to source from R at Time 0 but the buyer may want to use R at Time 1 depending on the realized shipment signal. At intermediate supplier R regular prices, i.e, w_R falls between w_U and $\eta_1(w_U, w_E)$, diversification (either alone or mixed with contingent sourcing) is optimal because it, in some sense, balances procurement-cost and shipment-risk considerations. Whether contingent sourcing is used with diversification or not depends on how much the buyer orders from R at Time 0. If supplier R's regular price is low enough, i.e., $w_U < w_R \leq \eta_2(w_U, w_E)$ [Case (iii)], then the buyer purchases enough from R at Time 0 to render contingent sourcing unattractive regardless of the shipment signal. However, at higher supplier R regular prices, i.e., $\eta_2(w_U, w_E) < w_R \leq \eta_1(w_U, w_E)$ [Case (ii)], the buyer purchases less from R at Time 0 and therefore resorts to contingent sourcing at Time 1 depending on the signal.

We note that the $\eta_1(w_U, w_E)$ and $\eta_2(w_U, w_E)$ thresholds coincide in the special case of perfect shipment information, i.e., when the realized signal perfectly predicts whether the shipment will arrive in a good or damaged condition. Formally, $\eta_1(w_U, w_E) = \eta_2(w_U, w_E)$ if $\rho = 1$.[10] Importantly, this implies that the mixed strategy is not optimal in the perfect shipment information case.[11] A

[10] To see this, at $\rho = 1$, we have $P_B = P_0$, $P_G = P_1$, and $P_{0G} = 0$, and hence $\eta_1(w_U, w_E) = \eta_2(w_U, w_E) = P_1 w_U + P_0 w_E$.

[11] Precisely speaking, in the perfect information case, if the wholesale prices are such that $\eta_1(w_U, w_E) = \eta_2(w_U, w_E) = w_R$ then multiple optimal solution exist, including the mixed strategy, because the buyer is indifferent between ordering from supplier R at Time 0 or at Time 1. In this very special case, we break the tie by assuming the buyer waits for more information and adopts the contingent sourcing strategy.

close inspection of the relevant thresholds in Proposition 1 reveals that the mixed strategy does not displace the diversification strategy when moving from perfect- to imperfect-information; instead the mixed strategy displaces the pure contingent sourcing strategy in a certain region. The reason that diversification might be added to contingent sourcing when the shipment signal is imperfect is as follows. Recall from Lemma 1 that the buyer only places a contingent order if the signal at Time 1 is bad. Because a good signal does not guarantee a good arrival under imperfect shipment information, the buyer faces residual supply uncertainty if the signal is good. It can be optimal for the buyer to hedge this uncertainty by diversifying its initial order; that is, a mixed strategy can be optimal. In contrast, there is no residual uncertainty under perfect shipment information because a good signal guarantees the order arrives in a good condition, and therefore the pure contingent sourcing strategy dominates (at least weakly) the mixed strategy in that special case.

4.2. Supplier Competition

Having characterized the buyer's optimal ordering strategy for any given set of wholesale prices, we now proceed to analyze the suppliers' pricing game. Substituting the buyer's optimal order quantities into supplier R's problem (3), for any given w_U, we can write supplier R's expected profit (payoff) as follows:

$$\pi_R(w_R, w_E|w_U) = \begin{cases} (w_R - c_R)Q_R^{iv} & \text{if } w_R \le w_U, \\ (w_R - c_R)Q_R^{iii} & \text{if } w_U < w_R \le \eta_2(w_U, w_E), \\ (w_R - c_R)Q_R^{ii} + P_B(w_E - c_R)Q_E^{ii} & \text{if } \eta_2(w_U, w_E) < w_R \le \eta_1(w_U, w_E), \\ P_B(w_E - c_R)Q_E^{i} & \text{if } \eta_1(w_U, w_E) < w_R. \end{cases} \tag{5}$$

Supplier R maximizes $\pi_R(w_R, w_E|w_U)$ by choosing w_R and w_E over $c_R \le w_R \le w_E \le m$. Note that $\pi_R(w_R, w_E|w_U)$ consists of four cases according to the buyer's four different ordering strategies as described in Proposition 1. When pricing, supplier R chooses among four alternative strategies. It may monopolize the buyer's business by offering a regular wholesale price $w_R \le w_U$, profit only from the buyer's initial order by offering a $w_R \in (w_U, \eta_2(w_U, w_E)]$, profit from both the initial order and the contingent order with a $w_R \in (\eta_2(w_U, w_E), \eta_1(w_U, w_E)]$, or forgo the buyer's initial order and profit only from the buyer's potential contingent order Q_E^* by setting a high w_R. Its optimal strategy will of course depend on supplier U's wholesale price choice w_U and its own production cost c_R. We have characterized supplier R's optimal wholesale price response (w_R^*, w_E^*) to any given w_U; the closed form expressions are relegated to Lemma B.1 in Appendix B.

Similarly, for any given $w_R \le w_E \le m$, supplier U's expected profit can be written as

$$\pi_U(w_U|w_R, w_E) = \begin{cases} (P_1 w_U - c_U)Q_U^{i} & \text{if } \eta_1(w_U, w_E) < w_R \\ (P_1 w_U - c_U)Q_U^{ii} & \text{if } \eta_2(w_U, w_E) < w_R \le \eta_1(w_U, w_E) \\ (P_1 w_U - c_U)Q_U^{iii} & \text{if } w_U < w_R \le \eta_2(w_U, w_E) \\ 0 & \text{if } w_U \ge w_R \end{cases} \tag{6}$$

By choosing w_U over $c_U \leq w_U \leq m$, supplier U maximizes $\pi_U(w_U|w_R, w_E)$. Depending on supplier U's production cost c_U and supplier R's wholesale prices, supplier U chooses either to obtain the buyer's entire initial order by offering a sufficiently low w_U, or to share the buyer's initial order with supplier R with a relatively high w_U. Supplier U will receive no business if $w_U \geq w_R$.

Without loss of generality, we restrict suppliers U and R's strategy spaces to $c_U/P_1 \leq w_U \leq m$ and $c_R \leq w_R \leq w_E \leq m$. A set of wholesale prices (w_U^I, w_R^I, w_E^I) constitutes a Nash equilibrium if (i) given w_U^I, w_R^I and w_E^I maximize (5) and (ii) given w_R^I and w_E^I, w_U^I maximizes (6). The superscript "I" represents the equilibrium solution with shipment information. If multiple equilibria exist, we follow the convention to select the Pareto-dominant equilibrium, i.e., the equilibrium in which the two suppliers' payoffs cannot be simultaneously improved under other equilibria.[12] Hereafter, we will simply refer to a Pareto-dominant equilibrium as an equilibrium.

In what follows, to better highlight and explain some key findings, we will first (§4.3) analyze the equilibria that occur in the two extreme cases of shipment information, those being perfect information ($\rho = 1$) and no information ($\rho = 0$). Then, in §4.4, we will turn to the imperfect information case ($0 < \rho < 1$) to develop more insights into the effect of shipment information accuracy.

4.3. Impact of Contingent Sourcing: Perfect vs No Shipment Information

When the shipment information is perfect ($\rho = 1$), the buyer knows with certainty whether supplier U's order will be good or bad at the time it decides on a contingent order. In contrast, when $\rho = 0$, the shipment signal is completely uninformative, and contingent sourcing is not relevant because there is no informative update.[13] Therefore, by comparing the equilibrium results under $\rho = 1$ and $\rho = 0$, we can examine the impact of contingent sourcing while abstracting away from the role of information accuracy.

4.3.1. Equilibrium with Perfect Shipment Information. To solve for the equilibrium with $\rho = 1$, we first obtain the closed-form expression of each supplier's best response function as given in Online Appendix A, and then adopt a graphical approach to identify all the possible intersections between the two suppliers' best response functions and thereby determine the equilibrium prices. For notational ease, we define four thresholds $\psi_1 = \frac{P_1 m + c_U}{2P_1}$, $\psi_2 = \frac{P_0 m + 2c_U/P_1}{P_0 + 2}$, $\psi_3 = \frac{P_0+1}{P_1} c_U - P_0 m$ and $\psi_4 = \frac{2c_U}{P_1} - m$. With these thresholds, we characterize the equilibrium in

[12] Precisely speaking, multiple Pareto-dominant equilibria may exist in our problem but they will lead to the same equilibrium order quantities and payoffs. For example, a range of values of w_E can support a Pareto-dominant equilibrium in which the buyer does not place an emergency order at all, since the value of w_E (within the range) is irrelevant to the problem.

[13] The case of $\rho = 0$ corresponds to a setting where no monitoring or inspection is possible before Time 1. Alternatively, one can interpret the case of $\rho = 0$ as a setting in which the buyer pre-commits to not using contingent sourcing in any circumstance, although our model does not assume such a commitment power for the buyer.

Proposition 2 below, along with a graphic illustration in Figure 2. When supplier R (U) does not receive the buyer's initial order in equilibrium, we write the corresponding wholesale price as its lowest possible value, i.e., $w_R^I = c_R$ ($w_U^I = c_U/P_1$).

PROPOSITION 2. (EQUILIBRIUM WITH PERFECT SHIPMENT INFORMATION) *With perfect shipment information ($\rho = 1$), the equilibrium is characterized by one of the following cases.*

(i) If $c_R > \psi_2$, then the buyer orders only from supplier U at Time 0 and, if $s = B$, places an emergency order with supplier R at Time 1;

(ii) if $\psi_3 < c_R \leq \psi_2$, then the buyer sources from both suppliers at Time 0, and does not order at Time 1 regardless of the realized signal s;

(iii) otherwise, the buyer sources exclusively from supplier R at Time 0.

The equilibrium wholesale prices, depending on c_R and thresholds ψ_1, ψ_2, ψ_3 and ψ_4, are given in Table 2.

Table 2 Equilibrium wholesale prices with perfect shipment information ($\rho = 1$)

Condition	w_U^I	w_E^I	w_R^I
(i-a) $c_R > \psi_1$	$\frac{P_1 m + c_U}{2P_1}$	$\frac{m + c_R}{2}$	$[P_1 w_U^I + P_0 w_E^I, w_E^I]$
(i-b) $\psi_2 < c_R \leq \psi_1$	c_R	$\frac{m + c_R}{2}$	$P_1 w_U^I + P_0 w_E^I$
(ii) $\psi_3 < c_R \leq \psi_2$	$\frac{P_0 m + c_R + 2c_U/P_1}{3 + P_0}$	$((w_R^I - P_1 w_U^I)/P_0, +\infty)$	$\frac{2P_0 m + 2c_R + c_U}{3 + P_0}$
(iii-a) $\psi_4 < c_R \leq \psi_3$	$\frac{c_U}{P_1}$	$[w_R^I, +\infty)$	$\frac{c_U}{P_1}$
(iii-b) $c_R \leq \psi_4$	$\frac{c_U}{P_1}$	$[w_R^I, +\infty)$	$\frac{m + c_R}{2}$

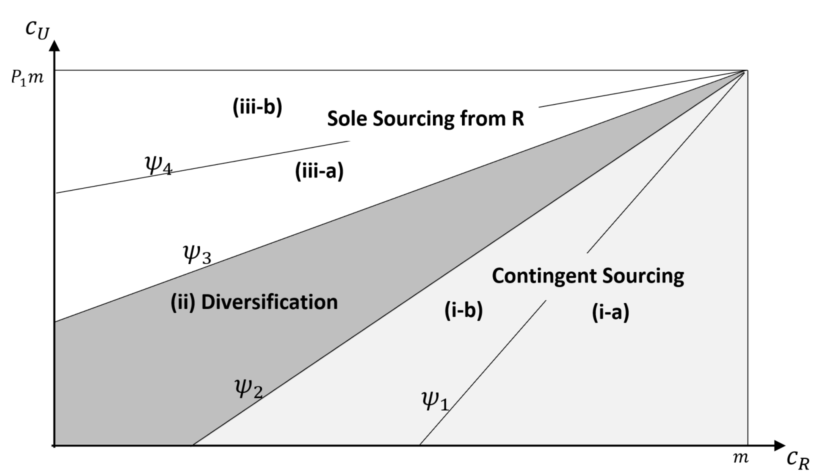

Figure 2 Illustration of the equilibrium with perfect shipment information ($\rho = 1$) for any given c_U and c_R.

Note that the thresholds ψ_1, ψ_2, ψ_3 and ψ_4 are all increasing functions of c_U and $\psi_1 \geq \psi_2 \geq \psi_3 \geq \psi_4$. So, the proposition suggests that three different types of equilibria may occur, depending on the suppliers' production costs c_U and c_R. If c_R is large enough relative to c_U, it is too costly for supplier R to compete with supplier U for the buyer's initial Time-0 order; thus, supplier R prefers to profit from the buyer's emergency order as described in Equilibrium (i) of Proposition 2. Note that supplier R is the only option for an emergency order at Time 1, and can therefore charge a monopolistic price $w_E^I = \frac{m+c_R}{2}$ for the contingent order. On the other hand, supplier U can charge a monopolistic price $w_U^I = \frac{P_1 m + c_U}{2P_1}$ at Time 0 if its cost c_U is dominantly lower than c_R; otherwise, it sets a limit price $w_U^I = c_R$ to preclude supplier R from competing for the initial order; these two subcases correspond to Equilibria (i-a) and (i-b) in Table 2, respectively.

As described in Equilibrium (ii), if c_R is moderate relative to c_U, then suppliers R and U will share the buyer's order at Time 0, that is, they induce the buyer to follow a diversification strategy. In such an equilibrium, supplier R sets w_E^I high enough to induce the buyer to order only at Time 0. Equilibrium (iii)—sole sourcing from supplier R—occurs if c_R is small enough relative to c_U, in which case supplier R will be able to price out supplier U at Time 0, either with a limit price as in Equilibrium (iii-a) or with a monopolistic price as in Equilibrium (iii-b).

4.3.2. Equilibrium with No Shipment Information. With $\rho = 0$, the signal s is always good (but not informative) and contingent sourcing becomes irrelevant. The buyer's problem is reduced to a single-stage optimization problem over the two initial order quantities Q_U and Q_R. Incidentally, this special-case model reduces to that studied in Shan et al. (2022). Proposition 3 below, which can be adapted from Theorem 1 of Shan et al. (2022)[14], presents the possible equilibrium outcomes when $\rho = 0$, where we use superscript "N" to denote the equilibrium prices with no shipment information. We define two additional thresholds $\phi_1 = \frac{(1+P_0)m + c_U}{2}$ and $\phi_2 = \frac{2P_0 m + c_U}{P_0 + 1}$.

Proposition 3. (Equilibrium without Shipment Information) *With no shipment information ($\rho = 0$), the equilibrium is characterized by one of the following cases.*

(i) If $c_R > \phi_2$, then the buyer sources only from supplier U;

(ii) if $\psi_3 < c_R \leq \phi_2$, then in equilibrium the buyer sources from both suppliers;

(iii) otherwise, the buyer sources only from supplier R.

The equilibrium wholesale prices, depending on c_R and thresholds ϕ_1, ϕ_2, ψ_3 and ψ_4, are given in Table 3.

[14] More specifically, in Shan et al. (2022) there can be multiple unreliable suppliers but the buyer cannot place contingent orders based on updated information. Additionally, in their formulation suppliers need not incur the production cost in case of a disruption; this is equivalent to replacing c_U with $P_1 c_U$ in our notation.

Table 3 **Equilibrium wholesale prices with no shipment information ($\rho = 0$)**

Condition	w_U^N	w_R^N
(i-a) $c_R > \phi_1$	$\frac{P_1 m + c_U}{2P_1}$	c_R
(i-b) $\phi_2 < c_R \le \phi_1$	$\frac{c_R - P_{0G} m}{P_{1G}}$	c_R
(ii) $\psi_3 < c_R \le \phi_2$	$\frac{P_0 m + c_R + 2c_U/P_1}{3+P_0}$	$\frac{2P_0 m + 2c_R + c_U}{3+P_0}$
(iii-a) $\psi_4 < c_R \le \psi_3$	$\frac{c_U}{P_1}$	$\frac{c_U}{P_1}$
(iii-b) $c_R \le \psi_4$	$\frac{c_U}{P_1}$	$\frac{m+c_R}{2}$

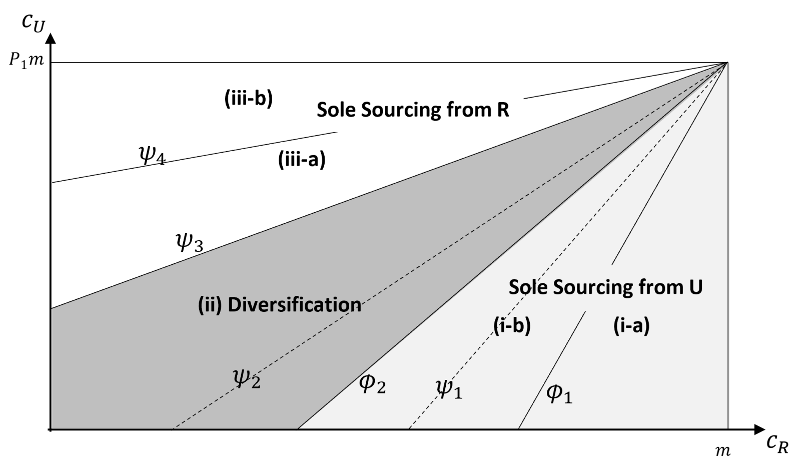

Figure 3 **Illustration of the equilibrium without contingent sourcing ($\rho = 0$) for any given c_U and c_R; in the graph, we always have $\psi_2 \le \phi_2$ and $\psi_1 \le \phi_1$ but $\phi_2 \le \psi_1$ iff $P_1 \ge 2/3$.**

In equilibrium the buyer either single sources from supplier U [Equilibrium (i)], single sources from supplier R [Equilibrium (iii)], or it diversifies the initial order across both suppliers [Equilibrium (ii)]. The different types of equilibria without shipment information are illustrated in Figure 3 for any combination of c_U and c_R. Although contingent sourcing is not an equilibrium strategy in this no-information case, the possibility of sourcing at Time 1 does influence the equilibrium wholesale prices in the sole-sourcing regions as characterized in Proposition 3.

4.3.3. Comparison of Equilibria. We now compare the equilibrium outcomes between the perfect- and no-information cases. We begin by noting that in both cases the same threshold ψ_3 specifies the boundary between diversification and sole sourcing from R. The key difference between the two cases is that when supplier R's regular cost is high, contingent sourcing occurs under perfect information ($\rho = 1$) but sole-sourcing from U occurs under no information ($\rho = 0$). However, the threshold cost at which these strategies emerge differs. That is, the boundary between diversification and contingent sourcing (ψ_2 in Figure 2) differs from the boundary between diversification and sole sourcing from U (ϕ_2 in Figure 3). Moreover, we can show that $\psi_2 \le \phi_2$ (and also that $\psi_1 \le \phi_1$).

Figure 4 overlays the cases with $\rho = 0$ and $\rho = 1$ as c_R changes with c_U being fixed. The possibility of contingent sourcing, or equivalently the availability of updated shipment information, causes the diversification region to contract and be replaced by contingent sourcing (in which only supplier U is used at Time 0 but supplier R is used in contingency). Sole sourcing from supplier U is also replaced by contingent sourcing. It is worth noting that the Equilibrium (i-a) region expands when contingent sourcing is possible; that is, supplier U is more likely to obtain the buyer's entire order at Time 0 *and* charge a monopolistic price, as the buyer is able to resort to supplier R contingent on updated shipment information.

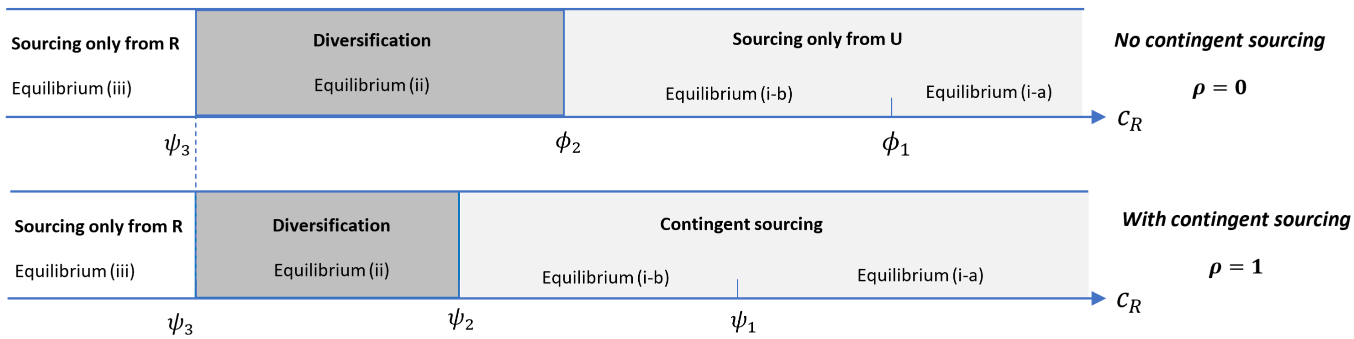

Figure 4 **Impact of contingent sourcing on the equilibrium outcome for a fixed c_U; in the graph, we always have $\psi_2 \leq \phi_2$ and $\psi_1 \leq \phi_1$ but $\phi_2 \leq \psi_1$ iff $P_1 \geq 2/3$.**

The possibility of contingent sourcing affects not only the buyer's sourcing strategy in equilibrium but also the suppliers' equilibrium wholesale prices:

COROLLARY 1. *If the buyer sources only from supplier U at Time 0 whether $\rho = 1$ or $\rho = 0$, with all else equal, supplier U's equilibrium price is higher (i.e., $w_U^I \geq w_U^N$) when contingent sourcing is possible (i.e., $\rho = 1$).*

Corollary 1 establishes that, when contingent sourcing is possible for the buyer, supplier U can use a higher price to preclude supplier R from competing for the initial order than it can when contingent sourcing is not possible. The rationale is as follows. With contingent sourcing not possible, supplier R will end up with zero profit if it does not receive some portion of the buyer's initial order. In contrast, with the possibility of contingent sourcing, the buyer may resort to supplier R at Time 1; hence, even if supplier R gives up on the buyer's initial order, it can receive a positive *expected* profit from the emergency order that is placed later if a bad signal is realized. In some sense, the possibility of contingent sourcing, or the presence of updated shipment information, gives supplier R a higher reservation value when competing for the initial order. Therefore, with the possibility of receiving an emergency order, supplier R will not compete as vigorously as it would without that possibility, which in turn increases supplier U's equilibrium price.

Next, we examine how the possibility of contingent sourcing affects the buyer's and the suppliers' expected profits in equilibrium. In particular, the following proposition establishes that as contingent sourcing becomes possible with updated shipment information, the buyer may be either better off or worse off, whereas the two suppliers will generally be (weakly) better off.

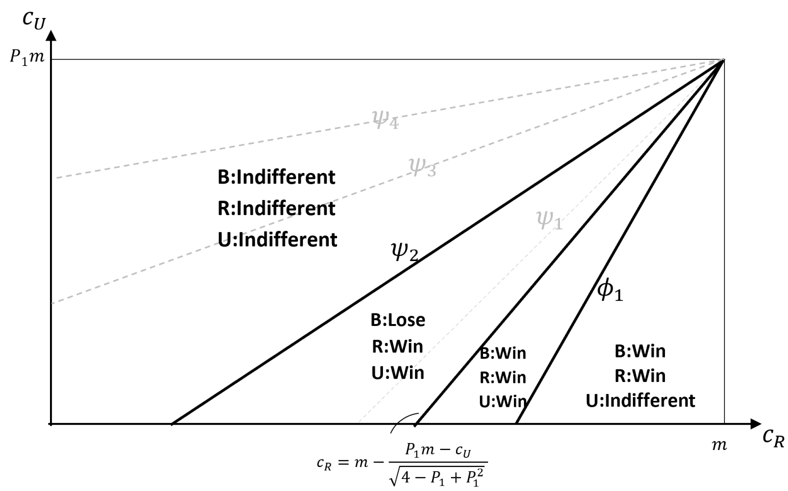

Figure 5 **Impact of contingent sourcing on the payoffs of the buyer (B), supplier R, and supplier U.**

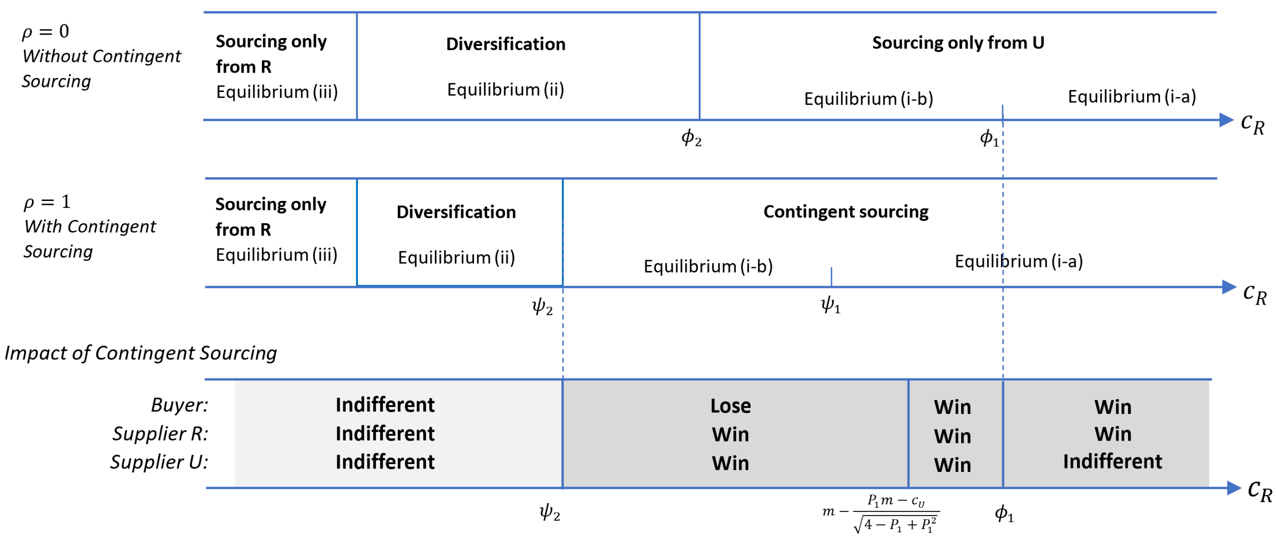

Figure 6 **Impact of contingent sourcing on the buyer's and the suppliers' expected profits with c_U fixed. Note: The graph illustrates the case of $P_1 \geq 2/3$; if $P_1 < 2/3$, we have $\frac{2P_0 m + c_U}{P_0 + 1} > \frac{m + c_U/P_1}{2}$ but the relative positions of all the other thresholds remain the same.**

PROPOSITION 4. *(i) If $c_R \geq \phi_1$, then the possibility of contingent sourcing makes the buyer and supplier R both better off and has no impact on supplier U's payoff.*

(ii) If $m - \frac{P_1 m - c_U}{\sqrt{4 - P_1 + P_1^2}} < c_R \leq \phi_1$*, then the possibility of contingent sourcing makes the buyer, supplier U, and supplier R all better off.*

(iii) If $\psi_2 < c_R \leq m - \frac{P_1 m - c_U}{\sqrt{4 - P_1 + P_1^2}}$*, then the possibility of contingent sourcing makes the buyer worse off but both suppliers better off.*

(iv) Otherwise, contingent sourcing will not occur in equilibrium and so it has no impact on all supply chain parties' payoffs.

Proposition 4 is illustrated in Figure 5 for any combination of c_U and c_R, and in Figure 6 with c_U fixed to compare the corresponding equilibria in different cases. The effects of contingent sourcing are twofold. On the one hand, it enables the buyer to be responsive to shipment spoilage. On the other hand, as discussed above, it can dampen the competition between suppliers and thus increase supplier U's wholesale price. The results in Proposition 4 are driven by these two effects.

In case (i), c_R is sufficiently large compared to c_U such that supplier U can charge a monopolistic price [i.e., Equilibrium (i-a) occurs] at Time 0, whether the buyer is able to place an emergency order with supplier R at Time 1 or not. Therefore, the buyer is better off with the possibility of contingent sourcing while supplier R's expected profit is improved due to the potential profit from the emergency order. As c_R becomes smaller such that supplier U can no longer charge a monopolistic price if contingent sourcing is impossible, the possibility of contingent sourcing will enable supplier U to offer a higher wholesale price, thus making it strictly better off. The buyer benefits from contingent sourcing but is hurt by the increased wholesale price. In case (ii) of Proposition 4, the benefit of contingent sourcing outweighs the effect of increased price, and so the buyer is better off with contingent sourcing. In case (iii), however, the effect of the increased price dominates the value of contingent sourcing. Consequently, as contingent sourcing becomes possible, the buyer is worse off while the two suppliers are better off. In case (iv) where c_R is small enough, supplier R prefers to profit from the buyer's initial order, whether contingent sourcing is possible or not. Hence, the possibility of contingent sourcing will make no difference to any supply chain member.

In general, Proposition 4 reveals an underlying tradeoff between the operational value of contingent sourcing and its softening effect on supplier competition. To ensure that the operational advantage outweighs the competition-softening disadvantage, in practice, the buying firm should ensure the unreliable supplier is sufficiently cost-efficient compared to the reliable supplier, i.e., c_U is sufficiently small relative to c_R.

4.4. Impact of Information Accuracy: The Case of Imperfect Shipment Information

We now turn to the case of $0 < \rho < 1$ in which the shipment information is informative but may not perfectly predict damage. Recall from §4.1 that a mixed strategy that combines diversification and contingent sourcing may be optimal for the buyer under imperfect information, i.e., sourcing strategy (ii) of Proposition 1. The possibility of the buyer adopting such a mixed strategy substantially complicates the suppliers' pricing game. As presented in Appendix B, the suppliers' best response functions become more involved and supplier U's best response is not even continuous.

For simplicity, in this subsection we assume supplier U's production cost to be zero, i.e., $c_U = 0$. Allowing a positive c_U does not bring much additional insight because our focus is on the cases when contingent sourcing is utilized in equilibrium, and this occurs only if c_U is sufficiently small. In Appendix B.4, we have numerically verified that our main results continue to hold for $c_U > 0$. Moreover, there may not exist a pure-strategy Nash equilibrium; see an example in Appendix B.3. Nevertheless, we are able to show that as long as c_R is greater than a threshold, there will always exist an equilibrium in which contingent sourcing is used. Define $\hat{\psi}_1 = \frac{(1+P_{0G})m}{2}$, $\hat{\psi}_2 = \frac{2P_0 - P_B(1+P_0)}{2-P_B(1+P_0)}m$ and $\psi_{mix} = \frac{2P_{0G}m}{1+P_{0G}}$.

Proposition 5. (Equilibrium with Imperfect Shipment Information) *Assuming $c_U = 0$ and $c_R \geq \hat{\psi}_2$, in equilibrium the buyer contingently sources from supplier R at Time 1.*

- *For information accuracy below a threshold ($\rho < \hat{\rho}$), (i) if $c_R > \psi_{mix}$, then the buyer orders only from supplier U at Time 0 and, if $s = B$, contingently sources from supplier R at Time 1; (ii) if $\hat{\psi}_2 \leq c_R \leq \psi_{mix}$, then the buyer orders from both suppliers at Time 0 and, if $s = B$, places an emergency order with supplier R at Time 1.*
- *For information accuracy above a threshold ($\rho \geq \hat{\rho}$), the buyer orders only from supplier U at Time 0 and, if $s = B$, contingently sources from supplier R at Time 1.*

The equilibrium prices w_U^I, w_R^I and w_E^I are given in Table 4.

Table 4 Equilibrium wholesale prices with imperfect shipment information (given $c_U = 0$ and $c_R \geq \hat{\psi}_2$)

Condition	w_U^I	w_E^I	w_R^I
For $\rho < \hat{\rho}$			
(i-a) $c_R > \hat{\psi}_1$	$\frac{m}{2}$	$\frac{m+c_R}{2}$	$[P_1 w_U^I + P_B w_E^I + P_G P_{0G} m, w_E^I]$
(i-b) $\psi_{mix} < c_R \leq \hat{\psi}_1$	$\frac{c_R - P_{0G}m}{P_{1G}}$	$\frac{m+c_R}{2}$	$P_1 w_U^I + P_B w_E^I + P_G P_{0G} m$
(ii) $\hat{\psi}_2 \leq c_R \leq \psi_{mix}$	$\frac{P_{1G}(c_R+P_0 m) - P_{1G}P_B(m+c_R)}{P_1(4-P_{1G})}$	$\frac{m+c_R}{2}$	$\frac{4(c_R+P_0 m) - P_{1G}P_B(m+c_R)}{2(4-P_{1G})}$
For $\rho \geq \hat{\rho}$			
(i-a) $c_R > \hat{\psi}_1$	$\frac{m}{2}$	$\frac{m+c_R}{2}$	$[P_1 w_U^I + P_B w_E^I + P_G P_{0G} m, w_E^I]$
(i-b) $\hat{\psi}_2 \leq c_R \leq \hat{\psi}_1$	$\frac{c_R - P_{0G}m}{P_{1G}}$	$\frac{m+c_R}{2}$	$P_1 w_U^I + P_B w_E^I + P_G P_{0G} m$

Note that if accuracy $\rho = 1$ and $c_U = 0$, $\hat{\psi}_2$ reduces to ψ_2, the threshold for a contingent sourcing equilibrium established in Proposition 2. So, Proposition 5 generalizes the contingent sourcing equilibrium under perfect shipment information as characterized in Proposition 2. Importantly, at a lower accuracy level, a new type of equilibrium may arise in which the buyer follows a mixed strategy that combines diversification and contingent sourcing; see case (ii) for $\rho < \hat{\rho}$. At a higher accuracy level ($\rho \geq \hat{\rho}$), the equilibrium outcome will be similar to the case of perfect information; the buyer uses supplier R only as a contingent option.

In §4.3 we showed that, due to the reduced competition between suppliers, the buyer may or may not benefit from contingent sourcing enabled by perfect shipment information. Proposition 6 below generalizes this result by showing that the buyer may *not* be better off with more accurate shipment information.

Proposition 6. (Impact of Shipment Information Accuracy) *Assume $c_U = 0$ and $c_R \geq \hat{\psi}_2$. Under Equilibria (i-a) and (ii) in Proposition 5, the buyer's expected profit is increasing in ρ; under Equilibrium (i-b), the buyer's expected profit is decreasing in ρ.*

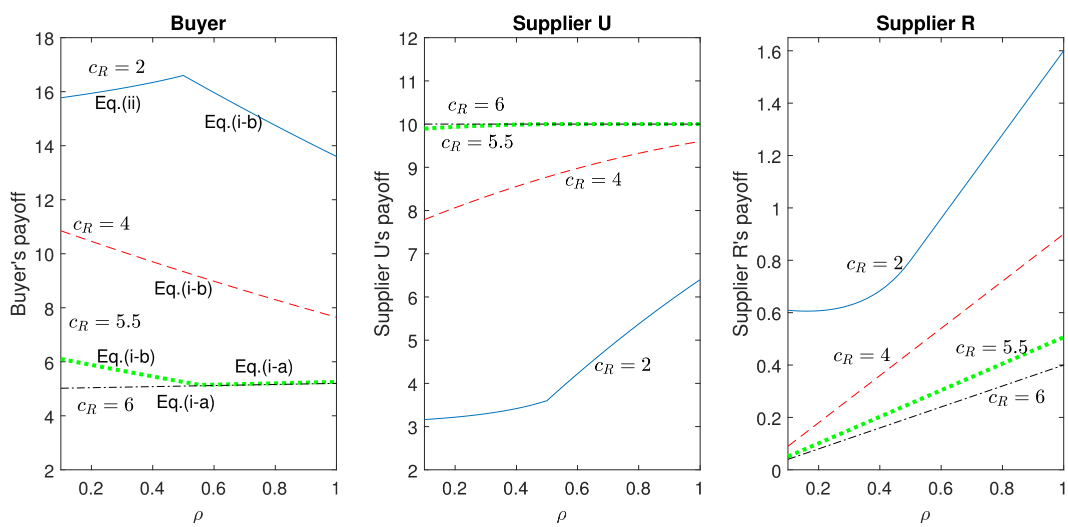

Figure 7 **Impact of shipment information accuracy ρ [$m = 10$, $c_U = 0$, $P_1 = 0.8$]**

As in the perfect information case, when R is used only for contingent sourcing, there are two subcases [i.e., Equilibria (i-a) and (i-b) in Table 4] in which supplier U either charges a monopolistic price or a limit price for the initial order. If Equilibrium (i-a) plays out in which supplier U charges a monopolistic price, a higher ρ will not change the equilibrium pries and so it simply improves the buyer's responsiveness. Under Equilibrium (ii) of Proposition 5 in which the buyer diversifies the initial order and contingently source from supplier R, an increase in ρ actually reduces the equilibrium prices w_U^I and w_R^I; intuitively, this is because a higher ρ makes the buyer opt more for contingent sourcing which intensifies the supplier competition for the initial order. Hence, the buyer is better off with a higher ρ if a mixed sourcing strategy is optimal in equilibrium. However, if Equilibrium (i-b) occurs in which supplier U uses a limit price to obtain the entire initial order, then a higher ρ makes it more attractive for supplier R to serve as a contingent source, thereby softening the competition for the initial order. So, in this case the buyer is worse off having more accurate information.

Figure 7 provides a numerical illustration with the success probability $P_1 = 0.8$. For $c_R = 2$, as ρ increases from 0.1 to 1, the buyer's payoff is first increasing and then decreasing as it switches from the mixed sourcing strategy [Equilibrium (ii)] to contingent sourcing with supplier U limit pricing [Equilibrium (i-b)]. For $c_R = 4$, the buyer's payoff is always decreasing in ρ as the equilibrium outcome stays as contingent sourcing with supplier limit pricing [Equilibrium (i-b)]. For $c_R = 5.5$, the buyer adopts contingent sourcing but as ρ increases, supplier U changes w_U^I from a limit price [Equilibrium (i-b)] to a constant monopolistic price [Equilibrium (i-a)], so the buyer's payoff is first decreasing and then increasing. For $c_R = 6$ or larger, regardless of the value of ρ, w_U^I stays as the monopolistic price [Equilibrium (i-a)], and the buyer's payoff is increasing in ρ as ρ does not impact the equilibrium prices. As for suppliers, in the example of $P_1 = 0.8$, both suppliers are generally better off with a higher ρ, but with a lower P_1 we observed that both suppliers' payoffs could be decreasing in ρ within a certain range. The ambiguous effect is because under the mixed sourcing strategy [Equilibrium (ii)], a higher ρ increases the competition for the initial order but, on the other hand, helps supplier R differentiate itself from supplier U as a contingent option.

As mentioned in the model section (and discussed and analyzed in Appendix S.1), a higher signal accuracy ρ can be achieved in practice through a superior monitoring/inspection technology, a shorter supplier R lead time, or the adoption of continuous monitoring instead of transit-point inspection. Our results indicate that, all else equal, a buying firm should exercise some caution before pursuing such "improvement" ideas because they might not be to its advantage; the benefit of the associated enhanced signal accuracy should be measured against its competition-dampening effect. As shown by the case of $c_R = 2$ in Figure 7, the buyer's payoff is maximized at approximately $\rho = 0.5$, in which case the buyer leverages the operational benefit of contingent sourcing while retaining a certain level of supplier competition intensity. It implies that in some cases, an appropriate level of signal inaccuracy may be beneficial to the buyer.

5. Extensions

We have analyzed a number of extensions to our model, and in what follows we briefly describe these extensions and summarize the main findings. Further details can be found in the Supplementary Materials of the unabridged paper.

5.1. Impacts of Delivery Reliability Improvement and Corrective Actions

Our model assumes that supplier U's delivery reliability P_1 is exogenously given. In the long run, however, supplier U might be able to influence P_1 by, for example, investing in a more-advanced cold-chain infrastructure or using a more-reliable transportation service provider. In §S.3 of the Supplementary Materials, we show that supplier U may or may *not* benefit from a higher reliability P_1. Although a higher P_1 increases supplier U's chance of successful delivery, it also intensifies its competition with supplier R for the buyer's initial order. When the competition-intensifying effect dominates, supplier U may be hurt by a higher reliability.

Different to reliability improvement, firms may be able to develop a tactical corrective-action capability that can quickly respond to a signal that a damage event may have occurred. For example, upon receipt of an alert from a transit-point inspection or from in-transportation monitoring sensors that a container seal has been compromised (which could result in future damage to its contents), the buyer, possibly in collaboration with supplier U and the transportation service provider, might attempt to fix the deviation before it results in damage, e.g., through repair of the container seal. In §S.4 of the Supplementary Materials, we analyze a setting where loss can be averted with a certain probability following a bad signal. We establish that the buying firm is more likely to benefit from enhanced shipment information if the corrective action is probabilistically more effective.

5.2. Incomplete Information

We assumed common knowledge of the underlying parameters in our base model. Although the buyer does not need to know the supplier costs when making its sourcing quantity decisions, in Proposition 4 we established the conditions under which a buyer would be better or worse off with contingent sourcing, and those conditions depend on the supplier costs. In effect, the buyer needs to know the supplier costs if it is to know whether or not it is better off when contingent sourcing is an option. In some settings, buyers can effectively estimate supplier production costs (and suppliers can estimate their competitors' costs), and so common knowledge is a reasonable approximation. This will not be the case in all settings, and it is of interest to consider a setting with private information.

If production costs are suppliers' private information, we can formulate the problem as an incomplete information game and solve for the Bayesian Nash equilibrium (BNE). For example, when c_U is private information of supplier U while the buyer and supplier R only know its probability distribution, under certain conditions, we are able to generalize Proposition 4 analytically, and show that the buyer can use the probability distribution of c_U, instead of a specific value, to determine if contingent sourcing is valuable. In general, given certain probability distributions of c_U and c_R, one can numerically find the BNE, thereby evaluating the benefit of contingent sourcing or enhanced shipment information. A similar approach can be used if the spoilage probability P_0 is known only between the buyer (receiver of the goods) and supplier U (sender of the goods) and so supplier R will compete with supplier U under incomplete information about P_0; see §S.5 of the Supplementary Materials for a more detailed discussion.

5.3. Emergency Contracting at Time 1

5.3.1. Supplier R Setting w_E at Time 1. In the base model, supplier R commits to the emergency wholesale price w_E at Time 0. Alternatively, w_E may be determined at Time 1 after the buyer has placed initial orders. Specifically, we consider an alternative sequence of events as follows. At Time 0, suppliers R and U simultaneously determine w_R and w_U, respectively; the buyer determines initial order quantities Q_R and Q_U. At Time 1, supplier R offers w_E; the buyer (privately) observes s and determines $Q_E(s)$. At Time 2, ordered items are delivered with yield loss being realized. To make the game well-defined, we assume that at Time 1, the buyer is not allowed to revise its initial order Q_R[15] and supplier R knows or can form a correct belief of Q_U, i.e., the buyer's order quantity placed with supplier U.

At Time 1, supplier R chooses w_E to maximize its *expected profit from the emergency order*: $(w_E - c_R)\sum_{s\in\{G,B\}} P_s Q_E^*(s)$ where $Q_E^*(s)$ is the buyer's optimal emergency order size given any initial order quantities Q_U and Q_R. Note that supplier R bases its pricing decision on the expected value of $Q_E^*(s)$ because the signal s is not observable to supplier R. As reported in §S.6 of the Supplementary Materials, we characterized supplier R's optimal emergency wholesale price w_E^* and the buyer's optimal emergency order $Q_E^*(s)$ for any given initial order quantities, and then developed a computational approach to determine the equilibrium. The main findings are the same as those discussed in §4.4. The buyer is better off with enhanced shipment information (i.e., a higher ρ) only if c_R is sufficiently large relative to c_U or if c_R is close to c_U such that a mixed sourcing strategy is adopted in equilibrium; in other cases, the buyer is worse off with enhanced shipment information. Therefore, our main results are robust whether w_E is determined at Time 1 or Time 0.

5.3.2. Supplier R Offering Screening Contracts at Time 1 From supplier R's perspective, at Time 1, the realized signal s can be viewed as the buyer's private information or "type." So, instead of offering a price-only contract w_E^*, supplier R might offer a menu of screening contracts to elicit this private information. We thus assume the same sequence of events as in §5.3.1 except

[15] This assumption is true if the payment for initial order Q_R has been settled before Time 1. Otherwise, if a total payment is made to supplier R for both the initial and emergency orders at or after Time 1, then the buyer may want to renegotiate Q_R as it can perform a re-optimization over (Q_R, Q_E) based on w_E and the earlier quote w_R. In anticipation of the buyer's re-optimization, in effect supplier R needs to determine both w_E and w_R at Time 0. As a consequence, the sequence of events will reduce to that considered in our base model.

that at Time 1, the supplier can offer a menu of contracts $\{Q_E(B), w_E(B)\}$ and $\{Q_E(G), w_E(G)\}$ for the buyer to choose from, where $Q_E(s)$ and $w_E(s)$ are respectively the purchase quantity and wholesale price intended for the type-s buyer. Note that in this extension we further depart from the base model as the contract form $\{Q_E(s), w_E(s)\}$ allows for any nonlinear pricing scheme (e.g., two-part tariffs) as opposed to price-only contracts. The formulation and detailed results for this model extension can be found in §S.7 of the Supplementary Materials.

To summarize the main results, we show that depending on how much the buyer has initially ordered, at Time 1 supplier R may choose to sell nothing, sell only to the buyer with a bad signal, or sell to both buyer types. Moreover, if in equilibrium emergency trade occurs only for a bad signal (i.e., $s = B$), then supplier R will extract all the surplus from the emergency trade, and so the buyer will not benefit from contingent sourcing. On the other hand, as a competitor at Time 0, supplier U will try to make the buyer purchase a large enough Q_U such that emergency trading is unnecessary given a good signal. Recall that in the base model, the buyer benefits from contingent sourcing only if c_R is sufficiently large relative to c_U. For the case with a powerful supplier R offering screening contracts, a small c_U will enable supplier U to sell a large enough Q_U resulting in no emergency trade for $s = G$. Consequently, all the value from contingent sourcing will be extracted by supplier R and the buyer will not benefit from contingent sourcing. Our numerical results confirmed the above reasoning. We find that the buyer will not be able to gain from contingent sourcing even for sufficiently large c_R. Therefore, buying firms in practice should be even more cautious about contingent sourcing if the contingent option is provided by a powerful supplier offering nonlinear, take-it-or-leave-it contracts.[16]

6. Conclusion

Our work explores the impact of contingent sourcing on a buyer sourcing from two competing suppliers for a single selling season. One supplier has a long lead time and is prone to yield loss during transportation. The other supplier is near (has a shorter lead time) and is not prone to yield loss. The usefulness of contingent sourcing relies on updated shipment (i.e., yield) information being available to the buyer at the time of the contingent decision. Our results establish that a feasible contingent sourcing option has a twofold effect. On the one hand it provides an operational advantage, enabling the buyer to respond to a potential yield loss. On the other hand it can soften

[16] These results are based on the assumption that the buyer is not allowed to revise Q_R after receiving the emergency contract offer. If the buyer is allowed to revise Q_R at Time 1, then it will re-optimize Q_R and Q_E based on the emergency contract menu and the regular wholesale price w_R. In anticipation of the buyer's re-optimization, supplier R has to, in effect, determine all the contract terms at Time 0. However, when competing with supplier U at Time 0, it may not have the power to offer nonlinear screening contracts. For example, the buyer may require the two competing suppliers to bid with price-only contracts. If that is the case, then the problem will reduce to our base model, in which case the buyer may or may not benefit from contingent sourcing.

the price competition between suppliers and result in higher wholesale prices for the buyer. Driven by these two opposing forces, the buyer may be better off or worse off with contingent sourcing. Furthermore, the buyer may not benefit from operational improvements (such as superior inspection technology, continuous monitoring, or a shorter contingent lead time) that enhance shipment information accuracy because they can soften supplier competition. To mitigate this downside of contingent sourcing and enhanced information, the buyer should ensure that the unreliable supplier is sufficiently cost-efficient relative to the reliable supplier. A corrective-action capability can also enable the buyer to better realize the value of enhanced shipment information. Although the buyer benefits if the unreliable supplier can improve its reliability, the supplier itself may not benefit.

There are a number of possible directions for further research. First, transportation service providers (TSPs), Maersk and Fedex for example, are investing in sophisticated IoT-based technologies to monitor en-route shipment conditions to better serve their customers' transportation-information needs. To focus on the buying firm's supplier sourcing strategies, we did not model the role of TSPs in providing monitoring services or the potential effect of TSP competition when buyers or suppliers choose transportation modes. Exploring the role of TSPs (and competition between TSPs) in providing enhanced shipment information and examining how they can monetize such investments could be promising directions for future research. Second, shipment information in our paper is modeled as a binary signal. Although we showed that this approach can capture quite-general damage and inspection settings, it cannot reflect all settings; for example, accumulation of adverse events leading to damage. Examining an information structure with more than two signal realizations would be of interest, as would allowing for a time-varying contingent price. However, such considerations might be best studied in a simplified dyadic supplier-buyer setting due to the anticipated tractability challenges in our competition model. Third, we have assumed an all-or-nothing random yield throughout the paper, as is common in the yield risk literature with supplier competition. For more general yield losses that are proportional to an order quantity, the buyer may over-order from supplier U to mitigate yield risks. This additional sourcing strategy will render the current model intractable. A future research direction is to develop a tractable model that incorporates general yield risks when suppliers compete. Finally, our findings indicate that enhanced shipment information may not necessarily benefit all supply chain members under wholesale price contracts. It is an important open question whether there exist more sophisticated coordination contracts that can make all supply chain members benefit from enhanced shipment information.

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Online Appendices to "Forewarned Is Forearmed? Contingent Sourcing, Shipment Information and Supplier Competition"

Appendix A: Supplementary Results for the Case of Perfect Shipment Information

PROPOSITION A.1. *With perfect shipment information ($\rho = 1$), given any $w_U \le m$ and $w_R \le w_E \le m$, the buyer's optimal order quantities are characterized by one of the following cases.*

(i) If $P_1 w_U + P_0 w_E \le w_R$, then $Q_U^* = \frac{m - w_U}{2}$, and $Q_R^* = 0$, $Q_E^* = \frac{m - w_E}{2}$.

(ii) If $w_U < w_R < P_1 w_U + P_0 w_E$, then $Q_U^* = \frac{w_R - w_U}{2P_0}$ and $Q_R^* = \frac{P_0 m - w_R + P_1 w_U}{2P_0}$, $Q_E^* = 0$.

(iii) If $w_R \le w_U$, then $Q_U^* = Q_E^* = 0$ and $Q_R^* = (m - w_R)/2$.

The buyer's optimal sourcing strategies are illustrated in Figure A.1

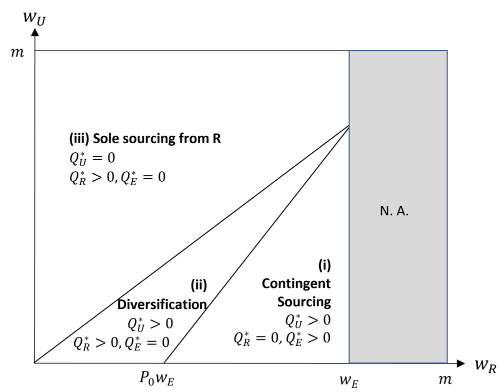

Figure A.1 **Structure of the buyer's optimal order quantities with** $\rho = 1$

LEMMA A.1. *With $\rho = 1$, for any given w_U, supplier R's best response is given as follows.*

(i) If $w_U > (m + c_R)/2$, then obtain all the buyer's order at time 1 with $w_R^* = (m + c_R)/2$ and any $w_E^* \ge w_R^*$.

(ii) If $(P_0 m + c_R)/(P_0 + 1) < w_U \le (m + c_R)/2$, then obtain all the buyer's order at time 1 with $w_R^* = w_U$ and any $w_E^* \ge w_R^*$.

(iii) If $c_R < w_U \le (P_0 m + c_R)/(P_0 + 1)$, then obtain a part of the buyer's order at time 1 with $w_R^* = (P_1 w_U + P_0 m + c_R)/2$ and any $w_E^* > (w_R^* - P_1 w_U)/P_0$.

(iv) If $w_U \le c_R$, then obtain the buyer's emergency order only with $w_E^* = (m + c_R)/2$ and any $w_R^* \ge P_0 w_E^* + P_1 w_U$.

LEMMA A.2. *With $\rho = 1$, for any given $w_R \le w_E$, supplier U's best response is given as follows.*

(i) If $w_R > P_0 w_E + (P_1 m + c_U)/2$, then $w_U^* = (P_1 m + c_U)/(2P_1)$.

(ii) If $(2P_0 w_E + c_U)/(P_0 + 1) < w_R \le P_0 w_E + (P_1 m + c_U)/2$, then $w_U^* = (w_R - P_0 w_E)/P_1$.

(iii) If $c_U/P_1 < w_R \le (2P_0 w_E + c_U)/(P_0 + 1)$, then $w_U^* = (P_1 w_R + c_U)/(2P_1)$.

(iv) If $w_R \le c_U/P_1$, then $w_U^* = c_U/P_1$.

Appendix B: Supplementary Results for the Case of Imperfect Shipment Information

B.1. Supplier R's Best Response

LEMMA B.1. *Given any w_U, supplier R's optimal wholesale prices are given by one of the following cases.*

(i) If $w_U > \frac{m+c_R}{2}$, *then* $w_R^* = (m+c_R)/2$ *and any* $w_E^* \geq w_R^*$;

(ii) if $\frac{P_0 m + c_R}{P_0+1} < w_U \leq \frac{m+c_R}{2}$, *then* $w_R^* = w_U$ *and any* $w_E^* \geq w_R^*$;

(iii) if $c_R < w_U \leq \frac{P_0 m + c_R}{P_0+1}$, *then* $w_R^* = \frac{P_0 m + P_1 w_U + c_R}{2}$ *and any* $w_E^* \geq (w_R^* - P_1 w_U)/P_0$;

(iv) if $(P_G c_R - (P_0 - P_B)m)/P_1 < w_U \leq c_R$, *then* $w_R^* = \frac{P_0 m + P_1 w_U + c_R}{2}$ *and* $w_E^* = \frac{m+c_R}{2}$;

(v) if $w_U \leq (P_G c_R - (P_0 - P_B)m)/P_1$, *then* $w_E^* = \frac{m+c_R}{2}$ *and any* $w_R^* \geq P_B w_E^* + P_1 w_U + P_G P_{0G} m$.

B.2. Supplier U's Best Response

LEMMA B.2. *Let* $A1 = P_B w_E + P_G P_{0G} m + P_1 m/2$, $A2 := \frac{(2P_0 - P_B P_{1G}) w_E}{1+P_{0G}}$, $B2 = P_B w_E + \frac{2 P_G P_{0G} m}{1+P_{0G}}$, $B3 = \frac{2 P_0 w_E}{1+P_0}$, $T_0 = \frac{2mP_0(1+P_0) - 4P_0 P_B (m - w_E) - 2(1-P_0)\sqrt{P_0 P_B (m-w_E)(m + mP_0 - P_B(m - w_E))}}{(1+P_0)^2}$ *and* $T_1 = P_B w_E / \left(1 - \sqrt{\frac{P_G(P_0 - P_B)}{P_0}}\right)$. *Given any* $w_R \leq w_E \leq m$ *and assuming* $c_U = 0$, *supplier U's optimal price is given by one of the following cases.*

(i) For $w_R > A1$, $w_U^* = m/2$.

(ii) For $\max(B2, B3) < w_R \leq A1$, $w_U^* = (w_R - P_B w_E - P_G P_{0G} m)/P_1$.

(iii) For $B2 < w_R \leq \max(B2, B3)$, $w_U^* = (w_R - P_B w_E - P_G P_{0G} m)/P_1$ *if* $w_R > T_b$; $w_U^* = \frac{w_R}{2}$ *if* $w_R \leq T_0$.

(iv) For $\min(B2, B3) < w_R \leq B2$, $w_U^* = \frac{P_{1G}(w_R - P_B w_E)}{2P_1}$.

(v) For $A2 < w_R \leq \min(B2, B3)$, $w_U^* = \frac{P_{1G}(w_R - P_B w_E)}{2P_1}$ *if* $w_R > P_B w_E / \left(1 - \sqrt{\frac{P_G(P_0 - P_B)}{P_0}}\right)$; $w_U^* = w_R/2$ *otherwise.*

(vi) For $w_R \leq A2$, $w_U^* = w_R/2$.

B.3. Example: Nonexistence of (Pure-Strategy) Nash Equilibrium

Consider a specific set of parameters: $m = 10$, $c_U = 0$, $c_R = 1$, $P_1 = 0.7$, $\rho = 0.5$. Figure B.1 shows that the two best response functions have no intersection because supplier U's optimal price is discontinuous in w_R. Note that given these parameter values, case (v) of Lemma B.2 never occurs such that $w_R^*(w_U)$ is always a unique value for any given w_U.

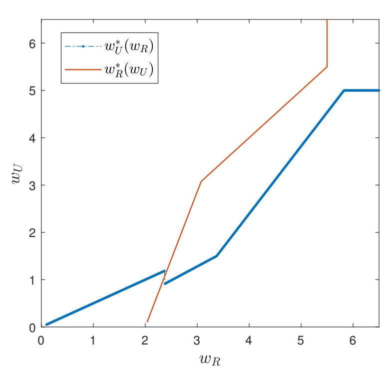

Figure B.1 **Example of no pure-strategy Nash equilibrium where** $w_E^* = (m + c_R)/2$

B.4. Supplementary Numerical Results: Imperfect Shipment Information with $c_U > 0$

In §4.4, we characterized the equilibrium solution in closed form for $c_U = 0$. We have numerically verified that the main insights remain to hold for $c_U > 0$. When searching for equilibrium wholesale prices, we employed a best-response dynamic procedure similar to Algorithm S.6.2 as described in Appendix S.7. In Figure B.2, we report a set of instances when $c_U = 1$ and c_R is varied from 3 to 7. The main observations on the effects of ρ are the same as presented in Figure 7 in the main paper.

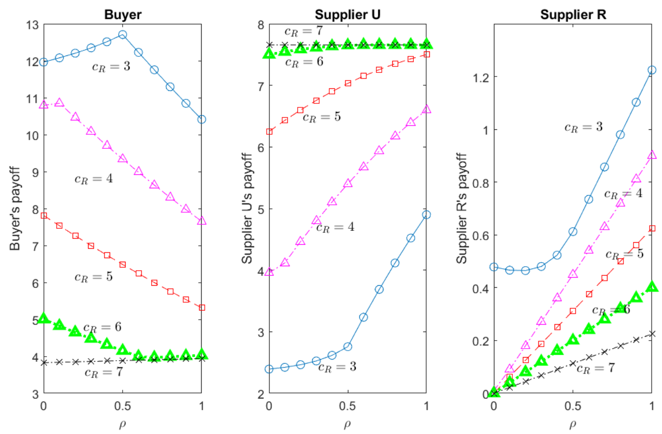

Figure B.2 **Impact of shipment information accuracy ρ [$m = 10$, $c_U = 1$, $P_1 = 0.8$]**

Appendix C: Proofs

C.1. Proofs of Results in the Main Paper

Proof of Lemma 1 We first provide the general optimality conditions for the buyer's problem, and then prove the lemma. Because of the concavity of $R(x)$, problem (2) is a concave maximization as concavity is preserved under (1) expectation and (2) affine composition [that is, $R(a_1Q_U + a_2Q_R + a_3Q_E(B) + a_4Q_E(G))$ is jointly concave in $(Q_U, Q_R, Q_E(B), Q_E(G))$ for any real vector (a_1, a_2, a_3, a_4)]. Thus, it suffices to analyze the KKT conditions as given below.

$$\frac{\partial L}{\partial Q_U} = \sum_{s\in\{B,G\}} P_s P_{1s} R'(Q_U + Q_R + Q_E(s)) - P_1 w_U + \lambda_U = 0 \tag{C.1}$$

$$\frac{\partial L}{\partial Q_R} = \sum_{s\in\{B,G\}} P_s \left(P_{0s} R'(Q_R + Q_E(s)) + P_{1s} R'(Q_U + Q_R + Q_E(s))\right) - w_R + \lambda_R = 0 \tag{C.2}$$

$$\frac{\partial L}{\partial Q_E(s)} = P_s \left(P_{0s} R'(Q_R + Q_E(s)) + P_{1s} R'(Q_U + Q_R + Q_E(s)) - w_E\right) + \lambda_E(s) = 0 \quad \forall s \in \{B,G\} \tag{C.3}$$

$$\lambda_R Q_R = 0,\ \lambda_U Q_U = 0,\ \lambda_E(s) Q_E(s) = 0\, \forall s \in \{B,G\} \tag{C.4}$$

where λ_R, λ_U, $\lambda_E(s) \geq 0$ represent the Lagrangian multipliers associated with Q_R, Q_U, $Q_E(s) \geq 0$ for all $s \in \{B,G\}$, respectively. As $R(Q) = \max_{q\leq Q}(m-q)q$, we have $R(Q) = \begin{cases} (m-Q)Q \text{ if } Q \leq m/2, \\ m^2/4 \text{ if } Q > m/2. \end{cases}$ Hence, $R'(Q) = \begin{cases} m - 2Q \text{ if } Q \leq m/2, \\ 0 \text{ if } Q > m/2. \end{cases}$

We prove the lemma by contradiction. First, suppose $Q_E^*(s) > 0$ for both $s = G, B$. Then, with a small positive number δ, a new solution with $Q_E^*(s) - \delta$ and $Q_R^* + \delta$ will (weakly) improve the buyer's payoff as $w_R \le w_E$. Thus, at least one of $Q_E^*(B)$ and $Q_E^*(G)$ must be zero. Suppose $Q_E^*(G) > 0$ and $Q_E^*(B) = 0$. By the KKT condition (C.3) of the buyer's problem, it follows that $\lambda_E^*(G) = 0$ and

$$P_G\left(P_{0G}R'(Q_R^* + Q_E^*(G)) + P_{1G}R'(Q_U^* + Q_R^* + Q_E^*(G)) - w_E\right) = 0, \tag{C.5}$$

and

$$P_B\left(P_{0B}R'(Q_R^*) + P_{1B}R'(Q_U^* + Q_R^*) - w_E\right) = -\lambda_E(B) \le 0 \tag{C.6}$$

As long as $P_G, P_B > 0$, (C.5) above implies that

$$\begin{aligned} w_E &= P_{0G}R'(Q_R^* + Q_E^*(G)) + P_{1G}R'(Q_U^* + Q_R^* + Q_E^*(G)) \\ &< P_{0G}R'(Q_R^*) + P_{1G}R'(Q_U^* + Q_R^*) \le P_{0B}R'(Q_R^*) + P_{1B}R'(Q_U^* + Q_R^*). \end{aligned}$$

which contradicts (C.6). In the above, the first inequality follows by the concavity of R. (Note that the strict inequality holds since R' is strictly decreasing whenever it is positive; moreover, $R'(Q_R^*)$ and $R'(Q_U^* + Q_R^*)$ cannot be both zero as otherwise (C.5) cannot hold for a positive w_E.) The second inequality follows as $R'(Q_R^*) \ge R'(Q_U^* + Q_R^*) \ge 0$ and $P_{0B} \ge P_{0G}$ and $P_{0s} = 1 - P_{1s}$ for all $s = \{G, B\}$. $\square$

Proof of Proposition 1 Lemma 1 holds generally for imperfect shipment information. So, we have $Q_E(G)^* = 0$ in the optimal solution to Problem (2). Together with the fact that $P_{0B} = 1$ and $P_{1B} = 0$ and $P_G P_{1G} = P_1$, the KKT conditions are given below.

$$\frac{\partial L}{\partial Q_U} = P_1 R'(Q_U + Q_R) - P_1 w_U + \lambda_U = 0 \tag{C.7}$$

$$\frac{\partial L}{\partial Q_R} = P_B R'(Q_R + Q_E(B)) + P_G P_{0G} R'(Q_R) + P_1 R'(Q_U + Q_R) - w_R + \lambda_R = 0 \tag{C.8}$$

$$\frac{\partial L}{\partial Q_E(B)} = P_B\left(R'(Q_R + Q_E(B)) - w_E\right) + \lambda_E(s) = 0 \tag{C.9}$$

$$\lambda_R Q_R = 0,\ \lambda_U Q_U = 0,\ \lambda_E(B) Q_E(B) = 0. \tag{C.10}$$

In what follows, we verify that the optimal solution given in the proposition satisfy the KKT conditions from case (iv) to case (i).

Case (iv). As $Q_R^* > 0$ and $Q_U^* = Q_E^*(B) = 0$, condition (C.8) implies $R'(Q_R^*) = w_R$, while conditions (C.7) and (C.9) imply $R'(Q_R^*) \le w_U$ and $R'(Q_R^*) \le w_E$, respectively. These conditions are satisfied if and only if $w_R \le w_U$. Invoking that $R'(Q) = (m - 2Q)^+$, we have $R'(Q_R^*) = w_R$ imply $Q_R^* = \frac{m - w_R}{2}$.

Case (iii). If $Q_U^* > 0$, $Q_R^* > 0$ and $Q_E^* = 0$, the KKT conditions imply $R'(Q_U^* + Q_R^*) = w_U$, $(P_B + P_G P_{0G})R'(Q_R^*) + P_1 R'(Q_U^* + Q_R^*) = w_R$ and $R'(Q_R^*) \le w_E$. Note that $P_B + P_G P_{0G} = P_0$. Substituting the equality conditions above and rearranging the terms, we can see $R'(Q_R^*) \le w_E$ holds iff $w_R \le P_0 w_E + P_1 w_U$. On the other hand, $w_U < w_R$ ensures that the first two conditions hold for a positive Q_R^* because $w_R = P_0 R'(Q_R^*) + P_1 R'(Q_U^* + Q_R^*) \ge R'(Q_U^* + Q_R^*) = w_U$ where the inequality follows since $R'(Q)$ is nonincreasing.

By $R'(Q) = (m - 2Q)^+$, $R'(Q_U^* + Q_R^*) = w_U$ implies $Q_U^* + Q_R^* = \frac{m - w_U}{2}$, and then $P_0 R'(Q_R^*) + P_1 R'(Q_U^* + Q_R^*) = w_R$ implies $Q_R^* = \frac{P_0 m - w_R + P_1 w_U}{2P_0}$.

Case (ii). If all quantities are positive, we have $R'(Q_U^* + Q_R^*) = w_U$, $P_B R'(Q_R^* + Q_E^*) + P_G P_{0G} R'(Q_R^*) + P_1 R'(Q_U^* + Q_R^*) = w_R$ and $R'(Q_R^* + Q_E^*) = w_E$. Note that as w_U and w_R are nonnegative, with $R'(Q) = (m - 2Q)^+$, neither $Q_U^* + Q_R^*$ or $Q_R^* + Q_E^*$ can exceed $m/2$. That is, the buyer never needs to hold back some amount of the available-to-sell quantity. Thus, we can simply use $R'(Q) = (m - 2Q)$ when solving the system of equations, which leads to the expressions of Q_R^*, Q_E^* and Q_U^* given in the proposition.

Case (i) If $Q_U^* > 0$, $Q_R^* = 0$ and $Q_E^* > 0$, the KKT conditions are reduced to $R'(Q_U^*) = w_U$, $P_B R'(Q_E^*) + P_G P_{0G} m + P_1 R'(Q_U^*) \le w_R$ and $R'(Q_E^*) = w_E$. From the first and the third conditions, the expressions of Q_U^* and Q_E^* follow immediately. Substituting the first and the third conditions into the second, we have the inequality condition specified in Case (iv).

□

Proof of Proposition 2 A set of wholesale prices (w_U^I, w_R^I, w_E^I) constitutes a Nash equilibrium if (1) given w_U^I, w_R^I and w_E^I satisfy one of the cases in Lemma A.1 and (2) given w_R^I and w_E^I, w_U^I satisfies one of the cases in Lemma A.2.

We will first find the equilibrium under which supplier R serves for the emergency order, and then show that whenever such an equilibrium exists, it is also unique (i.e., there is no other equilibrium in which the supplier chooses not to serve for the emergency order).

To begin, note that by the best response of supplier R, i.e., Lemma A.1, when an emergency ordering equilibrium exists, we must have $w_E^I = (m + c_R)/2$. When $w_E = (m + c_R)/2$ is given, the best responses of the two suppliers can be depicted in Figure C.1.

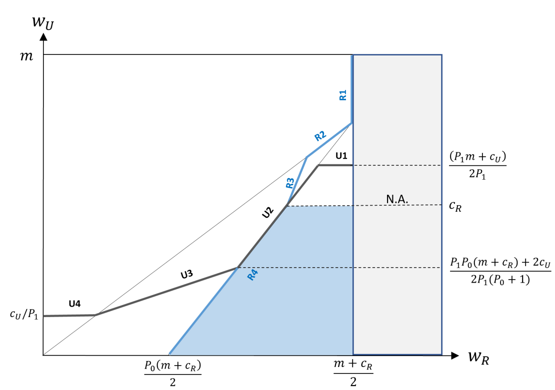

Figure C.1 Illustration of Best Response Functions with $w_E = (m + c_R)/2$

In the figure, supplier R's best response $w_R^*(w_U)$ consists of four parts denoted by R1, R2, R3, and R4, which corresponds to the four parts of Lemma A.1. Their algebraic expressions are given below:

R1: $w_R = (m + c_R)/2$; R2: $w_R = w_U$; R3: $w_R = (P_1 w_U + P_0 m + c_R)/2$; R4: $w_R \ge P_0(m + c_R)/2 + P_1 w_U$ (where $w_U \le c_R$).

Note that R4 corresponds to the case where supplier R opts for the emergency order with price $w_E = (m + c_R)/2$; in this case, any $w_R \ge P_0(m + c_R)/2 + P_1 w_U$ is optimal and so the best response R4 is represented by a shaded area.

In the figure, supplier U's best response $w_U^*(w_R)$ consists of four parts denoted by U1, U2, U3, and U4, with algebraic expressions as follows.

U1: $w_U = (P_1 m + c_U)/(2P_1)$; U2: $w_U = (w_R - P_0(m + c_R)/2)/P_1$; U3: $w_U = (P_1 w_R + c_U)/(2P_1)$; U4: $w_U = c_U/P_1$.

Also, note that the relative positions of the best response curves in Figure C.1 depend on the specific parameter values. To characterize all the possible equilibria in which supplier R serves for the emergency order, we need to find all possible intersections of the two best responses occurring in area R4.

By some straightforward algebra, we can show that U2 and U3 intersects at $w_U = \frac{P_1 P_0(m+c_R)+2c_U}{2P_1(P_0+1)}$. It follows that the two best responses intersect within area R4 iff $c_R \geq \frac{P_1 P_0(m+c_R)+2c_U}{2P_1(P_0+1)}$, or equivalently, $c_R \geq \frac{P_1 P_0 m+2c_U}{P_1 P_0+2P_1}$. This corresponds to the condition for Part (i) of Proposition 2. There are two different cases in which the intersection occurs in R4. First, R4 intersects with both U1 and U2 iff $c_R \geq (P_1 m + c_U)/(2P_1)$. In this case, we have a continuum of Nash equilibira: any $w_U \in [\frac{P_1 P_0(m+c_R)+2c_U}{2P_1(P_0+1)}, \frac{P_1 m+c_U}{2P_1}]$, along with $w_R = P_0(m + c_R)/2 + P_1 w_U$ and $w_E = (m + c_R)/2$, can constitute a Nash equilibrium. Under those equilibria, supplier R's payoff is the same, while supplier U's payoff is the maximum when $w_U^I = \frac{P_1 m+c_U}{2P_1}$, $w_E^I = (m + c_R)/2$ and any $w_R^I \geq P_0 w_E^I + P_1 w_U^I$. In other words, this set of equilibria Pareto dominates the other equilibria and so we select it as the unique equilibrium. This corresponds to Equilibrium (i-a) of Proposition 2. Second, R4 intersects with only U2 iff $\frac{P_1 P_0 m+2c_U}{P_1 P_0+2P_1} \leq c_R < (P_1 m + c_U)/(2P_1)$. Similar to the previous case, there is a continuum of equilibria with $w_U \in [\frac{P_1 P_0(m+c_R)+2c_U}{2P_1(P_0+1)}, c_R]$. We therefore select the unique Pareto dominant equilibrium in which $w_U^I = c_R$ and $w_E^I = (m + c_R)/2$ and $w_R^I = P_0 w_E^I + P_1 w_U^I$. This corresponds to Equilibrium (i-b) of Proposition 2.

To complete the proof of Part (i) of Proposition 2, we also need to show that if supplier U's best response intersects with R4 (i.e., $c_R \geq \frac{P_0 m+2c_U/P_1}{P_0+2}$) given $w_E = (m + c_R)/2$, there will be no other equilibrium in which supplier R does not serve for the emergency order when w_E can be varied (so the emergency ordering equilibrium characterized above is unique). Suppose that a no-emergency-ordering equilibrium exists, denoted by $(\hat{w}_U^I, \hat{w}_R^I, \hat{w}_E^I)$. Then, it must be supported by one of cases (i), (ii) and case (iii) in Lemma A.1. In what follows, we prove by contradiction none of these cases can support a Nash equilibrium given $c_R \geq \frac{P_0 m+2c_U/P_1}{P_0+2}$.

Suppose that it occurs when case (i) or case (ii) of Lemma A.1 holds; that is, in that equilibrium supplier R is exclusively used by the buyer for the first order. By Lemma A.1, this requires $\hat{w}_U^I > \frac{P_0 m+c_R}{P_0+1} \geq c_R$. On the other hand, to constitute a Nash equilibrium, supplier U's optimal wholesale price must fall into case (iv) of Lemma A.2 which requires $\hat{w}_U^I = c_U/P_1$. Notice that the condition for the emergency ordering equilibrium to exist, $c_R \geq \frac{P_0 m+2c_U/P_1}{P_0+2}$, implies that $c_R > c_U/P_1 = \hat{w}_U^I$ because $m > c_U/P_1$. This leads to a contradiction. So, a no-emergency ordering equilibrium, if exists, must be supported by case (iii) of Lemma A.1, which requires

$$\hat{w}_R^I = (P_1 \hat{w}_U^I + P_0 m + c_R)/2. \tag{C.11}$$

This further implies that in such an equilibrium, suppliers R and U must share the buyer's first order. To constitute a Nash equilibrium, supplier U's optimal wholesale price must fall into case (iii) of Lemma A.2 which requires

$$\hat{w}_U^I = \frac{P_1 \hat{w}_R^I + c_U}{2P_1}. \tag{C.12}$$

Solving the system of equations (C.11) and (C.12) yields $\hat{w}_U^I = \frac{P_0 m + c_R + 2c_U/P_1}{3+P_0}$ and $\hat{w}_R^I = \frac{2P_0 m + 2c_R + c_U}{3+P_0}$. The above point can be an equilibrium only if $\hat{w}_U^I \frac{P_0 m + c_R + 2c_U/P_1}{3+P_0} > c_R$ by Lemma A.1(iii); otherwise, supplier R would deviate to case (iv) serving for the emergency order. It follows that $\frac{P_0 m + c_R + 2c_U/P_1}{3+P_0} > c_R$ iff $c_R < \frac{P_0 m + 2c_U/P_1}{P_0+2}$, which contradicts with the condition $c_R \geq \frac{P_0 m + 2c_U/P_1}{P_0+2}$. As a result, part (i) of the proposition is proved.

Now we move on to find the no-emergency-ordering equilibrium under the case of $c_R < \frac{P_0 m + 2c_U/P_1}{P_0+2}$. The first possible type of equilibrium is such that the buyer uses both suppliers at time 0. Such an equilibrium is supported only when the optimal prices satisfy Lemma A.1(iii) and Lemma A.2(iii), which leads to the price pair $w_U^I = \frac{P_0 m + c_R + 2c_U/P_1}{3+P_0}$ and $w_R^I = \frac{2P_0 m + 2c_R + c_U}{3+P_0}$ as we found earlier. Additionally, Lemma A.1(iii) requires $c_R < w_U^I \leq \frac{P_0 m + c_R}{P_0+1}$, or equivalently, $\frac{P_0+1}{P_1} c_U - P_0 m \leq c_R \frac{P_0 m + 2c_U/P_1}{P_0+2}$. Along with any $w_E^I > (w_R^I - P_1 w_U^I)/P_0$, these wholesale prices constitute an equilibrium as described in part (ii) of Proposition 2. Graphically, this equilibrium corresponds to the intersection of R3 and U3 in Figure C.1 (and the intersection exists iff c_R lies in the interval characterized above).

The remaining type of equilibrium is one in which the buyer exclusively uses supplier R at time 0. This type of equilibrium is supported iff case (iv) of Lemma A.1, along with either case (i) of Lemma A.1 or case (ii) of Lemma A.1, holds. When Lemma A.2(iv) and Lemma A.1(ii) hold, we have Equilibrium (iii-a) of Proposition 2, graphically corresponding to the intersection of U4 and R2. When Lemma A.2(iv) and Lemma A.1(i) hold, we have Equilibrium (iii-b), graphically corresponding to the intersection of U4 and R1. □

Proof of Proposition 3 The proof is omitted, as it is analogous to that of Proposition 2 and much simpler since supplier R has only one decision variable w_R. Moreover, the proposition can also be derived from theorem 1 and corollary 1 of Shan et al. (2022) by treating their Supplier 1 (2) as our supplier U (R) and letting their Supplier 1's production cost c_1 to be c_U/P_1 (since in their model the supplier does not incur any production cost in case of a disruption). □

Proof of Corollary 1 It follows by comparing Equilibrium (i) in Propositions 2 and 3. □

Proof of Proposition 4 By Propositions 2 and 3, the buyer's expected profits π_B^I and π_B^N are piecewise, depending on which type of equilibrium occurs; the specific breakpoints are given in Propositions 2 and 3.

Note that $\frac{2P_0 m + c_U}{P_0+1} < \frac{m + c_U/P_1}{2}$ iff $P_0 < 1/3$. Assuming $P_0 < 1/3$, we have $\frac{P_0 m + 2c_U/P_1}{P_0+2} < \frac{2P_0 m + c_U}{P_0+1} < \frac{m + c_U/P_1}{2} < \frac{(1+P_0)m + c_U}{2}$, which partition the domain of c_R into four parts. Each part is associated with a different combination of equilibria under the two scenarios. Hence, we need to examine four subcases. In the following, we will present the proof for $P_0 < 1/3$. For $P_0 \geq 1/3$, we will have a slightly different ordering of the equilibrium breakpoints and we will briefly discuss the case of $P_0 \geq 1/3$ at the end of the proof.

Case 1. If $c_R > \frac{(1+P_0)m + c_U}{2}$, then Equilibrium (i-a) plays out in both scenarios. So, the buyer sources from supplier U at the same price $w_U^I = w_U^N = (m + c_U/P_1)/2$. However, with shipment information, the buyer is able to purchase from supplier R at $w_E^R = (m + c_R)/2$. Thus, $\pi_B^{N(ia)} \leq \pi_B^{I(ia)}$. In the proof, we use superscripts to indicate which type of equilibrium occurs in which scenario. For instance, superscript "N(ia)" denotes Equilibrium (i-a) under Scenario N, i.e., the equilibrium stated in case (i-a) of Proposition 3.

Case 2. If $\frac{m+c_U/P_1}{2} < c_R \leq \frac{(1+P_0)m+c_U}{2}$, then Equilibrium (i-b) plays out under scenario N whereas Equilibrium (i-a) plays out under scenario I. We have

$$\pi_B^{I(ia)} - \pi_B^{N(ib)} = \frac{-\left(P_1^2 - P_1 + 4\right)c_R^2 + 2m\left(P_1^2 - P_1 + 4\right)c_R - 2mP_1c_U + c_U^2 - m^2\left(4 - P_1\right)}{16P_1},$$

which is increasing in c_R within the domain of $c_R \leq m$. From the above expression, we have $\pi_B^{I(ia)} - \pi_B^{N(ib)} > 0$ iff $c_R > m - \frac{P_1 m - c_U}{\sqrt{P_1^2 - P_1 + 4}}$. Furthermore, note that

$$\left(\frac{m + c_U/P_1}{2}\right) - \left(m - \frac{P_1 m - c_U}{\sqrt{P_1^2 - P_1 + 4}}\right) = \frac{\left(2P_1 - \sqrt{P_1^2 - P_1 + 4}\right)\left(mP_1 - c_U\right)}{2P_1\sqrt{P_1^2 - P_1 + 4}} \leq 0$$

where the last inequality follows as $m > c_U/P_1$ and $2P_1 \leq \sqrt{P_1^2 - P_1 + 4}$ for all $P_1 \in [0,1]$, and that

$$\left(m - \frac{P_1 m - c_U}{\sqrt{P_1^2 - P_1 + 4}}\right) - \left(\frac{(1+P_0)m + c_U}{2}\right) = -\frac{\left(2 - \sqrt{P_1^2 - P_1 + 4}\right)\left(mP_1 - c_U\right)}{2\sqrt{P_1^2 - P_1 + 4}} \leq 0$$

where the last inequality follows as $m > c_U/P_1$ and $2 \geq \sqrt{P_1^2 - P_1 + 4}$ for all $P_1 \in [0,1]$, Hence, as c_R increases within the interval $(\frac{m+c_U/P_1}{2}, \frac{(1+P_0)m+c_U}{2}]$, $\pi_B^{I(ia)} - \pi_B^{N(ib)}$ changes its sign from negative to positive once at the threshold $c_R = m - \frac{P_1 m - c_U}{\sqrt{P_1^2 - P_1 + 4}}$.

Case 3. If $\frac{2P_0 m + c_U}{P_0 + 1} < c_R \leq \frac{m + c_U/P_1}{2}$, then Equilibrium (i-b) plays out in both scenarios. We therefore need to evaluate $\pi_B^{I(ib)} - \pi_B^{N(ib)}$. By the continuity of the profit functions and the above analysis, we have $\pi_B^{I(ib)} - \pi_B^{N(ib)} \leq 0$ at $c_R = \frac{m+c_U/P_1}{2}$. Moreover, at the other boundary point $c_R = \frac{2P_0 m + c_U}{P_0+1}$, we have $\pi_B^{I(ib)} - \pi_B^{N(ib)} = \frac{\left(3P_1^2 + P_1 - 4\right)\left(P_1 m - c_U\right)^2}{16(P_0+1)^2 P_1} \leq 0$ as $3P_1^2 + P_1 \leq 4$ for $P_1 \in [0,1]$. Additionally, taking the derivative of $\pi_B^{I(ib)} - \pi_B^{N(ib)}$ with respect to c_R yields

$$\frac{\partial \pi_B^{I(ib)} - \pi_B^{N(ib)}}{\partial c_R} = -\frac{\left(3P_1^2 + P_1 - 4\right)\left(m - c_R\right)}{8P_1} \geq 0$$

as $3P_1^2 + P_1 \leq 4$ and $m > c_R$. So, $\pi_B^{I(ib)} - \pi_B^{N(ib)}$ is monotone in c_R. Together with the fact that $\pi_B^{I(ib)} - \pi_B^{N(ib)} \leq 0$ at two boundary points, it follows that $\pi_B^{I(ib)} \leq \pi_B^{N(ib)}$ for all $c_R \in (\frac{2P_0 m + c_U}{P_0+1}, \frac{m + c_U/P_1}{2}]$.

Case 4. If $\frac{P_0 m + 2c_U/P_1}{P_0+2} < c_R \leq \frac{2P_0 m + c_U}{P_0+1}$, then Equilibrium (ii) plays out under scenario N whereas Equilibrium (i-b) plays out under Scenario I. First, note that as $c_R \to \frac{P_0 m + 2c_U/P_1}{P_0+2}$, we have $\pi_B^{I(ib)} - \pi_B^{N(ii)} \to 0$ by the continuity of π_B^I. (At $c_R = \to \frac{P_0 m + 2c_U/P_1}{P_0+2}$, the equilibrium under Scenario I converges to that under Scenario N.) In what follows, we prove that $\pi_B^{I(ib)} - \pi_B^{N(ii)}$ is decreasing in c_R, which will then imply $\pi_B^{I(ib)} \leq \pi_B^{N(ii)}$ for all $c_R \in (\frac{P_0 m + 2c_U/P_1}{P_0+2}, \frac{2P_0 m + c_U}{P_0+1}]$. Taking the derivative with respect to c_R and simplifying the terms, we have

$$\frac{\partial \pi_B^{I(ib)} - \pi_B^{N(ii)}}{\partial c_R} = \frac{P_1\left(4c_U - \left(3P_1^3 - 26P_1^2 + 63P_1 - 36\right)c_R + m\left(3P_1^3 - 26P_1^2 + 59P_1 - 36\right)\right)}{8\left(4 - P_1\right)^2\left(1 - P_1\right)}. \tag{C.13}$$

In (C.13), the denominator is positive. The numerator can be rewritten as $P_1\left[4(c_U - P_1 c_R) + f(P_1)(c_R - m)\right]$. where we define $f(p) = 36 - 59p + 26p^2 - 3p^3$. The first term $4(c_U - P_1 c_R)$ is negative because $c_R > \frac{P_0 m + 2c_U/P_1}{P_0+2} \geq c_U/P_1$ where the last inequality is due to $m \geq c_U/P_1$. For the second term, notice that $f'(p) = -59 + 52p - 9p^2 < 0$ for $p \in [0,1]$. So, $f(p)$ is a decreasing function. Since $c_R < m$, we have $f(P_1)(c_R - m) \leq f(1)(c_R - m) = 0$. It follows that the numerator of (C.13) is negative and so $\pi_B^{I(ib)} - \pi_B^{N(ii)}$ is decreasing in c_R. This completes the proof for the case of $P_0 < 1/3$.

If $P_0 \geq 1/3$, we will have $\frac{P_0 m+2c_U/P_1}{P_0+2} < \frac{m+c_U/P_1}{2} \leq \frac{2P_0 m+c_U}{P_0+1} < \frac{(1+P_0)m+c_U}{2}$. For $c_R > \frac{(1+P_0)m+c_U}{2}$, we have the same equilibrium outcomes as discussed above. For $\frac{2P_0 m+c_U}{P_0+1} < c_R \leq \frac{(1+P_0)m+c_U}{2}$, the profit functions to be compared are $\pi_B^{I(ia)}$ and $\pi_B^{N(ib)}$. In the proof of Case 2 above, we have shown that $\pi_B^{I(ia)} - \pi_B^{N(ib)} > 0$ iff $c_R > m - \frac{P_1 m - c_U}{\sqrt{P_1^2 - P_1 + 4}}$. Moreover,

$$\left(m - \frac{P_1 m - c_U}{\sqrt{P_1^2 - P_1 + 4}}\right) - \left(\frac{2P_0 m + c_U}{P_0 + 1}\right) = \frac{\left(\sqrt{P_1^2 - P_1 + 4} + P_1 - 2\right)(P_1 m - c_U)}{(2 - P_1)\sqrt{P_1^2 - P_1 + 4}} \geq 0$$

where the inequality follows by the fact that $\sqrt{P_1^2 - P_1 + 4} \geq 2 - P_1$ for all $P_1 \in [0,1]$. Thus, similar to the earlier analysis, $\pi_B^{I(ia)} - \pi_B^{N(ib)}$ changes its sign from negative to positive as c_R increases within the interval $[\frac{2P_0 m+c_U}{P_0+1}, \frac{(1+P_0)m+c_U}{2}]$. For $\frac{m+c_U/P_1}{2} < c_R \leq \frac{2P_0 m+c_U}{P_0+1}$, we need to compare $\pi_B^{I(ia)}$ and $\pi_B^{N(ii)}$. From the previous analysis, we know $\pi_B^{I(ib)} \leq \pi_B^{N(ii)}$. Furthermore, we have $\pi_B^{I(ia)} \leq \pi_B^{I(ib)}$ since $\pi_B^{I(ia)}$ is the buyer's profit when w_U^I is set to be the monopoly price whereas $\pi_B^{I(ib)}$ is associated with a lower w_U^I. Therefore, we can conclude $\pi_B^{I(ia)} \leq \pi_B^{N(ii)}$. Finally, for $\frac{P_0 m+2c_U/P_1}{P_0+2} < c_R \leq \frac{m+c_U/P_1}{2}$, the corresponding equilibrium profits are $\pi_B^{I(ib)}$ and $\pi_B^{N(ii)}$, and we have established $\pi_B^{I(ib)} \leq \pi_B^{N(ii)}$.

Summarizing all cases, we can conclude that $\pi_B^{I(ia)} > \pi_B^{N(ib)}$ iff c_R exceeds a unique threshold $m - \frac{P_1 m - c_U}{\sqrt{P_1^2 - P_1 + 4}}$.

Impact on Supplier U. If $c_R > \frac{(1+P_0)m+c_U}{2}$, then in both scenarios Equilibrium (i-a) plays out where supplier U sets the same wholesale price and receives the same order size, so its payoffs under the two scenarios are the same, i.e., $\pi_U^{I(ia)} = \pi_U^{N(ia)}$. For $c_R = \frac{(1+P_0)m+c_U}{2}$, the payoffs are also equal by the continuity of π_U^N. For $c_R < \frac{(1+P_0)m+c_U}{2}$, we argue that the supplier will be strictly better off with shipment information. To see this, note that under Equilibrium (i-a) of Scenario I, supplier U obtains the monopoly profit. So, $\pi_U^{I(ia)} > \pi_U^{N(ib)}$ and $\pi_U^{I(ia)} > \pi_U^{N(ii)}$. We only need to compare $\pi_U^{I(ib)}$ versus $\pi_U^{N(ib)}$ for $\frac{2P_0 m+c_U}{P_0+1} < c_R \leq \frac{m+c_U/P_1}{2}$, and $\pi_U^{I(ib)}$ versus $\pi_U^{N(ii)}$ for $\frac{P_0 m+2c_U/P_1}{P_0+2} < c_R \leq \frac{2P_0 m+c_U}{P_0+1}$.

First, for the case of $\frac{2P_0 m+c_U}{P_0+1} < c_R \leq \frac{m+c_U/P_1}{2}$, we have $\pi_U^{I(ib)} - \pi_U^{N(ib)} = \frac{(1-P_1)(m-c_R)(c_U+m-(P_1+1)c_R)}{2P_1}$ which is decreasing in c_R. At $c_R = \frac{m+c_U/P_1}{2}$, $\pi_U^{I(ib)} = \pi_U^{I(ia)}$. Thus, $\pi_U^{I(ib)} - \pi_U^{N(ib)}$ is lower bounded by $\pi_U^{I(ia)} - \pi_U^{N(ib)} > 0$, that is, $\pi_U^{I(ib)} > \pi_U^{N(ib)}$.

Second, to evaluate $\pi_U^{I(ib)} - \pi_U^{N(ii)}$ for the case of $\frac{P_0 m+2c_U/P_1}{P_0+2} < c_R \leq \frac{2P_0 m+c_U}{P_0+1}$, we notice that $\frac{\partial^2(\pi_U^{I(ib)} - \pi_U^{N(ii)})}{\partial c_R^2} = \frac{2P_1 f(P_1)}{2(4-P_1)^2(1-P_1)}$ where $f(p) = -17 + 24p - 9p^2 + p^3$. As $f'(p) = 24 - 18p + 3p^2 > 0$ for all $p \in [0,1]$, it follows that $f(P_1) \leq f(1) = -1 < 0$. Thus, $\pi_U^{I(ib)} - \pi_U^{N(ii)}$ is concave in c_R. Additionally, by continuity at boundary points, we have $\pi_U^{I(ib)} - \pi_U^{N(ii)} = 0$ at $c_R = \frac{P_0 m+2c_U/P_1}{P_0+2}$ and $\pi_U^{I(ib)} - \pi_U^{N(ii)} \geq 0$ at $c_R = \frac{2P_0 m+c_U}{P_0+1}$. Together with the concavity of $\pi_U^{I(ib)} - \pi_U^{N(ii)}$, we can conclude that $\pi_U^{I(ib)} > \pi_U^{N(ii)}$ for all $c_R \in (\frac{P_0 m+2c_U/P_1}{P_0+2}, \frac{2P_0 m+c_U}{P_0+1}]$.

Impact on Supplier R. Under scenario I, whether Equilibrium (i-a) or (i-b) occurs, supplier R's payoff is equal to $\pi_R^I = \frac{P_0(m-c_R)^2}{8}$. Under Scenario N, whenever $c_R > \frac{2P_0 m+c_U}{P_0+1}$ so that Equilibrium (i-a) or (i-b) occurs, supplier R receives zero profit, i.e., $\pi_R^{N(ia)} = \pi_R^{N(ib)} = 0$. Clearly, supplier R is better off under Scenario I. It remains to evaluate $\pi_R^I - \pi_R^{N(ii)}$ for the case of $\frac{P_0 m+2c_U/P_1}{P_0+2} < c_R \leq \frac{2P_0 m+c_U}{P_0+1}$. First, notice that $\frac{\partial^2 \pi_R^I - \pi_R^{N(ii)}}{\partial c_R^2} = \frac{P_1 f(P_1)}{4(1-P_1)(4-P_1)^2}$ where we define $f(p) = -24 + 29p - 10p^2 + p^3$. Furthermore, $f'(p) = 29 - 20p + 3p^2 > 0$ for all $p \in [0,1]$. So, $f(P_1) \leq f(1) = -4 < 0$, which implies $\pi_R^I - \pi_R^{N(ii)}$ is concave in c_R. On the other hand, by continuity, $\pi_R^I - \pi_R^{N(ii)} = 0$ at the left boundary $\frac{P_0 m+2c_U/P_1}{P_0+2}$ while $\pi_R^I - \pi_R^{N(ii)} > 0$ at the right boundary

$c_R = \frac{2P_0m+c_U}{P_0+1}$ since at the boundary point $\pi_R^{N(ii)} = \pi_R^{N(ib)} = 0$. Together with the concavity of $\pi_R^I - \pi_R^{N(ii)}$, it follows that $\pi_R^I - \pi_R^{N(ii)} > 0$ for all $c_R \in (\frac{P_0m+2c_U/P_1}{P_0+2}, \frac{2P_0m+c_U}{P_0+1}]$. $\square$

Proof of Proposition 5 First, note that Case (iii) [resp. Case (iv)] of Lemma B.2 will degenerate if $B2 > B3$ (resp. $B2 \le B3$). In fact, $B2 > B3$ iff ρ is smaller than a threshold $\hat{\rho}$ where $0 \le \hat{\rho} \le 1$. To see this, notice that $B3 = \frac{2P_0w_E}{1+P_0}$ is independent of ρ. Moreover, it is easy to verify that if $\rho = 0$, $B2 = \frac{2P_0m}{1+P_0} \ge B3$ and that if $\rho = 1$, $B2 = P_0w_E \le B3$. Then, it suffices to show $B2$ is decreasing in ρ. Recall that $P_B = P_0\rho$, $P_G = 1 - P_0\rho$ and $P_{0G} = \frac{P_0(1-\rho)}{P_1+P_0(1-\rho)}$. Invoking these relations in the expression of $B3$ and taking the second-order derivative, we have $\frac{\partial^2(B3)}{\partial\rho^2} = \frac{4m(P_0-1)^2P_0^2}{(P_0(2\rho-1)-1)^3} \le 0$ as $\rho \in [0,1]$. Hence, $\frac{\partial(B3)}{\partial\rho} \le \frac{\partial(B3)}{\partial\rho}|_{\rho=0} = \frac{P_0[(1+P_0)^2w_E - 2m(1+P_0^2)]}{(1+P_0)^2} \le -\frac{mP_0(1-P_0)^2}{(1+P_0)^2} < 0$ where the first inequality follows as $\frac{\partial^2(B3)}{\partial\rho^2} \le 0$ and the second inequality follows by $w_E \le m$.

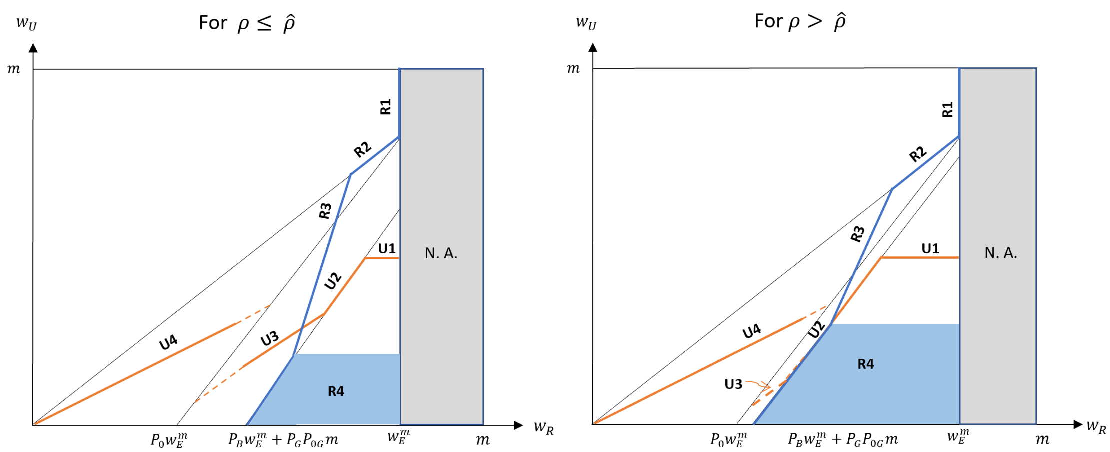

Figure C.2 **Illustration of Best Response Functions with imperfect shipment information where** $w_E^m = (m + c_R)/2$

Therefore, we can separate the analysis into two cases: $\rho < \hat{\rho}$ (i.e., $B2 > B3$) and $\rho \ge \hat{\rho}$ (i.e., $B2 \le B3$). For each case, we follow a similar geometric approach as in the proof of Proposition 2. For the two cases, the best responses of the two suppliers are illustrated in Figure C.2.

Supplier U's best response, corresponding to the line segments U1 - U4, is given by the following: U1: $w_U^* = \frac{m}{2}$; U2: $w_U^* = \frac{w_R - P_Bw_E^m - P_GP_{0G}m}{P_1}$; U3: $w_U^* = \frac{P_{1G}(w_R - P_Bw_E^m)}{2P_1}$; U4: $w_U^* = \frac{w_R}{2}$. The break points are as specified in Lemma B.2. Note that the best response of supplier U is not continuous.

Supplier R's best response, corresponding to R1 - R4, is given by the following: R1: $w_R^* = \frac{m+c_R}{2}$; R2: $w_R^* = w_U$; R3: $w_R^* = \frac{P_0m+P_1w_U+c_R}{2}$; R4: any $w_R^* \in [P_Bw_E^m + P_1w_U + P_GP_{0G}m, w_E^m]$. The break points are as specified in Lemma B.1.

As c_R increases, line segment R3 shifts to the right. The left end of R3 is at $\hat{w}_R = \frac{P_B(m+c_R)}{2} + P_Gc_R$. We thereby have the following possible intersections between the two responses.

First, consider the case of $\rho < \hat{\rho}$ (i.e., $B2 > B3$),

(i) If $\hat{w}_R > A1$, or equivalently, $c_R > (P_{0G} + P_{1G}/2)m$, then the intersection occurs between R4 and U1/U2. The Pareto-dominant equilibrium is $w_U^* = m/2$, $w_E^* = (m + c_R)/2$ and any $w_E^* \ge w_R^* \ge P_Bw_E^* + P_1w_U^* +$

$P_G P_{0G} m$. If $B2 < \hat{w}_R \leq A1$, i.e., $\frac{2P_{0G}m}{1+P_{0G}} < c_R \leq (P_{0G} + P_{1G}/2)m = \frac{(1+P_{0G})m}{2}$, then the intersection is between R3/R4 and U1/U2. The Pareto-dominant equilibrium is $w_U^I = \frac{c_R - P_{0G}m}{P_{1G}}$, $w_E^I = \frac{m+c_R}{2}$ and $w_R^I = P_B w_E^I + P_1 w_U^I + P_G P_{0G} m$. In these two cases, the buyer sources only from supplier U at time 0.

(ii) If $B3 \leq \hat{w}_R \leq B2$, i.e., $\frac{2P_0 - P_B(1+P_0)}{2-P_B(1+P_0)} m \leq c_R \leq \frac{2P_{0G}m}{1+P_{0G}}$, then the intersection is between R3 and U3 (and so the buyer orders from both suppliers at time 0). The corresponding equilibrium prices are $w_U^I = \frac{P_{1G}(c_R + mP_0 - P_B(m+c_R))}{P_1(4-P_{1G})}$, $w_R^I = \frac{4(c_R+mP_0) - P_{1G}P_B(c_R+m)}{2(4-P_{1G})}$ and $w_E^I = \frac{m+c_R}{2}$.

Next, consider the case of $\rho \geq \hat{\rho}$ (i.e., $B2 \leq B3$). We have only two possible cases: If $\hat{w}_R > A1$, then the intersection occurs between R4 and U1/U2; if $B3 < \hat{w}_R \leq A1$ (i.e., $\frac{2P_0 - P_B(1+P_0)}{2-P_B(1+P_0)} m \leq c_R \leq \frac{P_G P_{0G} + P_1/2}{P_G} m$), then the intersection occurs between R3/R4 and U2. The equilibrium prices are the same as in case (i) for $\rho < \hat{\rho}$.

If c_R continues to decrease such that $\hat{w}_R < B3$, then R3 would intersect with case (v) of Lemma B.2, which contains the discontinuous point between U3 and U4 . So, there can be no intersection, i.e., pure strategy Nash equilibrium. □

Proof of Proposition 6 The buyer's expected profit is written as follows.

$$\pi_B^I = \max_{Q_U, Q_R, Q_E \geq 0} P_1(R(Q_R + Q_U) - w_U^I Q_U) + P_0(1-\rho)R(Q_R) + P_0\rho(R(Q_R + Q_E) - w_E^I Q_E) - w_R^I Q_R \quad \text{(C.14)}$$

We first consider Equilibrium (ii) of Proposition 5. By the Envelop Theorem, it follows that

$$\frac{\partial \pi_B^I}{\partial \rho} = -Q_R^I \frac{\partial w_R^I}{\partial \rho} - P_1 Q_U^I \frac{\partial w_U^I}{\partial \rho} + P_0[R(Q_R^I + Q_E^I) - R(Q_R^I) - w_E^I Q_E^I] \quad \text{(C.15)}$$

where Q_U^I, Q_R^I, Q_E^I are the optimal quantities in case (iii) of Proposition 1. According to Equilibrium (ii) in Proposition 5, using the relations $P_B = P_0\rho$ and $P_{1G} = \frac{P_1}{P_1 + P_0(1-\rho)}$, we have $\frac{\partial w_U^I}{\partial \rho} = -\frac{P_1 P_0 (3m - c_R)}{(3 - P_0(4\rho - 1))^2} \leq 0$ and $\frac{\partial w_R^I}{\partial \rho} = -\frac{P_1^2 P_0(3m - c_R)}{2(3 - P_0(4\rho-1))^2} \leq 0$. The first two terms of C.15 are nonnegative. The third term of C.15 can be viewed as the improved profit due to the emergency order, conditional on $s = B$; it is nonnegative as Q_E^I is optimal. Thus, $\frac{\partial \pi_B^I}{\partial \rho} \geq 0$.

$$\frac{\partial \pi_B^I}{\partial \rho} = -P_1 Q_U^I \frac{\partial w_U^I}{\partial \rho} + P_0[R(Q_E^I) - w_E^I Q_E^I] \quad \text{(C.16)}$$

where w_E^I and w_U^I are as characterized in Equilibrium (i), including two different cases (a) and (b), in Proposition 5, and Q_U^I and Q_E^I are given in case (iv) of Proposition 1. The second term of (C.16) is nonnegative as Q_E^I is maximizing $R(Q_E) - w_E^I Q_E$ given $s = B$.

Under Equilibrium (i-a), both w_U^I and w_E^I are constant in ρ, so the first term of (C.16) is zero. π_B^I is thus increasing in ρ.

Under Equilibrium (i-b), we have $\frac{\partial w_U^I}{\partial \rho} = \frac{(m-c_R)P_0}{P_1} \geq 0$. So, we need to expand (C.16) to check the sign of $\frac{\partial \pi_B^I}{\partial \rho}$. Substituting the specific expressions into (C.16), we obtain $\frac{\partial \pi_B^I}{\partial \rho} = \frac{(m-c_R)\Gamma(\rho)}{16P_1}$ where

$$\Gamma(\rho) = m\left(P_0^2(8\rho - 3) - 3P_0 - 2\right) - c_R\left(P_0^2(8\rho + 1) - 11P_0 + 2\right).$$

Furthermore, $\Gamma'(\rho) = 8(m - c_R)P_0^2 \geq 0$. Thus, $\Gamma(\rho) \leq \Gamma(1) = -P_1((2 - 9P_0)c_R + m(5P_0 + 2))$. To prove that π_B^I is decreasing in ρ, it suffices to show $(2 - 9P_0)c_R + m(5P_0 + 2) \geq 0$. If $2 - 9P_0 \geq 0$, the inequality holds. If $2 - 9P_0 < 0$, then since $c_R \leq m$, we have $(2 - 9P_0)c_R + m(5P_0 + 2) \geq 4(1 - P_0)m \geq 0$.

Finally, using the definition of P_{0G} and rearranging the terms, we can rewrite the equilibrium conditions in Proposition 5 as follows. If $\rho \leq \frac{2mP_0 - (1+P_0)c_R}{2P_0(m-c_R)}$, Equilibrium (ii) occurs; if $\frac{2mP_0 - (1+P_0)c_R}{2P_0(m-c_R)} < \rho \leq \frac{(1+P_0)m - 2c_R}{2P_0(m-c_R)}$, Equilibrium (i-b) occurs; otherwise, Equilibrium (i) occurs. This completes the proof. □

C.2. Proofs of Results in Appendices A and B

Proof of Proposition A.1 Applying Lemma 1 and the assumption of $\rho = 1$, the KKT conditions (C.1)-(C.4) are reduced to

$$\frac{\partial L}{\partial Q_U} = P_1 R'(Q_U + Q_R) - P_1 w_U + \lambda_U = 0 \tag{C.17}$$

$$\frac{\partial L}{\partial Q_R} = P_1 R'(Q_U + Q_R) + P_0 R'(Q_R + Q_E) - w_R + \lambda_R = 0 \tag{C.18}$$

$$\frac{\partial L}{\partial Q_E} = P_0(R'(Q_R + Q_E) - w_E) + \lambda_E = 0 \tag{C.19}$$

$$\lambda_R Q_R = 0,\ \lambda_U Q_U = 0,\ \lambda_E Q_E = 0. \tag{C.20}$$

Next, we verify that the optimal solution characterized in the proposition satisfies the above KKT conditions case by case from case (iii) to (i).

For case (iii), $Q_U^* = Q_E^* = 0$ and $Q_R^* > 0$ are optimal iff $P_1 R'(Q_R^*) - P_1 w_U \leq 0$, $R'(Q_R^*) = w_R$, and $R'(Q_R^*) - w_E \leq 0$. These conditions hold simultaneously if $w_R \leq w_U$. Moreover, invoking the expression of R', we have $Q_R^* = (m - w_R)/2$.

For case (ii), $Q_U^* > 0$, $Q_R^* > 0$ and $Q_E^* = 0$ satisfy the KKT conditions iff $P_1 R'(Q_U^* + Q_R^*) - P_1 w_U = 0$, $P_1 R'(Q_U^* + Q_R^*) + P_0 R'(Q_R) - w_R = 0$, and $R'(Q_R^*) - w_E \leq 0$. The closed-form expressions given in case (ii) satisfy the first two equations. The last inequality holds given the first two equations due to the condition $w_R < P_1 w_U + P_0 w_E$.

For case (i), $Q_U^* > 0$, $Q_R^* = 0$ and $Q_E^* > 0$ satisfy the KKT conditions iff $P_1 R'(Q_U^*) - P_1 w_U = 0$, $P_1 R'(Q_U^*) + P_0 R'(Q_E^*) - w_R \leq 0$ and $R'(Q_E^*) = w_E$. The first and the third conditions are satisfied by the closed-form expressions of Q_U^* and Q_E^*. Substituting these equations into the second inequality, one can see that the second inequality holds iff $P_1 w_U + P_0 w_E \leq w_R$. [1] □

Proof of Lemma A.1 Substituting the buyer's optimal order quantities into supplier R's problem, for any given w_U, we can write supplier R's expected profit as

$$\pi_R(w_R, w_E | w_U) = \begin{cases} (w_R - c_R)(m - w_R)/2 & \text{if } w_R < w_U, \\ (w_R - c_R)(P_0 m - w_R + P_1 w_U)/(2P_0) & \text{if } w_U \leq w_R < P_1 w_U + P_0 w_E, \\ P_0(w_E - c_R)(m - w_E)/2 & \text{if } P_1 w_U + P_0 w_E \leq w_R. \end{cases} \tag{C.21}$$

Supplier R maximizes $\pi_R(w_R, w_E | w_U)$ by choosing w_R and w_E over $c_R \leq w_R \leq w_E \leq m$.

As two decision variables are involved in supplier R's problem, we separate the two-dimensional strategy space into two parts: (i) $w_R \geq P_1 w_U + P_0 w_E$ and (ii) $w_R < P_1 w_U + P_0 w_E$. In what follows, we will find $\sup_{w_R, w_E} \pi_R(w_R, w_E | w_U)$ over the two subregions respectively, and then compare the maximum profits to determine the global optimal solution.

Within the subregion (i), supplier R profits from the emergency order with optimal prices $w_E^* = (m + c_R)/2$ and any $w_R^* \geq P_1 w_U + P_0 w_E^*$; its maximum profit in subregion (i) is equal to $\pi_R^{(i)} = P_0(m - c_R)^2/8$.

[1] If $P_1 w_U + P_0 w_E = w_R$, then there are multiple optimal solutions as any quantities such that $Q_R^* + Q_E^* = \frac{m - w_E}{2}$ and $Q_U^* + Q_R^* = \frac{m - w_U}{2}$ are optimal. In this case, we break the tie by assuming the buyer to await for more information and adopt the contingent ordering strategy.

For the subregion (ii) (i.e., $w_R < P_1 w_U + P_0 w_E$) where supplier R profits from the initial order, we need to examine the first two cases of (C.21). For each case, the profit function is concave in w_R for any fixed w_E. So, for each of the two cases, we will maximize over w_R for fixed w_E and then maximize over w_E (if needed).

For the first case, we have the interior solution $w_R^* = (m + c_R)/2$ attained if $w_U > (m + c_R)/2$, in which case w_E^* can be any value within the subregion such that $P_0 w_E^* > (w_R^* - P_1 w_U)/P_0$. If $w_U \leq (m + c_R)/2$, under the first case we have the boundary solution $w_R^* \to w_U$ while w_E^* can take any value such that $w_R^* < P_1 w_U + P_0 w_E^*$. Under the second case of (C.21), if $\frac{P_0 m + c_R - 2P_0 w_E}{P_1} < w_U \leq \frac{P_0 m + c_R}{P_0 + 1}$, then the interior solution $w_R^* = \frac{P_0 m + P_1 w_U + c_R}{2}$ is attained; if $w_U > \frac{P_0 m + c_R}{P_0 + 1}$, we have the boundary solution $w_R^* = w_U$; again, w_E^* can be any value such that $w_R^* < P_1 w_U + P_0 w_E^*$. If $w_U \leq \frac{P_0 m + c_R - 2P_0 w_E}{P_1}$, we have $w_R^*(w_E) \to P_1 w_U + P_0 w_E$, which depends on the value of w_E. As $w_R^*(w_E) \to P_1 w_U + P_0 w_E$, the profit function goes to $\Pi(w_R^*(w_E), w_E | w_U) = \frac{1}{2}(m - w_E)(P_0 w_E + P_1 wU - c_R)$, which is concave in w_E. So, we can continue to maximize over w_E^* using the first order condition. It follows that the maximizer (in the limiting sense) is given by $w_E^* = \frac{P_0 m - P_1 w_U + c_R}{2P_0}$ which leads to $w_R^*(w_E^*) = \frac{P_0 m + P_1 w_U + c_R}{2}$. Also, recall that $w_R^*(w_E^*) \to P_1 w_U + P_0 w_E^*$ cannot be less than c_R. Therefore, we have the optimal solutions (in the limiting sense) as $w_R^* = \frac{P_0 m + P_1 w_U + c_R}{2}$ and $w_E^* = \frac{P_0 m - P_1 w_U + c_R}{2P_0}$ if $w_U \geq (c_R - P_0 m)/P_1$; otherwise, supplier R will get zero profit with $w_R^* = c_R$ (and $w_E^* = (c_R - P_1 w_U)/P_0$).

Combining the above cases and substituting the optimal solution for each case into the profit function, we have supplier R's maximum profit within subregion (ii) given as follows.

$$\pi_R^{(ii)} = \begin{cases} (m - c_R)^2/8 & \text{if } w_U > (m + c_R)/2 \\ (w_U - c_R)(m - w_U)/2 & \text{if } \frac{P_0 m + c_R}{P_0 + 1} < w_U \leq (m + c_R)/2 \\ (P_0 m + P_1 w_U - c_R)^2/(8P_0) & \text{if } \frac{c_R - P_0 m}{P_1} < w_U \leq \frac{P_0 m + c_R}{P_0 + 1} \\ 0 & \text{if } w_U \leq \frac{c_R - P_0 m}{P_1} \end{cases}$$

Supplier R will go for the emergency order if and only if $\pi_R^{(i)} > \pi_R^{(ii)}$. To find the threshold, we first show the following.

CLAIM 1. *$\pi_R^{(ii)}$ is continuous and increasing in w_U.*

Proof of Claim 1 It is straightforward to verify the continuity at points $w_U = \frac{m + c_R}{2}$, $\frac{P_0 m + c_R}{P_0 + 1}$ and $\frac{c_R - P_0 m}{P_1}$. Then, we examine the first-order derivative of $\pi_R^{(ii)}$ with respect to w_U:

$$\frac{\partial \pi_R^{(ii)}}{\partial w_U} = \begin{cases} 0 & \text{if } w_U > (m + c_R)/2 \\ \frac{m + c_R - 2w_U}{2} & \text{if } \frac{P_0 m + c_R}{P_0 + 1} < w_U \leq (m + c_R)/2 \\ \frac{P_1 (P_0 m + P_1 w_U - c_R)}{4P_0} & \text{if } \frac{c_R - P_0 m}{P_1} < w_U \leq \frac{P_0 m + c_R}{P_0 + 1} \\ 0 & \text{if } w_U \leq \frac{c_R - P_0 m}{P_1} \end{cases}$$

By checking the values at break points, one can verify that the above derivative is nonnegative and continuous in w_U. Thus, $\pi_R^{(ii)}$ is increasing in w_U. $\square$

Because the above claim holds true, along with the fact that $\pi_R^{(i)} = P_0 (m - c_R)^2/8$ is constant in w_U, it follows that there is a unique threshold $\hat{w}_U$ such that $\pi_R^{(i)} \geq \pi_R^{(ii)}$ if and only if $w_U \leq \hat{w}_U$. In fact, the threshold is given simply by $\hat{w}_U = c_R$, which can be directly verified with the expression of $\pi_R^{(ii)}$. Note that the value of $\pi_R^{(ii)}$ falls into the third case in the expression when $w_U = c_R$.

$\square$

Proof of Lemma A.2 For any given $w_R \le w_E \le m$, supplier U's expected profit can be written as

$$\pi_U(w_U|w_R,w_E) = \begin{cases} (P_1 w_U - c_U)(m-w_U)/2 & \text{if } P_1 w_U \le w_R - P_0 w_E \\ (P_1 w_U - c_U)(w_R - w_U)/(2P_0) & \text{if } w_R - P_0 w_E < P_1 w_U \le P_1 w_R \\ 0 & \text{if } w_U > w_R. \end{cases} \tag{C.22}$$

For the first case, the interior optimal solution is $w_U^* = (m + c_U/P_1)/2$, which is attained if $w_R > P_0 w_E + (P_1 m + c_U)/2$. Otherwise, if $w_R \le P_0 w_E + (P_1 m + c_U)/2$, then the boundary solution, $w_U^* = (w_R - P_0 w_E)/P_1$, is optimal under the first case.

For the second case, if $c_U/P_1 < w_R \le \frac{2P_0 w_E + c_U}{P_0+1}$, we have the interior solution $w_U^* = (P_1 w_R + c_U)/(2P_1)$. If $w_R \ge \frac{2P_0 w_E + c_U}{P_0+1}$, we have the solution at the left boundary $w_U^* = w_R - P_0 w_E$. If $w_R \le c_U/P_1$, then Supplier U will have to set $w_U^* = c_U$.

To combine the two cases, we need to compare the two thresholds:

$$P_0 w_E + (P_1 m + c_U)/2 - \frac{2P_0 w_E + c_U}{P_0+1} = \frac{P_1((P_0+1)m - 2P_0 w_E - c_U)}{2(P_0+1)} \ge \frac{P_1(P_1 m - c_U)}{2(P_0+1)} > 0$$

where the first inequality follows as $w_E \le m$ and the second follows as $P_1 m > c_U$ by assumption. This implies that there is no overlap between the regions for the two interior solutions to co-exist. So, the boundary solution $w_U^* = (w_R - P_0 w_E)/P_1$ if w_R is in between the two thresholds, i.e., $(2P_0 w_E + c_U)/(P_0+1) < w_R \le P_0 w_E + (P_1 m + c_U)/2$.

□

Proof of Lemma B.1 For any $c_U/P_1 \le w_U \le m$, supplier R maximizes $\pi_R(w_R, w_E|w_U)$, as expressed below, by choosing w_R and w_E over the domain $c_R \le w_R \le w_E \le m$.

$$\pi_R(w_R,w_E|w_U) = \begin{cases} (w_R - c_R)(m - w_R)/2 & \text{if } w_R \le w_U, \\ (w_R - c_R)(P_0 m - w_R + P_1 w_U)/(2P_0) & \text{if } w_U < w_R \le P_1 w_U + P_0 w_E, \\ (w_R - c_R)(P_G P_{0G} m - w_R + P_1 w_U + P_B w_E)/(2P_G P_{0G}) & \text{if } P_1 w_U + P_0 w_E < w_R \\ +P_B(w_E - c_R)(w_R - P_1 w_U - P_0 w_E)/(2P_G P_{0G}), & \le P_1 w_U + P_B w_E + P_G P_{0G} m \\ P_B(w_E - c_R)(m - w_E)/2 & \text{if } P_1 w_U + P_B w_E + P_G P_{0G} m < w_R. \end{cases} \tag{C.23}$$

For case (i) of (C.23), the optimal (monopolistic) price is attained at $w_R^* = (m + c_R)/2$ if $w_U > (m + c_R)/2$. It is also global optimal if attained. If $w_U \le (m + c_R)/2$, we have $w_R^* = w_U$ in the first case. This boundary solution can be considered in case (ii). Below, we will thus focus on cases (ii)-(iv) with $w_U \le (m + c_R)/2$.

Notice that case (iii) can include cases (ii) and (iv) as special cases when $w_R = P_1 w_U + P_0 w_E$, and when $w_R = P_1 w_U + P_B w_E + P_G P_{0G} m$, respectively. We will therefore first analyze case (iii). If an interior solution to the unconstrained problem under case (iii) is attained, then it must be global optimal. Under Case (iii), $\pi_R(w_R, w_E|w_U)$ is bilinear in w_E and w_R, which may not be jointly concave. To overcome this difficulty, we first search for the optimal $w_R^*(w_E)$ maximizing $\pi_R(w_R, w_E|w_U)$ for any given w_E, and then determine the optimal w_E^* that maximizes $\pi_R(w_R^o(w_E), w_E|w_U)$. For any fixed w_E, π_R is concave in w_R. Solving $\frac{\partial \pi_R(w_R, w_E|w_U)}{\partial w_R} = 0$, we obtain

$$w_R^*(w_E) = P_B w_E + \frac{1}{2}(P_G c_R + P_G P_{0G} m + P_1 w_U).$$

Substituting the above to the profit function and taking the second-order derivative with respect to w_E, we have

$$\frac{\partial^2 \pi_R(w_R^o(w_E), w_E|w_U)}{\partial w_E^2} = \frac{P_B(P_B - P_0)}{P_G P_{0G}} \leq 0$$

where the inequality follows as $P_B = (1-x)\rho \leq P_0 = (1-x)$. Hence, $\pi_R(w_R^*(w_E), w_E|w_U)$ is concave in w_E, and so we can obtain the interior optimal w_E^* by solving the first-order condition:

$$\frac{\partial \pi_R(w_R^o(w_E), w_E|w_U)}{\partial w_E} = P_B(c_R + m - 2w_E)/2 = 0.$$

Thus, $w_E^* = \frac{m+c_R}{2}$. Note that in deriving the above first order condition, we invoke the relation $P_0 - P_B = P_G P_{0G} = (1-x)(1-\rho)$. Substituting w_E^* into $w_R^*(w_E)$, we conclude that the interior optimal prices to case (iii) are given by $w_R^* = (P_0 m + c_R + P_1 w_U)/2$ and $w_E^* = (m + c_R)/2$.

Substituting the interior solution into the conditions of case (iii), we have the above solution attained (as the global optimal) iff $P_G c_R - (P_0 - P_B)m \leq P_1 w_U \leq P_1 c_R$. Moreover, it follows that if $w_U > c_R$, it is optimal to set $w_R = P_1 w_U + P_0 w_E$, which can be examined in case (ii); if $P_1 w_U < P_G c_R - (P_0 - P_B)m$, it is optimal to set $w_R = P_1 w_U + P_B w_E + P_G P_{0G} m$, which can be examined in case (iv).

If $w_U > c_R$, we need to examine case (ii). For case (ii), if $w_U \leq \frac{P_0 m + c_R}{P_0 + 1}$ we have the optimal solution attained at $w_R^* = \frac{P_0 m + c_R + P_1 w_U}{2}$ (along with any w_E^* such that $P_0 w_E^* + P_1 w_U \geq w_R^*$). Otherwise, $w_R^* = w_U$. If $P_1 w_U < P_G c_R - (P_0 - P_B)m)$, we have case (iv) where the optimal solution is clearly given by $w_E^* = \frac{m+c_R}{2}$ and any w_R^* satisfying the corresponding condition.

Combining all cases, we have the desired the results.

□

Proof of Lemma B.2 For any given $w_R \leq w_E \leq m$, supplier U maximizes the following profit function by choosing w_U.

$$\pi_U(w_U|w_R, w_E) = \begin{cases} (P_1 w_U - c_U)(m - w_U)/2 & \text{if } P_1 w_U < w_R - P_B w_E - P_G P_{0G} m \\ (P_1 w_U - c_U)\frac{w_R - P_B w_E - P_G w_U}{2 P_G P_{0G}} & \text{if } w_R - P_B w_E - P_G P_{0G} m \leq P_1 w_U < w_R - P_0 w_E \\ (P_1 w_U - c_U)(w_R - w_U)/(2P_0) & \text{if } w_R - P_0 w_E \leq P_1 w_U < P_1 w_R \\ 0 & \text{if } w_U \geq w_R \end{cases} \tag{C.24}$$

In most parts of the proof below, we work with a general c_U. The closed-form expressions in the lemma can readily be obtained by letting $c_U = 0$.

For case (i) of (C.24), we have the interior optimal price $w_U^* = (P_1 m + c_U)/(2P_1)$ attained if $w_R > A1 := P_B w_E + P_G P_{0G} m + (P_1 m + c_U)/2$; if $w_R \leq A1$, π_U is decreasing in w_U under case (i) and $w_U^* \to (w_R - P_B w_E - P_G P_{0G} m)/P_1$.

For case (ii), we have the interior solution $w_U^* = \frac{P_{1G}(w_R - P_B w_E) + c_U}{2P_1}$ attained if $A2 := \frac{(2P_0 - P_B P_{1G}) w_E + c_U}{1 + P_{0G}} < w_R \leq B2 := P_B w_E + \frac{2 P_G P_{0G} m + c_U}{1 + P_{0G}}$. If $w_R > B2$, then π_U is decreasing in w_U under case (ii) and $w_U^* = (w_R - P_B w_E - P_G P_{0G} m)/P_1$; if $w_R \leq A2$, then π_U is increasing under case (ii) and $w_U^* = (w_R - P_0 w_E)/P_1$.

Next, consider the case (iii). If $c_U/P_1 < w_R \leq B3 := \frac{c_U + 2P_0 w_E}{1 + P_0}$, the interior solution is attained at $w_U^* = \frac{P_1 w_R + c_U}{2P_1}$; if $w_R > B3$, π_U is decreasing under case (iii) and $w_U^* = (w_R - P_0 w_E)/P_1$; if $w_R \leq c_U/P_1$, then π_U is increasing and $w_U^* = c_U/P_1$ (and supplier U receives zero profit).

Notice that $A2 - B3 = \frac{P_{1G}P_B(c_U - P_1 w_E)}{(1+P_{0G})(1+P_0)} \le 0$. So, it is possible to have $A2 < w_R \le B3$ such that the interior solutions to cases (ii) and (iii) are both attained. (In other words, π_U can have two local maximizers!) In this case, we need to compare the two local maximizer and select the global optimal. Let $\pi_U^{(ii)}$ ($\pi_U^{(iii)}$) denote the optimal objective value of the second (third) case when the interior solution is attained. Under the assumption of $c_U = 0$, it follows that

$$\pi_U^{(iii)} - \pi_U^{(ii)} = -\frac{P_1\left(P_0(w_R - P_B w_E)^2 - P_G(P_0 - P_B)w_R^2\right)}{8P_0\left(P_0 - P_B\right)P_G}.$$

It follows that $\pi_U^{(iii)} \ge \pi_U^{(ii)}$ and thus $w_U^* = \frac{P_1 w_R + c_U}{2P_1}$ iff $w_R \le T_1 := P_B w_E / \left(1 - \sqrt{\frac{P_G(P_0 - P_B)}{P_0}}\right)$.[2]

Next, we put together all the possible cases.

- If $w_R > A1$, then the monopolistic price is optimal: $w_U^* = (P_1 m + c_U)/(2P_1)$.
- If $\max(B2, B3) < w_R \le A1$, π_U is decreasing in w_U over both cases (ii) and (iii). So, the boundary solution is optimal: $w_U^* = (w_R - P_B w_E - P_G P_{0G} m)/P_1$.
- If $B2 < w_R \le \max(B2, B3)$, then an interior solution is attained in case (iii) but π_U is decreasing in case (ii). In this case, we need to compare the profit under the boundary solution $w_U^* = (w_R - P_B w_E - P_G P_{0G} m)/P_1$ and that under the case-(iii) interior solution $w_U^* = \frac{P_1 w_R + c_U}{2P_1}$. Substituting the candidate solutions to the profit expressions, we have

$$\pi_U^{(iii)} - \pi_U^{boundary} = \frac{1}{8}\left(\frac{4\left(mP_0 - P_B\left(m - w_E\right) - w_R\right)\left(m - P_B\left(m - w_E\right) - w_R\right)}{P_1} + \frac{P_1 w_R^2}{P_0}\right).$$

It follows that $\frac{\partial^2 \pi_U^{(iii)} - \pi_U^{boundary}}{\partial w_R^2} = \frac{(P_0+1)^2}{4P_1 P_0} \ge 0$. So, $\pi_U^{(iii)} - \pi_U^{boundary}$ is convex in w_R. Additionally, notice that $\frac{\partial \pi_U^{(iii)} - \pi_U^{boundary}}{\partial w_R} = 0$ at $\bar{w}_R = \frac{2P_0(-2P_B(m - w_e) + mP_0 + m)}{(P_0+1)^2}$ and furthermore $\bar{w}_R - B3 = \frac{2P_0(-2P_B + P_0 + 1)(m - w_e)}{(P_0+1)^2} \ge 0$ since $P_B \le P_0$. Thus, within the relevant interval $w_R \in (B2, \max(B2, B3)]$, $\frac{\partial \pi_U^{(iii)} - \pi_U^{boundary}}{\partial w_R}$ is decreasing in w_R. Moreover, $\pi_U^{(iii)} - \pi_U^{boundary} = 0$ has two roots with respect to w_R; by the above observations, only the smaller root,

$$T_0 = \frac{2mP_0(1+P_0) - 4P_0 P_B(m - w_E) - 2(1 - P_0)\sqrt{P_0 P_B(m - w_E)(m + mP_0 - P_B(m - w_E))}}{(1+P_0)^2}$$

can fall into the relevant interval. It follows that the boundary solution $w_U^* = (w_R - P_B w_E - P_G P_{0G} m)/P_1$ is global optimal iff $w_R > T_0$.

- If $\min(B2, B3) < w_R \le B2$, the interior solution is attained under case (ii) while π_U is decreasing under case (iii). So, $w_U^* = \frac{P_{1G}(w_R - P_B w_E) + c_U}{2P_1}$.
- If $A2 < w_R \le \min(B2, B3)$, then an interior solution is attained under both cases (ii) and (iii). $w_U^* = \frac{P_{1G}(w_R - P_B w_E) + c_U}{2P_1}$ if $w_R > P_B w_E / \left(1 - \sqrt{\frac{P_G(P_0 - P_B)}{P_0}}\right)$ but $w_U^* = \frac{P_1 w_R + c_U}{2P_1}$ otherwise.
- If $c_U/P_1 < w_R \le A2$, then the interior solution in case (iii) is attained while π_U is increasing under case (ii). Thus, $w_U^* = \frac{P_1 w_R + c_U}{2P_1}$.

□

[2] To obtain the above threshold, we need $w_R \ge P_B w_E$. To see that this is indeed the case, using the relation $P_0 \ge P_B$, we have $A2 = \frac{2P_0 - P_B P_{1G}}{1+P_{0G}} w_E \ge P_B w_E$. Thus, whenever $A2 < w_R \le B3$, $w_R \ge P_B w_E$.

Supplementary Material for "Forewarned Is Forearmed? Contingent Sourcing, Shipment Information and Supplier Competition"

Appendix S.1: Factors Influencing the Accuracy of Shipment Information

We model the shipment information as a binary signal available to the buyer at the time of contingent sourcing. This binary-signal approach can capture various practical settings such as traditional inspection and continuous monitoring, as explained below.

Consider a setting illustrated in Figure S.1.1. The selling season starts at t_2 (Time 2). Supplier U has a long lead time, and the transportation starts at a departure time t_d and ends at t_2. Supplier R has a lead time of $t_2 - t_1$, so t_1 (Time 1) is the latest time possible to order from supplier R. We make two assumptions. First, supplier R's production and transportation are perfectly reliable. Second, R quotes a single (time-invariant) emergency wholesale price w_E, so the buyer does not benefit from placing an emergency order earlier than Time 1. Both assumptions are common in the existing literature related to contingent sourcing.

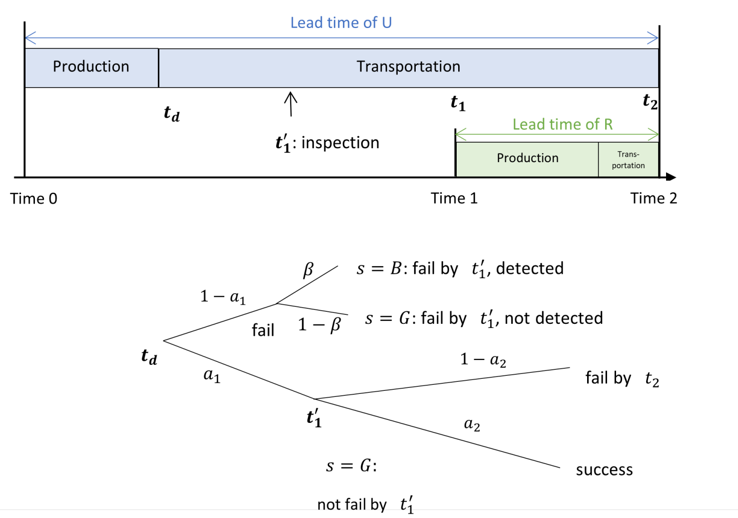

Figure S.1.1 Example: ρ depends on inspection time and precision

An adverse event that causes product damage may occur during U's transportation process between t_d and t_2.[3] We consider the arrival of adverse events as a counting process $\{N(t), t_d \leq t \leq t_2\}$. The product is damaged by any given time $t \in [t_d, t_2]$ iff $N(t) \geq 1$.

[3] Our framework can also allow failure during U's production process. A production failure is equivalent to assuming a positive probability of failure at t_d.

First, let us consider a setting in which inspections can be used to detect if the in-transit product is damaged. Typically, such inspections can only be conducted at certain locations (e.g., a transshipment warehouse) and may mistakenly overlook damage. For ease of exposition, consider a setting with only one inspection point, but our analysis can be extended to multiple inspection points.

If the inspection point is at some time t_1' where $t_1' > t_1$, then no shipment information for contingent sourcing will be collected by t_1. This corresponds to our model with $\rho = 0$. If the inspection point is at some $t_1' < t_1$, then the inspection can provide some useful information for contingent sourcing, and the information accuracy depends on the inspection precision itself as well as the time t_1'. Let $1-\beta$ be the probability that the inspection overlooks damage that has occurred. A higher β implies a more precise inspection. Let $a_1 = \Pr\{N(t_1') = 0\}$ represent the probability that no adverse event has occurred by t_1', and let $a_2 = \Pr\{N(t_2) - N(t_1') = 0 | N(t_1') = 0\}$ represent the probability of no adverse event occurring between t_1' and t_2, conditional on no adverse event before t_1'. Adopting the notation of our model, the probability of successful (resp. failed) delivery is given by $P_1 = a_1 a_2$ (resp. $P_0 = 1 - a_1 a_2$). As illustrated in Figure S.1.1, the signal available for contingent sourcing is $s = B$ iff damage occurs by t_1' and is successfully detected by the inspection. Thus, the probabilities of s being bad and good are given by $P_B = (1-a_1)\beta$. and $P_G = 1-(1-a_1)\beta$, respectively. The signal is imperfect in the sense that even with $s = G$, the buyer may receive the product damaged at t_2. Recall that in our model the accuracy of shipment information ρ is defined as $\Pr(s = B|\text{delivery fails})$. Under the context described above, we have

$$\rho = \frac{(1-a_1)\beta}{1-a_1 a_2}.$$

More specifically, if $N(t)$ is a homogeneous Poisson process with a rate of λ, it follows that

$$\rho = \frac{\beta[1-e^{-\lambda(t_1'-t_d)}]}{1-e^{-\lambda(t_2-t_d)}}. \tag{S.1.1}$$

Clearly, ρ is increasing in β and t_1'. That is, a more accurate signal of final arrival success is obtained if the inspection technology is more precise or if the inspection point occurs closer to t_1 (but not later than t_1).[4]

Advances in sensor technologies are now enabling (in some settings) a shipment to be continuously monitored during the entire transportation process as illustrated in Figure S.1.2. Suppose

[4] The above derivation can be extended to the case of $n > 1$ inspection points between t_d and t_1, each with a precision β. Let t_i' denote the time of the i-th inspection where $t_d \le t_1' < t_2' < ... < t_n' < t_1$. Define $a_1 = \Pr\{N(t_1') = 0\}$, and $a_i = \Pr\{N(t_i') - N(t_{i-1}') = 0 | N(t_{i-1}') = 0\}$ for $i = 2, 3, ..., n$, and $a_{n+1} = \Pr\{N(t_2) - N(t_n') = 0 | N(t_n') = 0\}$. The accuracy of shipment information in this case can be written as

$$\rho = \frac{\sum_{i=1}^{n}(\Pi_{k=1}^{i-1} a_k)(1-a_i)[1-(1-\beta)^{n-i+1}]}{1-\Pi_{i=1}^{n+1} a_i}.$$

that the sensor devices can perfectly detect an adverse event (if any) during supplier U's transportation process. This is equivalent to having $t_1' = t_1$ and $\beta = 1$ in the inspection setting described above.[5] Thus, if $N(t)$ is a homogeneous Poisson process with a rate of λ, then we have

$$\rho = \frac{1 - e^{-\lambda(t_1 - t_d)}}{1 - e^{-\lambda(t_2 - t_d)}}. \tag{S.1.2}$$

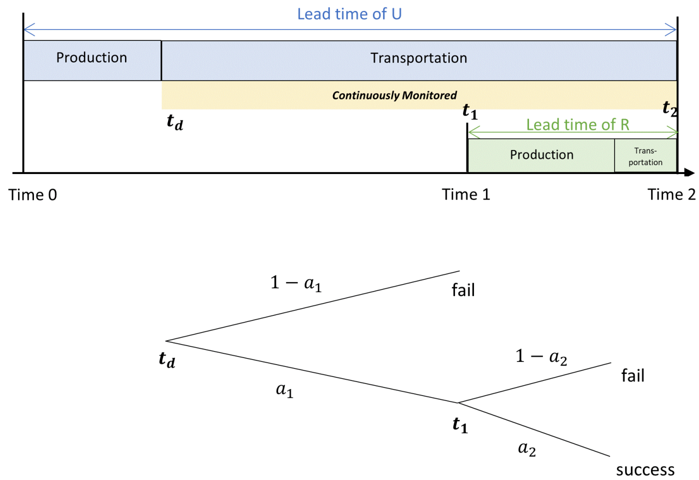

Figure S.1.2 Example: Perfect Continuous Monitoring

Comparing (S.1.2) to (S.1.1) at $\beta = 1$, we see that the value of ρ is higher with continuous monitoring than with inspection because $t_1' > t_1$. Additionally, per (S.1.2), ρ is higher when t_1 is larger, that is, when supplier R's lead time is shorter.

To summarize, our binary-signal model captures various practical settings and *an improvement in accuracy ρ can correspond to having an inspection point close to the time of the contingent*

To see this, recall that $\rho = \frac{\Pr\{N(t_2)\geq 1, \text{damage detected by at least one inspection}\}}{\Pr\{N(t_2)\geq 1\}}$. The denominator is given by $1 - \Pi_{i=1}^{n+1} a_i$. The numerator is equal to the following:

$$\begin{aligned}
&(1 - a_1)[1 - (1 - \beta)^n] \\
&+ a_1(1 - a_2)[1 - (1 - \beta)^{n-1}] \\
&+ a_1 a_2 (1 - a_3)[1 - (1 - \beta)^{n-2}] \\
&+ \ldots \\
&+ a_1 a_2 \ldots a_{n-1}(1 - a_n)[1 - (1 - \beta)]
\end{aligned}$$

where the first term is the probability that damage occurs before t_1' and is detected by at least one of the following n inspections, and the i-th term is the probability that damage occurs between t_{i-1}' and t_i' and is detected by at least one of the following $n - i + 1$ inspections.

[5] We could allow imperfect continuous monitoring which may fail to report damage that has actually occurred before t_1 based on the derivation described in Footnote 4.

sourcing decision, adopting continuous monitoring devices, increasing the precision of the inspection/monitoring technology, or reducing the reliable supplier's lead time.

We acknowledge that our binary-signal model cannot capture all settings. In particular, if order failure results from an accumulation of unfavorable conditions, we would need a more general information structure than our binary signal to fully reflect such a setting. For example, if failure arises only if a threshold number (n> 1) of adverse events has occurred then the signal space would need $n+1$ realized values to represent the cases of $N(t_1)=0,1,...,n-1$ and $N(t_1)\geq n$.[6] Another setting that our model does not capture is one in which supplier R offers a time-variant emergency price $w_E(t)$. In this case, the buyer would need to determine whether to place an emergency order based on the information collected up to each time t. These generalizations would render the first-stage supplier competition problem highly intractable because the buyer's optimal sourcing strategy (i.e., suppliers' demand functions in the first stage) will become much-more involved. However, one possible approach for future research is to focus on a single supplier contracting with the buyer. We expect that in a dyadic supply-chain setting, analyses of a richer signal space and the supplier's time-variant emergency pricing might be fruitful.

Appendix S.2: Auxiliary Results for the Case of No Shipment Information

In this section, we state the buyer's optimal order quantities in the second stage and the two suppliers' best response functions given no shipment information, i.e., $\rho=0$ The case of $\rho=0$ is a special case of the imperfect-shipment-information setting, and hence the proofs are omitted.

With $\rho=0$, w_E and Q_E are irrelevant. For any given w_U and w_R, the buyer maximize the profit function

$$\pi_B^N(Q_U,Q_R)=P_1R(Q_U+Q_R)+P_0R(Q_R)-P_1w_UQ_U-w_RQ_R \tag{S.2.1}$$

by choosing order quantities Q_U and Q_R.

PROPOSITION S.2.1. *With no shipment information ($\rho=0$), given any w_U and w_R, the buyer's optimal order quantities Q_U^* and Q_R^* are characterized by one of the following cases.*

(i) If $w_R>P_1w_U+P_0m$, then $Q_U^*=(m-w_U)/2$ and $Q_R^*=0$.

(ii) If $w_U<w_R\leq P_1w_U+P_0m$, then $Q_R^*=\frac{P_0m-w_R+P_1w_U}{2P_0}$, and $Q_U^*=\frac{w_R-w_U}{2P_0}$.

(iii) If $w_R\leq w_U$, then $Q_U^*=0$ and $Q_R^*=(m-w_R)/2$.

LEMMA S.2.1. *With $\rho=0$, for any given w_U, supplier R's best response is given as follows.*

(i) If $w_U>(m+c_R)/2$, then $w_R^*=(m+c_R)/2$.

[6] The buyer would want to know how close to the threshold the order is at the time of contingent sourcing and not just whether it was good or bad.

(ii) If $(P_0m+c_R)/(P_0+1)<w_U\le(m+c_R)/2$*, then* $w_R^*=w_U$.

(iii) If $(c_R-P_0m)/P_1<w_U\le(P_0m+c_R)/(P_0+1)$*, then* $w_R^*=(P_1w_U+P_0m+c_R)/2$.

(iv) If $w_U\le(c_R-P_0m)/P_1$*, then* $w_R^*=c_R$.

Lemma S.2.2. *With* $\rho=0$*, for any given* w_R*, supplier U's best response is given as follows.*

(i) If $w_R>P_0m+(P_1m+c_U)/2$*, then* $w_U^*=(m+c_U/P_1)/2$.

(ii) If $(2P_0m+c_U)/(P_0+1)<w_R\le P_0m+(P_1m+c_U)/2$*, then* $w_U^*=(w_R-P_0m)/P_1$.

(iii) If $c_U/P_1<w_R\le(2P_0m+c_U)/(P_0+1)$*, then* $w_U^*=(P_1w_R+c_U)/(2P_1)$.

(iv) If $w_R\le c_U/P_1$*, then* $w_U^*=c_U$.

The above results will be referenced in some of the model extension analyses below.

Appendix S.3: Impact of Success Probability P_1

We have assumed that supplier U's delivery reliability P_1 is exogenously given throughout the analysis. In the long run, supplier U might have influence over P_1 through, for example, investing in a more-advanced cold chain infrastructure or using a more-reliable transportation service provider. The following proposition sheds light on supplier U's incentive to improve P_1. The proof can be found at the end of this section.

Proposition S.3.1. *Consider the case of perfect shipment information, i.e.,* $\rho=1$*. (i) In a diversification equilibrium, supplier U's payoff is decreasing in its reliability* P_1 *iff* $c_RP_1(4+P_1-2P_1^2)+c_U(8-18P_1+9P_1^2-2P_1^3)<m(11P_1-7P_1^2-4)$*; the buyer's payoff is always increasing in* P_1*. (ii) In a contingent-sourcing equilibrium, supplier U's and the buyer's payoffs are increasing in* P_1*. (iii) The contingent sourcing threshold,* ψ_2*, is decreasing in* P_1*. That is, with all else fixed, contingent sourcing is more likely to occur in equilibrium as* P_1 *increases.*

As proven in part (i) of Proposition S.3.1, under a diversification equilibrium, supplier U may or may *not* be better off with a higher P_1. Although a higher P_1 increases supplier U's chance of successful delivery, it also intensifies its competition with supplier R for the buyer's initial order. When the competition-intensifying effect dominates, supplier U may be hurt by a higher reliability. For the buyer, a higher P_1 improves delivery reliability and intensifies supplier competition, and is thus always being beneficial.[7] Part (ii) of Proposition S.3.1 indicates that supplier U will always benefit from a higher P_1 under a contingent sourcing equilibrium as it obtains the entire initial order. Some benefit will pass to the buyer. Moreover, as part (iii) suggests, a higher P_1 makes supplier U more likely to win the buyer's entire initial order and force supplier R to be a contingent option.

[7] Note that Part (i) remains valid for imperfect shipment information ($\rho<1$), because under a diversification strategy, the equilibrium outcome is exactly the same as in the case of $\rho=1$ since the shipment information is not used.

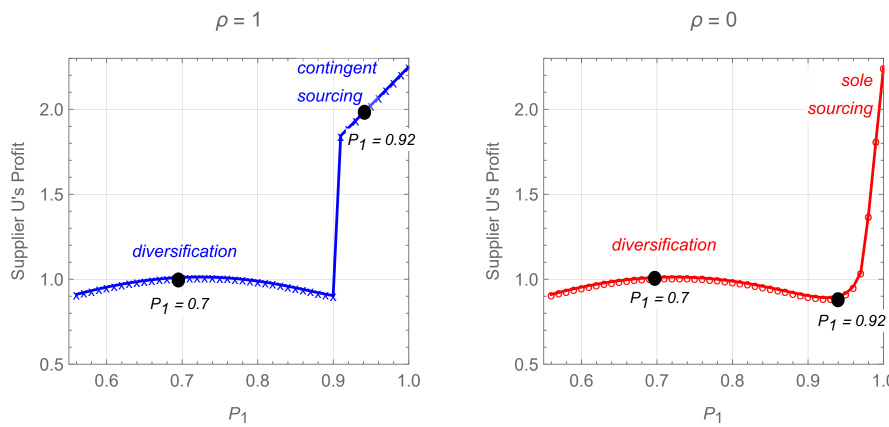

Figure S.3.1 **Impact of P_1 on supplier U's profit ($m = 10$, $c_U = 0.5$, $c_R = 1$).**

Figure S.3.1 illustrates the non-monotone effect of P_1 on supplier U's profit, both with perfect shipment information ($\rho = 1$) and with no information ($\rho = 0$). First, consider the left panel ($\rho = 1$). Diversification is the equilibrium outcome when $P_1 < 0.9$ and supplier U would favor a moderate reliability (in the 0.7 range) to a higher one (approaching 0.9). If the current reliability exceeds the local maximum in the diversification equilibrium, then supplier U will only want to increase the reliability if it can improve it enough to jump to the contingent-sourcing equilibrium (above 0.9 in the example). Cost-of-improvement aside, supplier U benefits significantly if it can shift the equilibrium through reliability improvement. Moreover, compared with the case of $\rho = 0$ (right panel of Figure S.3.1), we observe that with $\rho = 1$ supplier U will consider investing to improve P_1, e.g., from 0.7 to 0.92, but not do so with $\rho = 0$. So, enhanced shipment information can give supplier U (in a diversification equilibrium) greater incentive to improve P_1.

Proof of Proposition S.3.1 First, consider a diversification equilibrium as stated in Case (ii) of Proposition 2. Taking the derivative of π_U^I with respect to P_1 under the diversification equilibrium, we have

$$\frac{\partial \pi_U^I}{\partial P_1} = \frac{\Upsilon \cdot \Gamma}{2(1-P_1)^2 P_1^2 (4-P_1)^3}$$

where $\Gamma = P_1(c_R + m(1-P_1)) - c_U(2-P_1)$ and

$$\Upsilon = P_1 m(4 - 11P_1 + 7P_1^2) + c_R P_1(4 + P_1 - 2P_1^2) + c_U(8 - 18P_1 + 9P_1^2 - 2P_1^3).$$

Note that for a diversification equilibrium to exist, we have $\frac{P_0+1}{P_1} c_U - P_0 m < c_R$ [see part (ii) of Proposition 2], which holds iff $\Gamma > 0$. Thus, π_U^I is increasing in P_1 iff $\Upsilon < 0$. Simplifying the terms of Υ yields the condition given in the proposition.

For the buyer, by the Envelope Theorem it follows that

$$\frac{\partial \pi_B^I}{\partial P_1} = \frac{\partial \pi_B(Q_U^*, Q_R^*)}{\partial P_1} + \frac{\partial \pi_B(Q_U^*, Q_R^*)}{\partial w_U^I}\frac{\partial w_U^I}{\partial P_1} + \frac{\partial \pi_B(Q_U^*, Q_R^*)}{\partial w_R^I}\frac{\partial w_R^I}{\partial P_1}.$$

With a little abuse of notation, we omitted Q_E in the buyer's profit function since it is zero under diversification equilibrium. The first term is the direct effect of P_1, which is positive under the optimal solution. The effects of wholesale prices on π_B are negative, i.e., $\frac{\partial \pi_B(Q_U^*, Q_R^*)}{\partial w_U^I} \leq 0$ and $\frac{\partial \pi_B(Q_U^*, Q_R^*)}{\partial w_R^I} \leq 0$. It is straightforward to show that $\frac{\partial w_U^I}{\partial P_1} < 0$ and $\frac{\partial w_R^I}{\partial P_1} < 0$. As a result, $\frac{\partial \pi_B^I}{\partial P_1} \geq 0$.

In a contingent sourcing equilibrium, $\pi_U^I = (P_1 w_U^I - c_U)(m - w_U^I)/2$ where $w_U^I = \frac{P_1 m + c_U}{2P_1}$ [Equilibrium (ia)] or $w_U^I = c_R$ [Equilibrium (ib)]. It is straightforward to verify $\frac{\partial \pi_U^I}{\partial P_1} \geq 0$ for both cases.

For the buyer, under Equilibrium (ia), $\frac{\partial \pi_B^I}{\partial P_1} = \frac{1}{16}\left(2mc_R - \frac{c_U^2}{P_1^2} - c_R^2\right)$. Note that the condition for the existence of a contingent sourcing implies $c_R > \frac{P_0 m + 2c_U/P_1}{P_0+2} \geq \frac{c_U}{P_1}$ where the second inequality is due to $P_1 m \geq c_R$. Substituting $\frac{c_U}{P_1} \leq c_R$ into $\frac{\partial \pi_B^I}{\partial P_1}$, we have $\frac{\partial \pi_B^I}{\partial P_1} \geq 2mc_R - 2c_R^2 \geq 0$ as $m \geq c_R$. Under Equilibrium (ib), we have $\frac{\partial \pi_B^I}{\partial P_1} = \frac{3}{16}(m - c_R)^2 \geq 0$.

Finally, the contingent sourcing threshold $\psi_2 = \frac{P_0 m + 2c_U/P_1}{P_0+2}$ where $P_0 = 1 - P_1$. It follows that $\frac{\partial \psi_2}{\partial P_1} = -\frac{2(P_1^2 m + c_U(3-2P_1))}{P_1^2(3-P_1)^2} \leq 0$. $\square$

Appendix S.4: Corrective Action Given a Bad Signal

In practice, shipment monitoring technologies not only enable contingent sourcing, but also make it possible for supply chain managers to take corrective actions in the hope that yield loss is averted. Upon receipt of an alert from the monitoring sensors that there has been some disturbance during transit (e.g., harmful handling or temperature deviation), the buying firm—either in collaboration with the transportation provider or through direct technology—might first attempt to resolve the disturbance before it results in yield loss.[8] Motivated by this, we now consider P_0 as the probability of a disturbance (e.g., an undesired temperature change) occurring with supplier U's shipment. A bad signal $s = B$ will be realized if a disturbance is detected. Upon receiving a bad signal, corrective action will be taken that resolves the disturbance with probability y, where y represents the buyer's capability to resolve a disturbance before the disturbance causes yield loss. If an occurring disturbance is not detected, it will result in shipment spoilage with certainty. [9] To focus on the primary insights, we return to the perfect information setting and assume the cost of taking corrective actions to be low enough so that the buyer will always try to resolve a detected disturbance. With the corrective-action capability, the buyer can make the contingent ordering decision at Time 1 based on whether the disturbance was resolved.[10] As such, the probability

[8] For instance, in agriculture-and-food product transportation, "if the seal of a container is broken, or temperature and humidity controls within the container fail, the sensors issue immediate alerts to supply chain managers so the situation can be mitigated" (Shacklett 2018, paragraph 17), e.g., through repair of the container seal or controls.

[9] Because we assume that action is free, we are agnostic as to who (the buyer, the supplier, or the transportation provider) undertakes or pays for the corrective action if the action is not automated.

[10] It is reasonable to assume that the buyer knows whether a detected issue was successfully fixed. For temperature-sensitive products, such as certain medicines and vaccines, there is often a rigorously required temperature range that must be maintained. Temperature sensors can trigger an alert before an excursion from the allowed limits and the firm can track the temperature during corrective action to know whether the limits were breached (and so the product failed) or not during problem resolution.

(when the buyer orders) of delivery failure from supplier U is $\hat{P}_0 = P_0(1-y)$ and the probability of successful delivery is $\hat{P}_1 = 1 - \hat{P}_0$.

Absent any corrective-action capability ($y = 0$), we have established in Proposition 4 that the buyer benefits from shipment information only if supplier R's cost c_R is large enough. In contrast, when corrective action (with a positive probability of success) is available, the buyer can also benefit from shipment information even when c_R is low:

Proposition S.4.1. *Suppose that shipment information is perfect (i.e., $\rho = 1$) and that given a bad signal $s = B$, the detected disturbance can be resolved by a corrective action with probability of $y > 0$. Then, there exists two thresholds $\underline{c_R} < \bar{c}_R$ such that the buyer is better off with shipment information if and only if $c_R < \underline{c_R}$ or $c_R > \bar{c}_R$.*

Figure S.4.1 plots the effect of corrective action capability on the expected profits of each of the supply chain parties as a function of supplier R's cost c_R. Plots are shown for increasing corrective-action success probabilities and for the benchmark case with no shipment information. The case of $y = 0$ is equivalent to the setting considered in §3 where shipment information enables contingent sourcing but not corrective action.

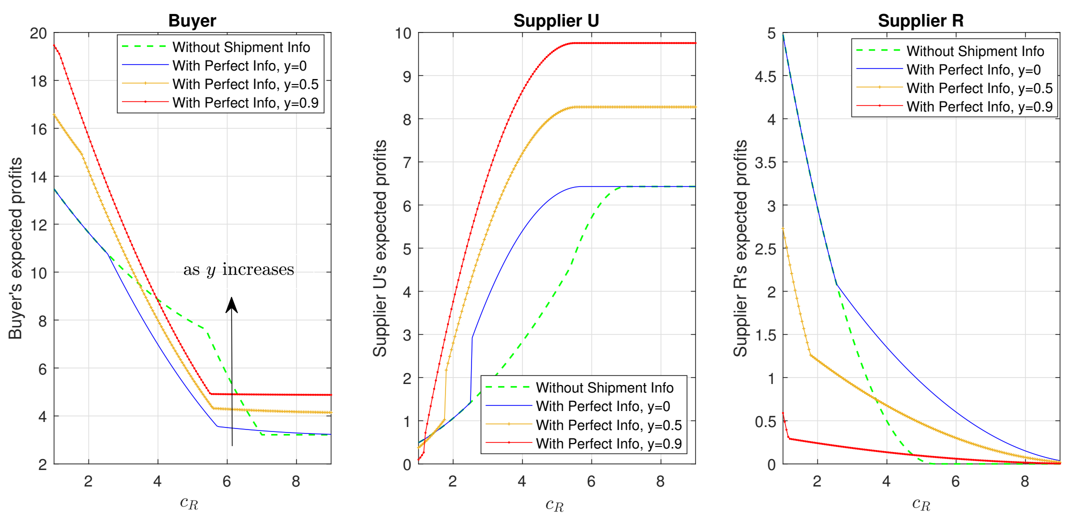

Figure S.4.1 Impact of corrective actions on the buyer's expected profits [$m = 10$, $c_U = 1$, $P_1 = 0.7$]

As illustrated in the left panel of Figure S.4.1, the buyer is more likely to benefit from shipment information as the success probability of corrective action y increases. The rationale is as follows. Corrective-action capability essentially reduces the unresolved disturbance probability for supplier U. This not only directly mitigates the buyer's risk but also attenuates the effect of reduced competition caused by contingent sourcing. With a higher y, a disturbance is more likely to be resolved so that the buyer is less likely to place an emergency order with supplier R. Being aware of this, supplier R has more incentive to compete for the initial order, which amplifies the competition to the benefit of the buyer. The impact of corrective-action capability on the suppliers can be seen in the right two panels of Figure S.4.1. Supplier R is generally worse off as corrective action can be taken; this can be seen by comparing the two $y > 0$ cases with $y = 0$. Supplier U is better off under corrective action in most cases except when c_R is very close to $c_U = 1$; in such instances, the amplified competition due to corrective actions has a dominant effect on supplier U. These findings suggest that to better unlock the promise of state-of-the-art shipment monitoring technologies, the buying firm should not rely on contingent sourcing as the only countermeasure to transportation disturbances because contingent sourcing can have a negative impact on supplier competition. The buyer should also develop the capability, possibly working with the supplier and transportation provider, to deploy personnel or automated container or packaging technology that can potentially resolve a detected disturbance before it results in actual yield loss.

Proof of Proposition S.4.1 We first consider the case when no contingent sourcing occurs in equilibrium, and then consider the case when a contingent sourcing equilibrium occurs.

If $c_R \leq \frac{\hat{P}_0 m + 2c_U/\hat{P}_1}{\hat{P}_0+2}$, then the buyer will not place any emergency order, i.e., $Q_E = 0$. As the emergency order is no long relevant, the buyer's problem is equivalent to one without shipment information. It suffices to show that the buyer's equilibrium payoff is increasing in P_1 under Equilibria (ii)(iii-a) and (iii-b), as the shipment information improves P_1 due to the corrective action, i.e., $y > 0$. For Equilibrium (ii) where both $Q_R^I > 0$ and $Q_U^I > 0$, by the Envelope Theorem, it is easy to show that the buyer's equilibrium payoff is decreasing in w_U^I and w_R^I. Further, by the expressions of w_U^I and w_R^I in Proposition 2, it follows that $\frac{\partial w_U^I}{\partial P_1} = \frac{-P_1^2(3m-c_R)-4(2-P_1)c_U}{(4-P_1)^2 P_1^2} \leq 0$ and $\frac{\partial w_R^I}{\partial P_1} = \frac{2c_R+c_U-6m}{(4-P_1)^2} \leq 0$. That is, both w_U^I and w_R^I decrease as P_1 increases, so the buyer's payoff is increasing in P_1. For Equilibrium (iii-a), the buyer's payoff is only relevant to and decreasing in w_R^I, while w_R^I decreases with P_1. For Equilibrium (iii-b), the buyer's payoff is constant in P_1. In summary, the buyer's payoff is increasing in P_1 and so it benefits from the shipment information.

For the case of $c_R > \frac{\hat{P}_0 m + 2c_U/\hat{P}_1}{\hat{P}_0+2}$, we need to examine different equilibria case by case as in the proof of Proposition 4. In the following, we focus on the case of $\frac{m+c_U/\hat{P}_1}{2} > \frac{2P_0 m + c_U}{P_0+1}$. If the reverse holds true, the proof is similar except that the combination of equilibria with and without shipment information is a bit different.

For $c_R > \frac{(1+P_0)m+c_U}{2}$, Equilibrium (i-a) occurs under both Scenarios I and N. Clearly, the buyer is better off with shipment information in this case.

For $\frac{m+c_U/\hat{P}_1}{2} < c_R \leq \frac{(1+P_0)m+c_U}{2}$, Equilibrium (i-a) occurs under Scenario I, while under Scenario N, Equilibrium (i-b) occurs. Invoking the corresponding equilibrium prices, one can verify that $\pi_B^{I(ia)} - \pi_B^{N(ib)}$ is quadratic, concave and increasing in c_R within $c_R \leq m$. Solving a quadratic inequality w.r.t. c_R, we obtain that $\pi_B^{I(ia)} \geq \pi_B^{N(ib)}$ iff $c_R \geq \bar{c}_R$ where

$$\bar{c}_R = m - \frac{[m(y+(1-y)P_1) - c_U]\sqrt{P_1}}{\sqrt{(y+(1-y)P_1)[4-(1-y)P_1+(1-y)P_1^2]}}. \tag{S.4.1}$$

We note that the threshold derived in Proposition 4 is a special case of $\bar{c}_R$ when $y=0$.

For $\frac{2P_0m+c_U}{P_0+1} < c_R \leq \frac{m+c_U/\hat{P}_1}{2}$, we have Equilibrium (i-b) under both Scenarios I and N. One can verify that $\pi_B^{I(ib)} - \pi_B^{N(ib)} = -\frac{(1-P_1)(4-3P_1(y-1))(m-c_R)^2}{16P_1} \leq 0$.

For $\frac{\hat{P}_0m+2c_U/\hat{P}_1}{\hat{P}_0+2} < c_R \leq \frac{2P_0m+c_U}{P_0+1}$, we have Equilibrium (i-b) under Scenario I and Equilibrium (ii) under Scenario N.

$\frac{\partial(\pi_B^{I(ib)} - \pi_B^{N(ii)})}{\partial c_R} = -\frac{A}{8(P_1-4)^2(1-P_1)}$. where

$$A = -4P_1(c_U + 30my - 9m) + c_R\left(-3P_1^4(y-1) + P_1^3(30y-26) + P_1^2(63-99y) + 12P_1(10y-3) - 48y\right)$$
$$+ 3mP_1^4(y-1) + mP_1^3(26-30y) + mP_1^2(99y-59) + 48my$$

Furthermore, $\frac{\partial A}{\partial y} = 3\left(P_1^2 - 5P_1 + 4\right)^2(m - c_R) \geq 0$. So, A is increasing in y and $\frac{\partial(\pi_B^{I(ib)} - \pi_B^{N(ii)})}{\partial c_R}$ is decreasing in y. That is, $\frac{\partial(\pi_B^{I(ib)} - \pi_B^{N(ii)})}{\partial c_R} \leq \frac{\partial(\pi_B^{I(ib)} - \pi_B^{N(ii)})}{\partial c_R}|_{y=0}$. The right-hand side of the inequality is in fact (C.13) in the proof of Proposition 4 when there is no corrective action. Recall that we have established that $\frac{\partial(\pi_B^{I(ib)} - \pi_B^{N(ii)})}{\partial c_R}|_{y=0} \leq 0$. Thus, $\pi_B^{I(ib)} - \pi_B^{N(ii)}$ is decreasing in c_R. On the other hand, with a positive y, we have $\pi_B^{I(ib)} > \pi_B^{N(ii)}$ at the left boundary point $c_R = \frac{\hat{P}_0m+2c_U/\hat{P}_1}{\hat{P}_0+2}$ where $\pi_B^{I(ib)} = \pi_B^{I(ii)}$, while $\pi_B^{I(ib)} \leq \pi_B^{N(ii)}$ at the right boundary $c_R = \frac{2P_0m+c_U}{P_0+1}$ where $\pi_B^{N(ii)} = \pi_N^{I(ib)}$ Therefore, there exists a $\underline{c_R}$ within the considered interval such that $\pi_B^{I(ib)} \geq \pi_B^{N(ii)}$ iff $c_R \leq \underline{c_R}$. $\square$

Appendix S.5: Incomplete Information

S.5.1. Analysis

We assumed common knowledge of the underlying parameters in our base model. Although the buyer does not need to know the supplier costs when making its sourcing quantity decisions, in Proposition 4 we established the conditions under which a buyer would be better or worse off with contingent sourcing, and those conditions depend on the supplier costs. In effect, the buyer needs to know the supplier costs if it is to know whether or not it is better off when contingent sourcing is an option. In some settings, buyers can effectively estimate supplier production costs (and suppliers can estimate their competitors' costs), and so common knowledge is a reasonable approximation. This will not be the case in all settings, and it is of interest to consider a setting with private information. To do so, we need to solve for the Bayesian Nash equilibrium (BNE) in an incomplete information game. As we show in what follows, our result can be extended to such a game.

Table S.5.1 Characterization of the BNE with perfect shipment information assuming $c_R > \psi_2(h)$

Case	Condition	w_U^{l*}	w_U^{h*}	w_E^*	w_R^*
I-aa	$c_R > \psi_1(h)$	$\frac{P_1 m + c_U^l}{2P_1}$	$\frac{P_1 m + c_U^h}{2P_1}$	$\frac{m+c_R}{2}$	$w_R^* \geq P_1 w_U^h + P_0 w_E^*$
I-ab	$\psi_1(l) < c_R \leq \psi_1(h)$	$\frac{P_1 m + c_U^l}{2P_1}$	c_R	$\frac{m+c_R}{2}$	$w_R^* = P_1 c_R + P_0 w_E^*$
I-bb	$\psi_2(h) < c_R \leq \psi_1(l)$	c_R	c_R	$\frac{m+c_R}{2}$	$w_R^* = P_1 c_R + P_0 w_E^*$

To demonstrate that we can generalize Proposition 4 analytically, let us consider perfect shipment information ($\rho = 1$) and focus on a case in which only c_U is private information while c_R is common knowledge. Assume $c_U = c_U^l$ with probability α and $c_U = c_U^h$ with probability $1-\alpha$, where $c_U^l < c_U^h$. Only supplier U observes its type $i \in \{l, h\}$. Supplier R and the buyer only know the probability α. In practice, the probability distribution of c_U can be estimated using public sources such as local wage information, raw material and energy prices.

The supplier production costs are not relevant to the buyer's ordering decision. Thus, given (w_R, w_E) and w_U the buyer's optimal order quantities are the same as characterized in the base model. The supplier competition becomes an incomplete information game. We need to solve for a pure-strategy Bayesian Nash equilibrium (BNE). For each type $i \in \{l, h\}$, supplier U chooses a wholesale price w_U^i such that $w_U^{i*} \in \arg\max_{w_U^i}(w_U^i - c_U^i)Q_U^*(w_U^i, w_R, w_E)$. Supplier R chooses (w_R, w_E) to maximize its *expected* payoff:

$$(w_R^*, w_E^*) \in \arg\max_{w_R, w_E}(w_R - c_R)E_i[Q_R^*(w_U^i, w_R, w_E)] + P_0(w_E - c_R)E_i[Q_E^*(w_U^i, w_R, w_E)]$$

where the expectation is taken over supplier U's type i. A strategy profile $(w_U^{l*}, w_U^{h*}; w_R^*, w_E^*)$ constitutes a BNE if the wholesale prices maximize the corresponding payoffs. We have three best response functions for the two types of supplier U and supplier R, respectively.

We focus here on the most relevant cases, i.e., when contingent sourcing occurs in equilibrium, by assuming $c_R > \psi_2(h)$. This is not unreasonable in many practical situations, while other players may not know supplier U's specific production cost they can know that supplier U which is subject to yield risk will have a meaningfully lower cost than the reliable supplier R. Define type-dependent thresholds $\psi_1(i) = \frac{P_1 m + c_U^i}{2P_1}$ and $\psi_2(i) = \frac{P_0 m + 2c_U^i/P_1}{P_0 + 2}$. The BNE with perfect shipment information is as characterized below. All the proofs of the propositions in this section can be found in §S.5.2.

PROPOSITION S.5.1. *Assuming perfect shipment information and $c_R > \psi_2(h)$, a BNE exists as characterized in Table S.5.1.*

Define $\phi_1(i) = \frac{(1+P_0)m + c_U^i}{2}$ and $\phi_2(i) = \frac{2P_0 m + c_U^i}{P_0 + 1}$ for $i \in \{l, h\}$. Similarly, we can derive the BNE absent of shipment information or contingent sourcing under the condition of $c_R > \psi_2(h)$.

Table S.5.2 **Characterization of the BNE without shipment information assuming** $c_R > \phi_2(i), \forall i$

Case	Condition	w_U^{l*}	w_U^{h*}	w_R^*
N-aa	$c_R > \phi_1(h)$	$\frac{P_1 m + c_U^l}{2P_1}$	$\frac{P_1 m + c_U^h}{2P_1}$	c_R
N-ab	$\phi_1(l) < c_R \le \phi_1(h)$	$\frac{P_1 m + c_U^l}{2P_1}$	$\frac{c_R - P_0 m}{P_1}$	c_R
N-bb	$\phi_2(h) < c_R \le \phi_1(l)$	$\frac{c_R - P_0 m}{P_1}$	$\frac{c_R - P_0 m}{P_1}$	c_R

Proposition S.5.2. *Assuming $c_R > \phi_2(h)$ and no shipment information such that contingent sourcing is not possible, a BNE exists as characterized in Table S.5.2.*

We can now compare the buyer's expected profits with and without contingent sourcing. Let us focus on a representative case of $\phi_2(h) < \psi_1(l)$. Note that $\phi_2(h) < \psi_1(l)$ iff $2P_1 c_U^h - (2 - P_1)c_U^l \le (3P_1 - 2)P_1 m$, which holds when c_U^h and c_U^l are not too different from each other and $P_1 > 2/3$. As mentioned, the buyer and supplier R can obtain reasonable estimate of supplier U's production cost through benchmarking and public sources. Hence, the gap between c_h and c_l would not be too large in practice. We note that a similar analysis can be conducted for the case of $\phi_2(h) \ge \psi_1(l)$.

Proposition S.5.3. *Assuming $c_R > \phi_2(h)$ and $\phi_2(h) < \psi_1(l)$, there exists a threshold κ such that contingent sourcing makes the buyer better off for $c_R > \kappa$ but worse off for $c_R \le \kappa$. Moreover, for $\phi_1(l) \le \psi_1(h)$,*

$$\kappa = \begin{cases} m - \frac{P_1 m - c_U^l}{\sqrt{4 - P_1 + P_1^2(4\alpha - 3)}} & \text{if } \alpha > 1 - \frac{P_1}{4(1+P_1)} \\ m - \frac{(P_1 m - c_U^h)\sqrt{1-\alpha}}{\sqrt{4(1-\alpha) - P_1 + P_1^2}} & \text{otherwise;} \end{cases}$$

for $\phi_1(l) > \psi_1(h)$,

$$\kappa = \begin{cases} m - \frac{P_1 m - c_U^l}{\sqrt{4 - P_1 + P_1^2(4\alpha - 3)}} & \text{if } \alpha > A_1 \\ m - \sqrt{\frac{\alpha(P_1 m - c_U^l)^2 + (1-\alpha)(P_1 m - c_U^h)^2}{4 - P_1 + P_1^2}} & \text{if } A_2 < \alpha \le A_1 \\ m - \frac{(P_1 m - c_U^h)\sqrt{1-\alpha}}{\sqrt{4(1-\alpha) - P_1 + P_1^2}} & \text{otherwise;} \end{cases}$$

where $A_1 = \frac{(P_1 m - c_U^h)^2(4 + 3P_1)P_0}{4P_1^2(c_U^h - c_U^l)(2P_1 m - c_U^l - c_U^h)}$ and $A_2 = 1 - \frac{P_0 P_1 (P_1 m - c_U^l)^2}{4(c_U^h - c_U^l)(2P_1 m - c_U^l - c_U^h)}$.

The above result generalizes the condition we derived earlier in the base model for the effect of contingent sourcing on the buyer. The buyer can use the probability distribution of c_U, instead of a specific value, to determine if contingent sourcing is valuable. It can be seen that the generalized threshold κ depends on c_U^l, c_U^h and the l-type probability α; as α becomes larger, κ is closer to $m - \frac{P_1 m - c_U^l}{\sqrt{4 - P_1 + P_1^2}}$, the original threshold under c_U^l.

In general, there can be more than two types for each supplier, and shipment information can be imperfect. Much more complicated BNE may arise in which, for instance, the buyer chooses a diversification strategy for some supplier types but uses contingent sourcing for other types. Although analytical results may be impossible to derive, to evaluate the effect of contingent sourcing, we can always numerically find the BNE for the incomplete information game and then evaluate the buyer's expected payoff. In general, given that supplier U's cost c_U^i is drawn from one of m values where $i \in 1,2,...,m$ and the i-type is associated with a probability mass α_i, and similarly supplier R's cost c_R^j is drawn from one of n values where $j \in \{1,2,...,n\}$ and the corresponding probability mass is β_j. Each supplier's type is privately observed by itself, while the competitor and the buyer only know the prior distribution. A BNE, constituted by a set of type-dependent prices w_U^{i*}, w_R^{j*} and w_E^{j*} is defined as

$$w_U^{i*} \in \arg\max(w_U^i - c_U^i) \sum_{j=1}^{n} \beta_j Q_U^*(w_U^i, w_R^j) \; \forall i \in \{1,2,...,m\}$$

$$(w_R^{j*}, w_E^{j*}) \in \arg\max(w_R^j - c_R^j) \sum_{i=1}^{n} \alpha_i Q_R^*(w_U^i, w_R^j, w_E^j) + (w_E^j - c_R^j) P_B \sum_{i=1}^{n} \alpha_i Q_E^*(w_U^i, w_R^j, w_E^j) \forall j \in \{1,2,...,n\}$$

For any given (w_U^i, w_R^j, w_E^j), the buyer's order quantities can be efficiently computed per the closed-form expressions given by Proposition 1. If the buyer wants to specifically evaluate the benefit of improving ρ to ρ' (e.g., adopting more advanced shipment monitoring devices), a best-response algorithm similar to Algorithm S.6.2 can be used to determine the BNE with ρ and ρ' respectively. Then, the buyer can evaluate the change in the resulting expected payoffs under the two BNE. Because of incomplete information, in each iteration $m+n$ best responses need to be calculated for each player of each type.

In the main paper we provided justification that the delivery probability P_1 may be common knowledge reasonable settings. However, it may not be common knowledge in all settings. For example, P_1 may be known to the buyer (as receiver of the goods) and supplier U (as sender of the goods) but unknown to supplier R. In this case, supplier R will compete with supplier U based on its belief about P_1, thus engaging in an incomplete information game similar to that with private cost information as we analyzed in the above. A similar approach can be used to address this setting if supplier R offers a pre-committed contract (w_R, w_E) at the first stage as assumed in the base model. If we consider an alternative sequence of events where supplier R offers the emergency contract at Time 1 as discussed in our model extension (§5.3), the problem can be challenging. This is because in this situation the buyer's initial order quantity Q_R at Time 0 can be an informative signal to convey its knowledge about P_1 to supplier R who in turn determines the emergency contract. Consequently, supplier R will first compete with supplier U in an incomplete information simultaneous-move game, and then become involved in a signaling game when the buyer places initial orders. The overall game appears intractable. To explore such a situation can be a valuable direction for future research but we suspect a different model framework with simplification on other aspects is required.

S.5.2. Proofs of Results in Appendix S.5

Proof of Proposition S.5.1 For each type i, supplier U's best response is given by Lemma A.2 provided $c_U = c_U^i$.

We need to analyze supplier R's best response under incomplete information. For tractability, we focus on the equilibria in which $w_U^l < c_R$ and $w_U^l \le w_U^h$ and so restrict attention to these cases when analyzing supplier R's best response function.

Note that we still need to examine if supplier R opts to profit from the buyer's initial order in the proof to establish that supplier R will not deviate from a contingent sourcing equilibrium. Therefore, we consider supplier R optimizing over (w_R, w_E) for *three* separate cases and then select the global optimal solution.

(i) If $w_R - P_0 w_E \ge P_1 w_U^i$ for both i, then supplier R profits from the emergency order irrespective of supplier U's type, for which case it is easy to show that supplier R's maximum payoff $\pi_R^i = \frac{1}{8}P_0(m-c_R)^2$.

(ii) If $P_1 w_U^l \le w_R - P_0 w_E < P_1 w_U^h$, then supplier R will profit from the initial order if supplier U is h-type but from the emergency order if supplier U is l-type. In this case, we have

$$\pi_R^{ii} = \max_{w_R, w_E} (w_R - c_R)(1-\alpha)Q_R^*(w_U^h, w_R, w_E) + \alpha P_0(w_E - c_R)Q_E^*(w_U^l, w_R, w_E)$$

By Proposition A.1, $Q_E^*(w_U^l, w_R, w_E) = (m - w_E)/2$ and $Q_R^*(w_U^h, w_R, w_E)$ is independent of w_E. Thus, the above problem can be decomposed into maximizing the first term over w_R and maximizing the second term over w_E. Ignoring the constraint $P_1 w_U^l \le w_R - P_0 w_E < P_1 w_U^h$ for the moment, we have $w_E^* = \frac{m+c_R}{2}$ and

$$\pi_R^{ii} = (1-\alpha)\max_{w_R}(w_R - c_R)Q_R^*(w_U^h, w_R) + \frac{1}{8}\alpha P_0(m-c_R)^2.$$

Note that $\pi_R^i \ge \pi_R^{ii}$ iff $\frac{1}{8}P_0(m-c_R)^2 \ge \max_{w_R}(w_R - c_R)Q_R^*(w_U^h, w_R, w_E)$. This is the same comparison we have analyzed in the proof of Lemma A.1. The previously established result implies that $\pi_R^i \ge \pi_R^{ii}$ iff $w_U^h \le c_R$. So, if $w_U^h \le c_R$, case (i) yields the global optimal solution.

For the case of $w_U^h > c_R$, we restrict attention to the case that supplier R shares the initial order with type-h supplier U. So, in the above, $Q_R^*(w_U^h, w_R)$ is given by case (ii) of Proposition A.1. This leads to an optimal $w_R^* = \frac{P_1 w_U^h + P_0 m + c_R}{2}$ under the condition of $c_R < w_U^h \le \frac{P_0 m + c_R}{P_0 + 1}$. Finally, one can verify that $P_1 w_U^l \le w_R^* - P_0 w_E^* < P_1 w_U^h$ holds at w_R^* and w_E^* for $w_U^l \le c_R < w_U^h$. So, the solution (w_R^*, w_E^*) is attainable.

(iii) If $w_U^l \le w_R$ and $w_R - P_0 w_E < P_1 w_U^l$, then $\pi_R^{iii} = \max_{w_R}(w_R - c_R)\frac{P_0 m - w_R + P_1(\alpha w_U^l + (1-\alpha)w_U^h)}{2P_0}$. The interior solution is given by $w_R^* = \frac{P_0 m + P_1(\alpha w_U^l + (1-\alpha)w_U^h) + c_R}{2}$ which leads to $\pi_R^{iii} = \frac{(P_0 m + P_1(\alpha w_U^l + (1-\alpha)w_U^h) + c_R)^2}{8P_0}$.

Comparing the profits under (ii) and (iii), we have $\pi_R^{ii} - \pi_R^{iii} = -\frac{P_1\alpha}{8P_0}D(c_R)$ where $D(c_R)$ is a quadratic convex function which is decreasing if $c_R \geq w_U^l$. We have $\pi_R^{ii} > \pi_R^{iii}$ iff $c_R > D(\alpha)$ where

$$D(\alpha) = \frac{1}{1+P_0}\left(P_0 m + w_U^l - \sqrt{P_0^2(m-w_U^l)^2 + (1-P_0^2)(1-\alpha)(w_U^h - w_U^l)^2}\right).$$

Note that $D(1) = w_U^l$ and $D(\alpha)$ is increasing in α. Thus, $c_R \geq w_U^l$ is a *sufficient* condition for strategy (ii) to be optimal for supplier R. On a side note, recall that under complete information, $c_R \geq w_U$ is actually a sufficient and necessary condition for supplier R to opt for emergency order. Given incomplete information, profiting partially from emergency order becomes possible, the change in $D(\alpha)$ shows that supplier R has more incentive to serve for an emergency order (partially).

The best response of supplier R (restricted to the case of $w_U^l \leq c_R$) is therefore given by

R(i) If $w_U^h \leq c_R$ for all i, $w_E^* = \frac{m+c_R}{2}$ and any $w_R^* \geq P_0 w_E^* + P_1 w_U^h$.

R(ii) If $w_U^l \leq c_R$ and $c_R < w_U^h \leq \frac{P_0 m + c_R}{P_0+1}$, $w_R^* = \frac{P_1 w_U^h + P_0 m + c_R}{2}$, $w_E^* = \frac{m+c_R}{2}$.

In principle, one can obtain each possible equilibrium and the associated conditions by examining all the possible intersections of the three best response functions: supplier R's and the two types of supplier U's best responses. Instead of enumerating all the possible cases, we focus on the most relevant cases as to the impact of contingent sourcing. The three cases presented in Table S.5.1 are obtained by the following intersections.

- Case I-aa. Intersection of R(i), U^l(i) and U^h(i).
- Case I-ab. Intersection of R(i), U^l(i) and U^h(ii).
- Case I-bb. Intersection of R(i), U^l(ii) and U^h(ii).

In the above, we use, for instance, U^l(i) to represent the part (i) of l-type supplier U's best response given in Lemma A.2. $\square$

Proof of Proposition S.5.2 Some results in §a:NoIoT-results of this document will be used in the proof.

Supplier U's best response is as given in Lemma S.2.2 provided either $c_U = c_U^l$ or $c_U = c_U^h$.

Let $\bar{w}_U = \alpha w_U^l + (1-\alpha) w_U^h$. Supplier R's best response is given by $w_R = \arg\max_{w_R} \pi_R(w_R | w_U^l, w_U^h)$ where

$$\begin{aligned}\pi_R(w_R|w_U^l, w_U^h) &= (w_R - c_R)\left[\alpha Q_R^*(w_U^l, w_R) + (1-\alpha) Q_R^*(w_U^h, w_R)\right] \\ &= \begin{cases} (w_R - c_R)[P_0 m - w_R + P_1 \bar{w}_U]/(2P_0) \text{ if } w_U^h < w_R \leq P_1 w_U^l + P_0 m < w_R \\ (w_R - c_R)(1-\alpha)(P_0 m - w_R + P_1 w_U^h)/(2P_0) \text{ if } P_1 w_U^l + P_0 m < w_R \leq P_1 w_U^h + P_0 m \\ 0 \text{ if } w_R > P_1 w_U^h + P_0 m \end{cases}\end{aligned}$$

where the different cases follow from Q_R^* as characterized in Proposition S.2.1. Note that without loss of generality we have focused the case of $w_U^l \leq w_U^h$ and omitted the case when supplier R monopolizes the market which occurs if $w_R \leq w_U^h$.

For the first case, the interior solution is $w_R^o = \frac{P_1(\alpha w_U^l + (1-\alpha) w_U^h) + P_0 m + c_R}{2}$ which is attainable if $2w_U^h - P_1 \bar{w}_U - P_0 m < c_R \leq P_0 m + 2P_1 w_U^l - P_1 \bar{w}_U$. If attainable, it is also global optimal.

If $c_R > P_0 m + 2P_1 w_U^l - P_1 \bar{w}_U$, then the optimal solution has to be found in the second/third case. For the second case, the interior solution is $w_R^* = \frac{P_1 w_U^h + P_0 m + c_R}{2}$, which is attainable if $P_0 m + 2P_1 w_U^l - P_1 w_U^h < c_R \leq P_1 w_U^h + P_0 m$. If $c_R > P_1 w_U^h + P_0 m$, we will have the third case.

Combining the above cases and noticing that the second-case solution is dominated by the first case when the two solutions are both attainable, we obtain supplier R's best response (excluding the uninteresting monopolistic case) as follows.

- R(i): $w_R^* = c_R$ if $c_R > P_1 w_U^h + P_0 m$.
- R(ii): $w_R^* = \frac{P_1 w_U^h + P_0 m + c_R}{2}$ if $P_0 m + 2P_1 w_U^l - P_1 \bar{w}_U < c_R < P_1 w_U^h + P_0 m$
- R(iii): $w_R^* = \frac{P_1 \bar{w}_U + P_0 m + c_R}{2}$ if $w_U^h - P_1 \bar{w}_U - P_0 m < c_R \leq P_0 m + 2P_1 w_U^l - P_1 \bar{w}_U$

Each possible equilibrium and the associated conditions can be obtained by examining the intersection of the best responses of supplier R and the two types of supplier U. Specifically, the three cases presented in Table S.5.2 are obtained by the following three types of intersections.

- Case N-aa: intersection of R(i), U^l(i) and U^h(i).
- Case N-ab: intersection of R(i), U^l(i) and U^h(ii).
- Case N-bb: intersection of R(i), U^l(ii) and U^h(ii).

In the above, we use, for instance, U^l(i) to represent the part (i) of l-type supplier U's best response given in Lemma S.2.2.

□

Proof of Proposition S.5.3 Note that we always have $\psi_1(i) \leq \phi_1(i)$ for each given i, $\phi_2(h) < \phi_1(h)$, $\phi_1(l) < \phi_1(h)$, and $\psi_1(l) < \psi_1(h)$. Assuming $\psi_1(l) \geq \phi_2(h)$, there are two different cases with $\psi_1(h) \geq \phi_1(l)$ and $\psi_1(h) < \phi_1(l)$. We analyze the two cases separately below.

For $\phi_1(l) \leq \psi_1(h)$, the relation among thresholds is shown in Figure S.5.1.

	Case 1	*Case 2*	*Case 3*	*Case 4*	*Case 5*
I	bb	ab	ab	aa	aa
N	bb	bb	ab	ab	aa

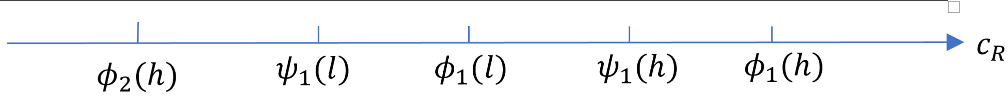

Figure S.5.1 Impact of contingent sourcing on the BNE under incomplete information if $\phi_1(l) \leq \psi_1(h)$

The buyer's expected profit under scenario $S \in \{I, N\}$ is given by $\pi_B^S = \alpha \pi_B^{Sl} + (1-\alpha)\pi_B^{Sh}$ where π_B^{Si} denotes the profit given that supplier U is of type $i \in \{l, h\}$ under scenario $S \in \{I, N\}$.

First, we have $\pi_B^I \leq \pi_B^N$ for Case 1 and $\pi_B^I > \pi_B^N$ for Case 5. This is because we can directly apply the previous result in the proof of Proposition 4 in these two cases, as the buyer ends up in the same type of equilibrium for both i. The previous result has established that for any given c_U, the buyer's payoff is lower (higher) under I than under N if the equilibrium type is b, i.e., supplier U limiting pricing (a, i.e., supplier U pricing as a monopoly).

For Case 2, we have $\frac{\partial}{\partial c_R}(\pi_B^I - \pi_B^N) = \frac{(m-c_R)(4-P_1(1+3P_1-4\alpha P_1))}{8P_1} \geq 0$ for all $\alpha \in [0,1]$. So, $\pi_B^I - \pi_B^N$ is increasing.

For Case 3, we have $\frac{\partial}{\partial c_R}(\pi_B^I - \pi_B^N) = \frac{(m-c_R)P_0(4+3P_1-4\alpha(P_1+1))}{8P_1}$. So, $\pi_B^I - \pi_B^N$ is increasing for $\alpha \leq 1 - \frac{P_1}{4(1+P_1)}$ but decreasing otherwise. Moreover, the sign of $\pi_B^I - \pi_B^N$ is easy to determine in this case. Note that $\pi_B^I - \pi_B^N = -\frac{(m-c_R)^2 P_0(4+3P_1-4\alpha(P_1+1))}{16P_1}$. Thus, $\pi_B^I - \pi_B^N \leq 0$ for $\alpha \leq 1 - \frac{P_1}{4(1+P_1)}$, and $\pi_B^I - \pi_B^N > 0$ otherwise.

For Case 4, $\frac{\partial}{\partial c_R}(\pi_B^I - \pi_B^N) = \frac{(m-c_R)[4(1-\alpha)-P_1P_0]}{8P_1}$. So, $\pi_B^I - \pi_B^N$ is increasing for $\alpha \leq 1 - \frac{P_1P_0}{4}$ but decreasing otherwise.

Putting together the above monotone properties along with the continuity of the buyer's profit and the positivity/negativity of $\pi_B^I - \pi_B^N$ in cases 1,3 and 5, we can conclude $\pi_B^I - \pi_B^N$ changes its sign from negative to positive only once as c_R increases, as shown in Table S.5.3 where the sign-changing case is marked with $\star$.

Table S.5.3 Monotone properties and the sign of $\pi_B^I - \pi_B^N$

Condition	Case 1	Case 2	Case 3	Case 4	Case 5
$\alpha > 1 - \frac{P_0P_1}{4}$	$-$	$\uparrow^\star$	$+$	$\downarrow$	$+$
$1 - \frac{P_1}{4(1+P_1)} < \alpha \leq 1 - \frac{P_0P_1}{4}$	$-$	$\uparrow^\star$	$+$	$\uparrow$	$+$
$\alpha \leq 1 - \frac{P_1}{4(1+P_1)}$	$-$	$\uparrow$	$-$	$\uparrow^\star$	$+$

For $\alpha > 1 - \frac{P_1}{4(1+P_1)}$, κ is given by the smaller root of c_R for $\pi_B^I - \pi_B^N = 0$ under Case 2, i.e., $\kappa = m - \frac{P_1 m - c_U^l}{\sqrt{4-P_1+P_1^2(4\alpha-3)}}$.

For $\alpha \leq 1 - \frac{P_1}{4(1+P_1)}$, κ is given by the smaller root of c_R for $\pi_B^I - \pi_B^N = 0$ under Case 4, i.e., $\kappa = m - \frac{(P_1 m - c_U^h)\sqrt{1-\alpha}}{\sqrt{4(1-\alpha)-P_1+P_1^2}}$.

For $\phi_1(l) > \psi_1(h)$, the relation among thresholds is shown in Figure S.5.2. Compared to the previous analysis, only the third case changes. In Case 3$'$, $\pi_B^I - \pi_B^N$ is increasing in c_R. Examining the two boundary points of Case 3$'$, we have

$$\pi_B^I - \pi_B^N|_{c_R=\psi_1(h)} \geq 0 \text{ iff } \alpha \geq A_1 := \frac{(P_1 m - c_U^h)^2(4+3P_1)P_0}{4P_1^2(c_U^h - c_U^l)(2P_1 m - c_U^l - c_U^h)}$$

and

$$\pi_B^I - \pi_B^N|_{c_R=\phi_1(l)} \geq 0 \text{ iff } \alpha \geq A_2 := 1 - \frac{P_0P_1(P_1 m - c_U^l)^2}{4(c_U^h - c_U^l)(2P_1 m - c_U^l - c_U^h)}$$

	Case 1	Case 2	Case 3′	Case 4	Case 5
I	bb	ab	aa	aa	aa
N	bb	bb	bb	ab	aa

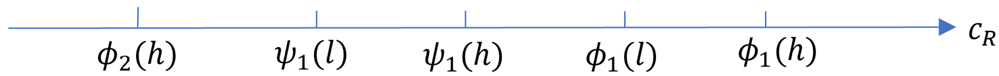

Figure S.5.2 Impact of contingent sourcing on the BNE under incomplete information if $\phi_1(l) > \psi_1(h)$

One can verify that $A_1 > A_2$ iff $\phi_1(l) > \psi_1(h)$, i.e., the case being considered. As a result, as c_R increases, $\pi_B^I - \pi_B^N$ changes its sign from negative to positive in Case 2 if $\alpha > A_1$, in Case 3′ if $A_2 < \alpha \leq A_3$, and in Case 4 otherwise. The sign-changing points for Cases 2 and 4 are the same as before; for Case 3′ is given by $\kappa = m - \sqrt{\frac{\alpha(P_1 m - c_U^l)^2 + (1-\alpha)(P_1 m - c_U^h)^2}{4 - P_1 + P_1^2}}$ □

Appendix S.6: Supplier R Setting w_E at Time 1

We consider the sequence of events as follows. At Time 0, suppliers R and U simultaneously determine w_R and w_U, respectively; the buyer determines initial order quantities Q_R and Q_U. At Time 1, supplier R offers w_E; the buyer (privately) observes s and determines $Q_E(s)$. At Time 2, ordered items are delivered with yield loss being realized. We assume that at Time 1 the buyer is not allowed to revise Q_R and supplier R can observe or form a correct belief of Q_U when choosing w_E.

S.6.1. Supplier R's Emergency Pricing

Suppose that supplier R determines w_E at Time 1 after the buyer receives a signal s. To supplier R, s is a random variable. So, supplier R maximizes its expected profit from the emergency order: $V = (w_E - c_R)\sum_{s\in\{G,B\}} P_s Q_E^*(s)$ where $Q_E^*(s)$ is the optimal solution to the buyer's emergency sourcing problem:

$$\max_{Q_E(s)\geq 0} P_{1s}R(Q_U + Q_R + Q_E(s)) + P_{0s}R(Q_R + Q_E(s)) - w_E Q_E(s) \text{ for both } s \in \{G, B\}.$$

It is easy to show the following.

Lemma S.6.1. *Given w_E, the buyer's optimal emergency order quantities $Q_E^*(G)$ and $Q_E^*(B)$ are given below.*

(i) $Q_E^*(G) = Q_E^*(B) = 0$ *if* $w_E \geq m - 2Q_R$.

(ii) $Q_E^*(G) = 0, Q_E^*(B) = \frac{1}{2}(m - 2Q_R - w_E)$ *if* $m - 2Q_R - 2P_{1G}Q_U \leq w_E < m - 2Q_R$.

(iii) $Q_E^*(G) = \frac{1}{2}(m - 2Q_R - 2P_{1G}Q_U - w_E), Q_E^*(B) = \frac{1}{2}(m - 2Q_R - w_E)$ *if* $w_E < m - 2Q_R - 2P_{1G}Q_U$.

Accordingly, supplier R's optimal emergency price w_E^* depends on whether it intends to sell to the buyer for any signal s, for only $s = B$, or not to sell at all.

PROPOSITION S.6.1. *Supplier R's optimal emergency wholesale price* w_E^* *and the expected profit from emergency order* V^* *are given by one of the following cases:*

(i) If $c_R \geq m-2Q_R$*, then supplier R will not offer the emergency order.*

(ii) If $m-2Q_R-2P_{1G}(1+\sqrt{P_B})Q_U \leq c_R < m-2Q_R$*, then* $w_E^* = \frac{1}{2}(m-2Q_R+c_R)$*, and* $V^* = \frac{1}{8}P_B(m-2Q_R-c_R)^2$*; the buyer orders* $Q_E^*(G)=0$ *and* $Q_E^*(B)=\frac{1}{4}(m-2Q_R-c_R)$*.*

(iii) Otherwise, $w_E^* = \frac{1}{2}[m-2Q_R-2P_{1G}P_GQ_U+c_R]$ *and* $V^* = \frac{1}{8}[m-2(Q_R+P_{1G}P_GQ_U)-c_R]^2$*; the buyer orders* $Q_E^*(G)=\frac{1}{4}[m-2Q_R-2P_{1G}(1+P_B)Q_U-c_R]$ *and* $Q_E^*(B)=\frac{1}{4}(m-2Q_R+2P_{1G}P_GQ_U-c_R)$*.*

S.6.2. The Buyer's Initial Ordering Problem

When deciding on the initial orders, the buyer maximizes the expected profit as given below.

$$\pi_B(Q_U,Q_R) = \sum_{s\in\{G,B\}} P_s[P_{1s}R(Q_U+Q_R+Q_E^*(s))+P_{0s}R(Q_R+Q_E^*(s))-w_E^*Q_E^*(s)]-P_1w_UQ_U-w_RQ_R \tag{S.6.1}$$

where $Q_E^*(s)$ and w_E^* depends on (Q_U,Q_R) as characterized in Proposition S.6.1. It is easy to see that Case(i) of Proposition S.6.1 will never occur in equilibrium as Q_R cannot exceed $(m-c_R)/2$ unless $w_R \leq c_R$. To determine the buyer's optimal initial order sizes, we need to solve two subproblems corresponding to cases (ii) and (iii) of Proposition S.6.1, respectively. For each subproblem, substituting the corresponding closed-form expressions of $Q_E^*(s)$ and w_E^* into (S.6.1), we have a concave maximization problem with a similar structure to the buyer's problem in our base model. By exploiting the optimality conditions of each subproblem, we develop a solution approach as described in Algorithm S.6.2. In Steps 1 and 2, we determine the solutions to the two subproblems, respectively, ignoring the condition, $m-2Q_R-2P_{1G}(1+\sqrt{P_B})Q_U \leq c_R$ or $> c_R$; see cases (ii) and (iii) of Proposition S.6.1. In Step 3, we check if each solution satisfies the corresponding condition: If both do, pick the one leading to the highest profit; if only one does, the one will be the global optimal; if neither does, then the global optimal solution must be on the boundary $m-2Q_R-2P_{1G}(1+\sqrt{P_B})Q_U = c_R$, which can be found in Step 4.

PROPOSITION S.6.2. *If supplier R offers* w_E *at Time 1, for any given* w_U, w_R*, the buyer's optimal initial order quantities* Q_U^* *and* Q_R^* *can be computed by Algorithm S.6.1*

ALGORITHM S.6.1. Finding Q_U^* and Q_R^* given w_U, w_R if supplier R sets w_E at Time 1.

Step 1. Set $(Q_U^{(1)}, Q_R^{(1)})$ by the following:

(i) If $w_R > P_1w_U + \frac{1}{4}[P_Bc_R + m(3+P_G-4P_1)]$ and $m > w_U$, then $Q_U^{(1)} = (m-w_U)/2$, $Q_R^{(1)} = 0$.

(ii) If $\frac{1}{4}[P_Bc_R + w_U(3+P_G)] < w_R \leq P_1w_U + \frac{1}{4}[P_Bc_R + m(3+P_G-4P_1)]$, then $Q_U^{(1)} = \frac{4w_R-(3+P_G)w_U-P_Bc_R}{2(3+P_G-4P_1)}$, $Q_R^{(1)} = \frac{4P_1w_U-4w_R+m(3+P_G-4P_1)+P_Bc_R}{2(3+P_G-4P_1)}$.

(iii) If $w_R \le \frac{1}{4}[P_B c_R + w_U(3+P_G)]$ and $m(3+P_G)+P_B c_R > 4w_R$, then $Q_U^{(1)} = 0$ and $Q_R^{(1)} = \frac{m(3+P_G)+P_B c_R - 4w_R}{2(3+P_G)}$.

(iv) Otherwise, $Q_U^{(1)} = Q_R^{(1)} = 0$.

Step 2. Set $(Q_U^{(2)}, Q_R^{(2)})$ by the following:

(i) If $(4P_{0G}+3P_1)w_R > P_{0G}(3m+c_R)+3P_1 w_U$ and $3m+c_R > 4w_U$, then $Q_U^{(2)} = \frac{3m+c_R-4w_U}{2(4P_{0G}+3P_1)}$, $Q_R^{(2)} = 0$.

(ii) If $(4P_{0G}+3P_1)w_R \le P_{0G}(3m+c_R)+3P_1 w_U$ and $w_R > w_U$, then $Q_U^{(2)} = \frac{w_R - w_U}{2P_{0G}}$, $Q_R^{(2)} = \frac{P_{0G}(3m+c_R) - w_R(4P_{0G}+3P_1)+3P_1 w_U}{6P_{0G}}$.

(iii) If $w_R \le w_U$ and $3m + c_R > 4w_R$, then $Q_U^{(2)} = 0$, $Q_R^{(2)} = \frac{3m-4w_R+c_R}{6}$.

(iv) Otherwise, $Q_U^{(2)} = Q_R^{(2)} = 0$.

Step 3. Check the feasibility of $(Q_U^{(1)}, Q_R^{(1)})$ and $(Q_U^{(2)}, Q_R^{(2)})$ and output the optimal solution:

(i) If $m - 2Q_R^{(i)} - 2P_{1G}(1+\sqrt{P_B})Q_U^{(i)} \le c_R$ for both $i = 1,2$, output $(Q_U^*, Q_R^*) = (Q_U^{(1)}, Q_R^{(1)})$.

(ii) If $m - 2Q_R^{(i)} - 2P_{1G}(1+\sqrt{P_B})Q_U^{(i)} > c_R$ for both $i = 1,2$, output $(Q_U^*, Q_R^*) = (Q_U^{(2)}, Q_R^{(2)})$.

(iii) If $m - 2Q_R^{(1)} - 2P_{1G}(1+\sqrt{P_B})Q_U^{(1)} \le c_R$ and $m - 2Q_R^{(2)} - 2P_{1G}(1+\sqrt{P_B})Q_U^{(2)} > c_R$, output $(Q_U^*, Q_R^*) = (Q_U^{(i)}, Q_R^{(i)})$ where $i = \arg\max_{i=1,2} \pi_B(Q_U^{(i)}, Q_R^{(i)})$, and π_B is as specified in (S.6.1).

(iv) Otherwise, go to Step 4.

Step 4. Output $(Q_U^*, Q_R^*) = (Q_U^{(3)}, Q_R^{(3)})$ where

$$Q_R^{(3)} = \max\left(0, \min\left(\frac{m-c_R}{2}, \frac{m}{2} + \frac{(1-\sqrt{P_B})w_U - w_R + c_R\left(\frac{P_B}{4} + \frac{P_1\sqrt{P_B} - P_G P_{0G}}{P_{1G}(1+\sqrt{P_B})^2}\right)}{\frac{3P_B}{2} + \frac{2P_0 P_G}{P_{1G}(1+\sqrt{P_B})^2}}\right)\right)$$

and $Q_U^{(3)} = \frac{m - 2Q_R^{(3)} - c_R}{2P_{1G}(1+\sqrt{P_B})}$.

S.6.3. The Supplier Pricing Game at Time 0

At Time 0, suppliers U an R simultaneously choose w_U and w_R to maximize their payoffs. Supplier U's payoff is given by

$$\pi_U(w_R|w_U) = (P_1 w_U - c_U)Q_U^* \tag{S.6.2}$$

where Q_U^* is from the output by Algorithm S.6.1 given (w_U, w_R). Supplier R's payoff is however much more involved as given below.

$$\pi_R(w_R|w_U) = (w_R - c_R)Q_R^* + V^*(Q_U^*, Q_R^*) \tag{S.6.3}$$

where

$$V^*(Q_U^*, Q_R^*) = \begin{cases} \frac{1}{8}P_B(m - 2Q_R^* - c_R)^2 \text{ if } m - 2Q_R^* - 2P_{1G}(1+\sqrt{P_B})Q_U^* \le c_R \\ \frac{1}{8}[m - 2Q_R^* - 2P_1 Q_U^* - c_R]^2 \text{ otherwise.} \end{cases}$$

In the above, (Q_U^*, Q_R^*) is the output from Algorithm S.6.1 given (w_U, w_R).

The first-stage competition is analytically intractable due to the complexity of the buyer's ordering decision characterized by Algorithm S.7.1. We can nevertheless use a numerical approach to

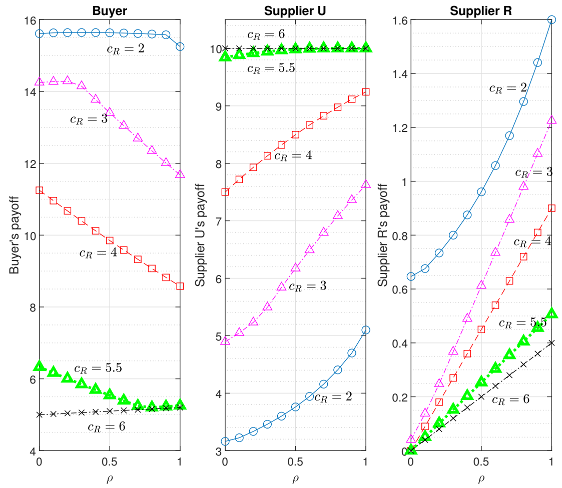

Figure S.6.1 **Impact of ρ when w_E is renegotiable at Time 1 [$m = 10$, $c_U = 0$, $P_1 = 0.8$].**

compute a Nash equilibrium (if any) as stated in Algorithm S.6.2. We follow the idea of best-response dynamics: To start, w_U^0 is calculated as if supplier U is a monopoly; given w_U^0, we determine supplier R's best response w_R^0 by an exhaustive search; given w_R^0, we then find supplier U's best response w_U^1; continue this procedure until (w_U, w_R) converges, or a maximum number of iterations N is reached. Since we are unable to establish the existence of Nash equilibrium for the game, in theory the procedure may not necessarily converge. If the algorithm is terminated as N iterations are completed, we output “na” to represent no equilibrium found.

ALGORITHM S.6.2. Finding the equilibrium wholesale prices (w_U^I, w_R^I)

* Specify the maximum number of iterations N and a tolerance level ϵ.

Step 0. Initialize $w_U^0 = \frac{m+c_U/P_1}{2}$, and $w_R^0 = \arg\max_{w_R} \pi_R(w_R|w_U^0)$ where π_R is as given in (S.6.3).

Step $\mathbf{t = 1, 2, \ldots}$ Iteratively calculate the best responses until the solution converges with a tolerance ϵ or the maximum number of iterations is reached.

—Set $w_U^t = \arg\max_{w_U} \pi_U(w_U|w_R^{t-1})$ where π_U is given in (S.6.2).

—Set $w_R^t = \arg\max_{w_R} \pi_R(w_R|w_U^t)$ where π_R is as given in (S.6.3).

—If $|w_U^t - w_U^{t-1}| < \epsilon$ and $|w_R^t - w_R^{t-1}| < \epsilon$, then stop and output $(w_U^I, w_R^I) = (w_U^t, w_R^t)$; else if $t > N$, then stop and output $(w_U^I, w_R^I) = (na, na)$; otherwise, continue to Step $t+1$.

Note that in Step 0, we choose supplier U's monopolistic price as the starting point, as it emulates a practical situation where the buyer previously relied only on supplier U and later included supplier R – a local supplier – in the supply base. In this case, the most reasonable equilibrium (if any) is one to which our algorithm converges.

In the numerical study, we set $N = 3000$ and $\epsilon = 10^{-4}$; in all instances we tested, the algorithm converged to an equilibrium. A representative set of instances is reported in Figure S.6.1. The observations are mainly the same as discussed in our base model; see Figure 7 in §4.4 for a comparison. The buyer's payoff is increasing ρ only if c_R is sufficiently large relative to c_U or if c_R is close to c_U such that a mixed sourcing strategy is adopted in the equilibrium. (In Figure S.6.1, the curves for $c_R = 2$ and $c_R = 3$ slightly increase at first, because in those cases a mixed sourcing strategy is adopted in equilibrium.) Therefore, our main results are robust whether w_E is renegotiable or not.

Remark. The assumption that w_E is renegotiable but Q_R is not has some nuanced implications on supplier R's pricing decision. In fact, supplier R prefers to manipulate the two wholesale prices (w_R, w_E) and sell to the buyer at both Time 0 and Time 1 even if $\rho = 0$, i.e., contingent sourcing is impossible. Consider the special case where c_R is sufficiently low so that supplier R monopolizes the market. Solving supplier R's two-period monopoly pricing problem, we can show that it is optimal to set $w_R^* = \frac{9m+7c_R}{16}$ at Time 0 and then charge $w_E^* = \frac{3m+5c_R}{8} \le w_R^*$ at Time 1 to sell an extra amount. When competing with the other supplier, supplier R will hope to follow the above manipulation strategy and sell a positive "emergency" quantity at Time 1, regardless of what signal the buyer receives. For this reason, in the numerical study, we observed that if $\rho = 0$ and c_R is small enough, supplier R will sell at both Times 0 and 1 even though the buyer does not receive any useful shipment information at Time 1.

Supplier R's manipulation behavior on two wholesale prices relies on the assumption that w_E is renegotiable but Q_R is not. Suppose now that the buyer can revise Q_R upon receiving w_E. The buyer actually has an incentive to do so, as it can perform a re-optimization over Q_R and Q_E based on w_E and the earlier quote w_R. Anticipating the buyer to re-optimize over Q_R and Q_E, in effect supplier R has to determine both w_R and w_E at Time 0. Knowing this, the buyer will just collect both suppliers' quotes before deciding on order quantities at Time 0. As a consequence, the game will become what we assumed in the base model.

S.6.4. Proofs of Results in Appendix S.6

Proof of Lemma S.6.1 The optimal $Q_E^*(s)$ is derived immediately from the first-order optimality condition. $\square$

Proof of Proposition S.6.1 By Lemma S.6.1, clearly, supplier R will not offer any emergency ordering opportunity if $c_R \ge m - 2Q_R$. There remains two cases to be discussed.

If supplier R sells only for $s = B$, then $m - 2Q_R - 2P_{1G}Q_U \le w_E < m - 2Q_R$. The corresponding interior solution is given by $w_E^{(1)} = \frac{1}{2}(m - 2Q_R + c_R)$ which yields a profit $V_1^* = \frac{1}{8}P_B(m - 2Q_R - c_R)^2$; the interior solution is attainable iff $m - 2Q_R - 4P_{1G}Q_U \le c_R < m - 2Q_R$.

If supplier R sells for both $s \in \{G, B\}$, then $w_E < m - 2Q_R - 2P_{1G}Q_U$. The corresponding interior solution is $w_E^{(2)} = \frac{1}{2}[m - 2Q_R - 2P_{1G}P_G + c_R]$ which yields a profit of $V_2^* = \frac{1}{8}[m - 2(Q_R + P_{1G}P_GQ_U) - c_R]^2$; the interior solution is attainable iff $c_R < m - 2Q_R - 2P_{1G}(1 + P_B)Q_U$.

The ranges of c_R for the above two cases overlap. So, if $m-2Q_R-4P_{1G}Q_U \le c_R < m-2Q_R-2P_{1G}(1+P_B)Q_U$, we need to compare V_1^* and V_2^* to determine which of $w_E^{(1)}$ and $w_E^{(2)}$ is optimal. We have $V_1^* \ge V_2^*$, i.e., $w_E^* = w_E^{(1)}$ iff $c_R \ge m-2Q_R-2P_{1G}(1+\sqrt{P_B})Q_U$.

The proposition follows by combining the above cases and noticing that $m-2Q_R-2P_{1G}(1+\sqrt{P_B})Q_U$ falls between $m-2Q_R-4P_{1G}Q_U$ and $m-2Q_R-2P_{1G}(1+P_B)Q_U$. $\square$

Proof of Proposition S.6.2 Note that case (i) of Proposition S.6.1 can be eliminated from the consideration, because Q_R will not exceed $\frac{m-c_R}{2}$ for any $w_R \ge c_R$ even if supplier R is a monopoly. So, we need to examine two different cases for $\pi_B(Q_U, Q_R)$, corresponding to cases (ii) and (iii) of Proposition S.6.1.

Case (B1). For $m-2Q_R-2P_{1G}(1+\sqrt{P_B})Q_U \le c_R$, i.e., case (ii) of Proposition S.6.1, we have $\frac{\partial^2\pi_B}{\partial Q_U^2} = -2P_1 \le 0$, $\frac{\partial^2\pi_B}{\partial Q_R^2} = -\frac{1}{2}(3+P_G) \le 0$, $\frac{\partial^2\pi_B}{\partial Q_R^2}\frac{\partial^2\pi_B}{\partial Q_U^2} - (\frac{\partial^2\pi_B}{\partial Q_U \partial Q_R})^2 = P_1(3P_0 + P_G P_{0G})$. Thus, π_B is jointly concave in Q_U and Q_R. To characterize the optimal solution, the approach is similar to the proof of Proposition A.1. By the first-order conditions, we have four possible cases: (i) $Q_U^* > 0$, $Q_R^* = 0$, $\frac{\partial\pi_B}{\partial Q_U} = 0$ and $\frac{\partial\pi_B}{\partial Q_R} \le 0$; (ii) $Q_U^*, Q_R^* > 0$, $\frac{\partial\pi_B}{\partial Q_U} = 0$ and $\frac{\partial\pi_B}{\partial Q_R} = 0$; (iii) $Q_U^* = 0$, $Q_R^* > 0$, $\frac{\partial\pi_B}{\partial Q_U} \le 0$ and $\frac{\partial\pi_B}{\partial Q_R} = 0$; (iv) $Q_U^* = 0$, $Q_R^* = 0$, $\frac{\partial\pi_B}{\partial Q_U} \le 0$ and $\frac{\partial\pi_B}{\partial Q_R} \le 0$. The closed-form order quantities and conditions for the above cases can be derived accordingly, as stated in Step 1 of Algorithm S.6.1.

Case (B2). For $m-2Q_R-2P_{1G}(1+\sqrt{P_B})Q_U > c_R$, i.e., case (iii) of Proposition S.6.1, we have $\frac{\partial^2\pi_B}{\partial Q_U^2} = -\frac{1}{2}P_1(4P_{0G}+3P_1) \le 0$, $\frac{\partial^2\pi_B}{\partial Q_R^2} = -\frac{3}{2}$, $\frac{\partial^2\pi_B}{\partial Q_R^2}\frac{\partial^2\pi_B}{\partial Q_U^2} - (\frac{\partial^2\pi_B}{\partial Q_U \partial Q_R})^2 = 3P_{0G}P_1 \ge 0$. Thus, π_B is jointly concave in Q_U and Q_R. Similar to Case (B1), the optimal quantities under case (B2) can be characterized as in Step 2 of Algorithm S.6.1.

After obtaining the optimal quantities for cases (B1) and (B2), we can check if the two sets of quantities satisfy $m-2Q_R-2P_{1G}(1+\sqrt{P_B})Q_U \le c_R$ and $m-2Q_R-2P_{1G}(1+\sqrt{P_B})Q_U > c_R$, respectively. If only one of them satisfies the corresponding constraint, then that is the global optimal solution (as the problem is continuous at the boundary $m-2Q_R-2P_{1G}(1+\sqrt{P_B})Q_U = c_R$). If both satisfy the constraints, pick the one leading to the highest π_B as stated in Step 3. Otherwise, we will need to consider the solution over the boundary: $m-2Q_R-2P_{1G}(1+\sqrt{P_B})Q_U = c_R$: **Case (B3).** Given $m-2Q_R-2P_{1G}(1+\sqrt{P_B})Q_U = c_R$, supplier R is different between cases (ii) and (iii) of Proposition S.6.1. We break the tie by assuming the supplier R to follow case (ii), i.e., sell a positive quantity only for $s = B$. The buyer's problem can be transformed into a maximization of a single-variable concave function: $\pi_B(\frac{m-2Q_R-c_R}{2P_{1G}(1+\sqrt{P_B})}, Q_R)$ subject to $0 \le Q_R \le \frac{m-c_R}{2}$. It is straightforward to characterize the optimal Q_R as given in Step 4. $\square$

Appendix S.7: Supplier R Offers Screening Contracts at Time 1

We consider the following sequence of events. At Time 0, suppliers U and R simultaneously determine w_U and w_R, respectively; the buyer decides on initial order quantities Q_U and Q_R. At Time 1, the signal $s \in \{B, G\}$ is realized and privately observed by the buyer; then, supplier R offers a menu of contracts $\{Q_E(B), w_E(B)\}$ and $\{Q_E(G), w_E(G)\}$ for the buyer to choose from, where $Q_E(s)$ and $w_E(s)$ are respectively the purchase quantity and wholesale price intended for the type-s buyer. At Time 2, the actual yield loss and each player's payoff are realized. We assume that Q_R cannot be revised at Time 1, and supplier R can observe or form a correct belief of Q_U when designing the contracts. The proofs of all the results in this appendix can be found in §S.7.4.

S.7.1. Supplier R's Optimal Contracts

We analyze the game backward. Consider supplier R's contract design problem at Time 1. By determining the optimal menu of supply contracts $\{Q_E(s), w_E(s)\}$ where $s \in \{B, G\}$, supplier R maximizes its expected profit *from the emergency order* as given below:

$$\max_{Q_E(\cdot), w_E(\cdot)} \quad \sum_{s \in \{B,G\}} P_s \left((w_E(s) - c_R) Q_E(s) \right) \tag{S.7.1}$$

The following incentive compatible (IC) constraints ensure that the buyer with signal s will prefer the contract intended for it.

$$\pi_B(G|G) \geq \pi_B(B|G), \; \pi_B(B|B) \geq \pi_B(G|B) \tag{S.7.2}$$

where

$$\pi_B(s'|s) = P_{1s} R(Q_U + Q_R + Q_E(s')) + P_{0s} R(Q_R + Q_E(s')) - w_E(s') Q_E(s')$$

representing the payoff of a buyer with a signal s but choosing a contract intended for type s'.

For convenience, let $\emptyset$ represent a dummy contract $\{0, 0\}$; the buyer chooses $\emptyset$ if not purchasing any emergency quantity from supplier R. The individual rationality (IR) constraints can thus be written as follows.

$$\pi_B(G|G) \geq \pi_B(\emptyset|G), \; \pi_B(B|B) \geq \pi_B(\emptyset|B) \tag{S.7.3}$$

where $\pi_B(\emptyset|s) = P_{1s} R(Q_U + Q_R) + P_{0s} R(Q_R)$.

Let $u(s) = \pi_B(s|s)$ represent the type-s buyer's payoff when truthfully revealing its type. By a standard technique, we can reformulate supplier R's mechanism design problem as follows.

$$\max \quad \sum_{s \in \{B,G\}} P_s \left[P_{1s} R(Q_U + Q_R + Q_E(s)) + P_{0s} R(Q_R + Q_E(s)) - c_R Q_E(s) - u(s) \right] \tag{S.7.4}$$

$$u(G) \geq u(B) + (P_{1G} - P_{1B})[R(Q_U + Q_R + Q_E(B)) - R(Q_R + Q_E(B))] \tag{IC-G}$$

$$u(B) \geq u(G) - (P_{1G} - P_{1B})[R(Q_U + Q_R + Q_E(G)) - R(Q_R + Q_E(G))] \tag{IC-B}$$

$$u(G) \geq P_{1G} R(Q_U + Q_R) + P_{0G} R(Q_R) \tag{IR-G}$$

$$u(B) \geq P_{1B}R(Q_U + Q_R) + P_{0B}R(Q_R) \tag{IR-B}$$

Under supplier R's optimal contracts, the emergency selling quantities $Q_E^*(s)$, the buyer's payoffs $u(s)$, and supplier R's expected profit V from the emergency order are characterized in Proposition S.7.1. Note that we allow for imperfect shipment information in the analysis.

Proposition S.7.1. *Suppose that supplier R can offer a menu of screening contracts at Time 1. The following hold true under supplier R's optimal contracts.*

(i) If $m - 2Q_R \leq c_R$, then supplier R will shut down the emergency ordering opportunity; the buyer gets its reservation value $u(s) = \pi_B(\emptyset|s)$ for both $s \in \{G, B\}$ and supplier R earns $V = 0$.

(ii) If $m - 2Q_R - \frac{2P_{1G}}{P_G}Q_U \leq c_R < m - 2Q_R$, then supplier R will offer a contract such that $Q_E^*(B) = \frac{1}{2}(m - 2Q_R - c_R)$, $Q_E^*(G) = 0$; the buyer gets $u(s) = \pi_B(\emptyset|s)$ for both $s \in \{G, B\}$; supplier R earns $V = \frac{1}{4}P_B(m - 2Q_R - c_R)^2$.

(iii) If $c_R < m - 2Q_R - \frac{2P_{1G}}{P_G}Q_U$, supplier R will offer a contract such that $Q_E^*(B) = \frac{1}{2}(m - 2Q_R - c_R)$, $Q_E^*(G) = \frac{1}{2}(m - 2Q_R - c_R - 2\frac{P_{1G}}{P_G}Q_U)$; the buyer with $s = G$ and $s = B$ gets $u(G) = \pi_B(\emptyset|G)$, $u(B) = \pi_B(\emptyset|B) + r(Q_U, Q_R)$, respectively, where

$$r(Q_U, Q_R) = P_{1G}Q_U(m - 2Q_R - \frac{2P_{1G}}{P_G}Q_U - c_R)$$

is the type-B buyer's information rent; supplier R earns $V = \frac{1}{4}(m - 2Q_R - c_R)^2 - r(Q_U, Q_R)$.

Depending on how much the buyer has initially ordered, at Time 1 supplier R may choose to sell nothing, sell only to the buyer with a bad signal, or sell to both buyer types, as stated in cases (i)-(iii) of Proposition S.7.1, respectively. A key message from Proposition S.7.1 is summarized as follows: *If in equilibrium emergency trade occurs only for $s = B$, then supplier R will extract all the surplus from the emergency trade, and so the buyer will not benefit from contingent sourcing.*

The above results imply that the buyer cannot obtain any surplus from contingent sourcing unless initial order sizes Q_U and Q_R are small enough [see the condition of case (iii) of Proposition S.7.1] such that supplier R opts to sell at Time 1 even for a good signal. However, as a competitor at Time 0, supplier U will try to make the buyer purchase a large enough Q_U such that emergency trading is unnecessary given a good signal. Recall that in the base model, the buyer benefits from contingent sourcing only if c_R is sufficiently large relative to c_U. For the case with a powerful supplier R offering screening contracts, a small c_U will enable supplier U to sell a large enough Q_U resulting in no emergency trade for $s = G$. Consequently, all the value from contingent sourcing will be extracted by supplier R and the buyer will not benefit from contingent sourcing. Our numerical study as reported below confirmed the above reasoning.

S.7.2. Buyer's Initial Orders

To fully solve the game, we need to first solve the buyer's initial ordering problem and then find the equilibrium wholesale prices of the supplier competition. Anticipating the possible payoffs from emergency contracting, the buyer's expected profit can be written as

$$\pi_B(Q_U,Q_R)=\begin{cases} P_G[P_{1G}R(Q_U+Q_R)+P_{0G}R(Q_R)]+P_BR(Q_R)-P_1w_UQ_U-w_RQ_R \\ \qquad \text{if } m-2Q_R-(2P_{1G}/P_G)Q_U\le c_R \\ P_G[P_{1G}R(Q_U+Q_R)+P_{0G}R(Q_R)]+P_B[R(Q_R)+r(Q_U,Q_R)]-P_1w_UQ_U-w_RQ_R \\ \qquad \text{if } m-2Q_R-(2P_{1G}/P_G)Q_U> c_R \end{cases} \tag{S.7.5}$$

where $r(Q_U,Q_R)$ is as defined in Proposition S.7.1.

Exploiting the optimality conditions of the two cases for the above problem, we develop the following algorithm to compute the buyer's optimal (Q_U^*,Q_R^*) for any given (w_R,w_U).

PROPOSITION S.7.2. *Given any w_R and w_U, the buyer's optimal initial order quantities Q_U^* and Q_R^* can be computed with Algorithm S.7.1.*

ALGORITHM S.7.1. Finding Q_U^* and Q_R^* given (w_U,w_R) if supplier R offers screening contracts at Time 1.

Step 1. Set $(Q_U^{(1)},Q_R^{(1)})$ by the following:

(i) If $w_R>P_1w_U+P_0m$ and $m>w_U$, then $Q_U^{(1)}=\frac{m-w_U}{2}$, $Q_R^{(1)}=0$.

(ii) If $w_U<w_R\le P_1w_U+P_0m$, then $Q_R^{(1)}=\frac{P_0m-w_R+P_1w_U}{2P_0}$, $Q_U^{(1)}=\frac{w_R-w_U}{2P_0}$.

(iii) If $w_R\le w_U$ and $m>w_R$, then $Q_U^{(1)}=0$ and $Q_R^{(1)}=(m-w_R)/2$.

(iv) Otherwise, $Q_U^{(1)}=Q_R^{(1)}=0$.

Step 2. Set $(Q_U^{(2)},Q_R^{(2)})$ by the following:

(i) If $(2P_{1G}P_B+P_G^2)w_R-P_GP_1w_U\ge(2P_{1G}-3P_1+P_G^2)m+P_BP_1c_R$ and $m-P_Bc_R>P_Gw_U$, then $Q_U^{(2)}=\frac{P_1(m-P_Bc_R-P_Gw_U)}{2P_{1G}(2P_{1G}P_B+P_G^2)}$, $Q_R^{(2)}=0$.

(ii) If $(2P_{1G}P_B+P_G^2)w_R-P_GP_1w_U<(2P_{1G}-3P_1+P_G^2)m+P_BP_1c_R$ and $w_R-P_Gw_U>P_Bc_R$, then $Q_U^{(2)}=\frac{P_1(w_R-P_Bc_R-P_Gw_U)}{2P_{1G}(2P_{1G}-3P_1+P_G^2)}$, $Q_R^{(2)}=\frac{(2P_{1G}-3P_1+P_G^2)m+P_BP_1c_R-(2P_GP_B+P_G^2)w_R+P_GP_1w_U}{2(2P_{1G}-3P_1+P_G^2)}$.

(iii) If $w_R-P_Gw_U\le P_Bc_R$ and $m>w_R$, then $Q_U^{(2)}=0$, $Q_R^{(2)}=\frac{m-w_R}{2}$.

(iv) Otherwise, $Q_U^{(2)}=Q_R^{(2)}=0$.

Step 3. Check the feasibility of $(Q_U^{(1)},Q_R^{(1)})$ and $(Q_U^{(2)},Q_R^{(2)})$ and output the optimal solution:

(i) If $m-2Q_R^{(1)}-\frac{2P_{1G}}{P_G}Q_U^{(1)}\le c_R$ and $m-2Q_R^{(2)}-\frac{2P_{1G}}{P_G}Q_U^{(2)}\le c_R$, output $(Q_U^*,Q_R^*)=(Q_U^{(1)},Q_R^{(1)})$.

(ii) If $m-2Q_R^{(1)}-\frac{2P_{1G}}{P_G}Q_U^{(1)}> c_R$ and $m-2Q_R^{(2)}-\frac{2P_{1G}}{P_G}Q_U^{(2)}> c_R$, output $(Q_U^*,Q_R^*)=(Q_U^{(2)},Q_R^{(2)})$.

(iii) If $m-2Q_R^{(1)}-\frac{2P_{1G}}{P_G}Q_U^{(1)}\le c_R$ and $m-2Q_R^{(2)}-\frac{2P_{1G}}{P_G}Q_U^{(2)}> c_R$, output $(Q_U^*,Q_R^*)=(Q_U^{(i)},Q_R^{(i)})$ where $i=\arg\max_{i=1,2}\pi_B(Q_U^{(i)},Q_R^{(i)})$, and π_B is as specified in (S.7.5).

(iv) Otherwise, go to Step 4.

Step 4. Output $(Q_U^*,Q_R^*)=(Q_U^{(3)},Q_R^{(3)})$ according to the following:

(i) If $P_{1G}w_R-P_GP_1w_U\ge(P_{1G}-2P_{1G}P_G^2+P_G^3)m+P_G^2(P_{1G}-P_G)c_R$, then $Q_U^{(3)}=\frac{P_G(m-c_R)}{2P_{1G}}$, $Q_R^{(3)}=0$.

(ii) if $(1-P_G^2)P_{1G}c_R \le P_{1G}w_R - P_GP_1w_U < (P_{1G}-2P_{1G}P_G^2+P_G^3)m + P_G^2(P_{1G}-P_G)c_R$, then $Q_U^{(3)} = \frac{P_1[w_R-P_G^2w_U-(1-P_G^2)c_R]}{2P_{1G}(P_{1G}-2P_{1G}P_G^2+P_G^3)}$, $Q_R^{(3)} = \frac{(P_{1G}-2P_{1G}P_G^2+P_G^3)m+P_G^2(P_{1G}-P_G)c_R-P_{1G}w_R+P_GP_1w_U}{2(P_{1G}-2P_{1G}P_G^2+P_G^3)}$.

(iii) Otherwise, $Q_U^{(3)} = 0$, $Q_R^{(3)} = \frac{m-c_R}{2}$.

S.7.3. The Supplier Pricing Game at Time 0

In the first stage, suppliers U and R simultaneously determine w_U and w_R to maximize their payoffs, anticipating the buyer to choose the optimal order quantities (Q_U^*, Q_R^*) as determined by Algorithm S.7.1. Supplier U's payoff is the same as in the base model. However, supplier R's payoff includes its profit from the initial order as well as that from the screening contract. Overall, supplier R's payoff can be written as

$$\pi_R(w_R|w_U) = (w_R - c_R)Q_R^* + V(Q_U^*, Q_R^*) \tag{S.7.6}$$

where (Q_U^*, Q_R^*) are the output of Algorithm S.7.1 and

$$V(Q_U,Q_R) = \begin{cases} 0 \text{ if } m-2Q_R \le c_R \\ \frac{1}{4}P_B(m-2Q_R-c_R)^2 \text{ if } m-2Q_R-\frac{2P_{1G}}{P_G}Q_U \le c_R < m-2Q_R \\ \frac{1}{4}P_B(m-2Q_R-c_R)^2 - P_BP_{1G}Q_U(m-2Q_R-\frac{2P_{1G}}{P_G}Q_U-c_R) \text{ otherwise.} \end{cases} \tag{S.7.7}$$

Supplier U's payoff is the same as in the base model except that the buyer's order quantity Q_U^* should now be computed by Algorithm S.7.1:

$$\pi_U(w_U|w_R) = (P_1w_U - c_U)Q_U^*. \tag{S.7.8}$$

The first-stage competition is analytically intractable due to the complexity of the buyer's ordering decision characterized by Algorithm S.7.1.

We followed the best-response procedure as described in Algorithm S.6.2 of Appendix S.6 to compute the equilibrium in the supplier pricing game. A representative set of numerical instances is shown in Figure S.7.1 in comparison with the results from our base model. We have tested many other sets of parameters and obtained similar observations.

As can be seen from Figure S.7.1, the buyer's payoffs are generally lower when supplier R can offer screening contracts at Time 1 than in our base model. Recall that in the base model the buyer is able to benefit from contingent sourcing or an increased accuracy of shipment information when c_R is sufficiently larger than c_U. However, this is not the case if supplier R offers screening contracts. From the cases of $c_R = 5.5$ and $c_R = 6$ in Figure S.7.1, we can see that the buyer's payoff can be increasing in ρ in the base model, whereas it stays constant in ρ if supplier R offers screening contracts. As discussed, when c_U is low enough compared to c_R, supplier U will attract the buyer to purchase a large initial order, which makes it unnecessary to buy under a good signal. By Proposition S.7.1, in this case all the surplus from emergency trading will be taken by supplier

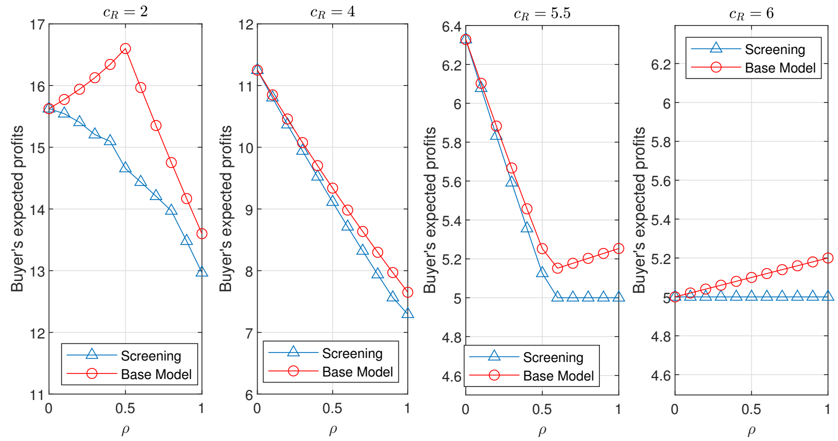

Figure S.7.1 **Impact of shipment information accuracy ρ when supplier R offers screening contracts at Time 1 [$m = 10$, $c_U = 0$, $P_1 = 0.8$]**

R. In addition, the first panel of Figure S.7.1 shows that although the buyer may be better off with an appropriate level of information accuracy in the base model, with a powerful supplier R offering screening contracts, it is mostly worse off with enhanced shipment information.

Finally, we would like to remark that the above analysis is based on the assumption that the buyer is not allowed to revise Q_R after receiving the emergency contract. Actually, the buyer has an incentive to renegotiate Q_R at Time 1, as it can do a re-optimization based on the emergency contract and the regular wholesale price w_R. If the buyer is allowed to revise Q_R, then to make the contract renegotiation-proof, supplier R in effect needs to determine and commit to all the contract terms at Time 0. However, in view of a competing supplier available at Time 0, supplier R may not have the monopoly power to offer a menu of nonlinear contracts. For example, the buyer can ask competing suppliers to bid with price-only contracts. If that is the case, the problem will reduce to the setting considered in our base model.

S.7.4. Proofs of Results in Appendix S.7

Proof of Proposition S.7.1 Unlike the standard mechanism design problem, the buyer's reservation value is type-independent. We solve the problem with a case-by-case discussion. In the proof, we will mostly work with general probability notation P_{1s} and P_{0s}, thus allowing for general imperfect shipment information ($0 \geq \rho \leq 1$). Recall that under the assumed information structure, we have $P_{1B} = 0$ and $P_{0B} = 1$, which will be invoked when appropriate.

Define shorthand notation $\Delta R(x) = R(Q_U + Q_R + x) - R(Q_R + x)$. Note that the two IC constraints hold iff

$$(P_{1G} - P_{1B})\Delta R(Q_E(B)) \leq u(G) - u(B) \leq (P_{1G} - P_{1B})\Delta R(Q_E(G)).$$

Case 1. Suppose that both IR constraints are binding, which implies $u(G) - u(B) = (P_{1G} - P_{1B})\Delta R(0)$. Hence, to satisfy the IC constraints, we must have

$$\Delta R(Q_E(B)) \le \Delta R(0) \le \Delta R(Q_E(G)).$$

By concavity of $R(\cdot)$, $\Delta R(x)$ is decreasing in x. Hence, the IC constraints are equivalent to $Q_E(B) \ge Q_E(G) = 0$.

On the other hand, due to the binding IR constraints, supplier R's problem is reduced to maximizing $V = \sum_{s\in\{B,G\}} P_s\left[P_{1s}R(Q_U + Q_R + Q_E(s)) + P_{0s}R(Q_R + Q_E(s)) - c_R Q_E(s)\right]$ over $Q_E(s)$. By the first-order condition, we have

- $Q_E^*(B) = Q_E^*(G) = 0$ if $P_{1B}R'(Q_U + Q_R) + P_{0B}R'(Q_R) \le c_R$.
- $Q_E^*(B) = \frac{m-2Q_R-2P_{1s}Q_u-c_R}{2}$, $Q_E^*(G) = 0$ if $P_{1G}R'(Q_U + Q_R) + P_{0G}R'(Q_R) \le c_R < P_{1B}R'(Q_U + Q_R) + P_{0B}R'(Q_R)$, or equivalently, $m - 2Q_R - 2P_{1G}Q_U \le c_R < m - 2Q_R$ (as $P_{0B} = 1$ and $P_{1B} = 0$).
- Otherwise, $Q_E^*(s) > 0$ for both s; this violates the IC constraints so the two IR constraints cannot hold simultaneously.

By the above analysis, we can conclude that if $m - 2Q_R - 2P_{1G}Q_U \le c_R$, both IR constraints will be binding and supplier R will extract all the surplus, which is clearly the global optimal solution. In the following discussion, it suffices to consider $m - 2Q_R - 2P_{1G}Q_U > c_R$.

Case 2. If (IR-B) is binding while (IR-G) is not, then (IC-G) must be binding in the solution. We have $u(B) = P_{1B}R(Q_U + Q_R) + P_{0B}R(Q_R)$ and $u(G) = u(B) + (P_{1G} - P_{1B})\Delta R(Q_E(B))$. We argue that this contradicts with (IR-G) not binding, i.e., $u(G) > P_{1G}R(Q_U + Q_R) + P_{0G}R(Q_R)$. Substituting the expressions of $u(G)$ and $u(B)$ into (IR-G), we have

$$P_{1B}R(Q_U + Q_R) + P_{0B}R(Q_R) + (P_{1G} - P_{1B})\Delta R(Q_E(B)) > P_{1G}R(Q_U + Q_R) + P_{0G}R(Q_R),$$

or equivalently, $(P_{1G} - P_{1B})[\Delta R(Q_E(B)) - \Delta R(0)] > 0$. The strict inequality cannot hold as $P_{1G} \ge P_{1B}$ and $\Delta R(x)$ is decreasing. Hence, this case can be ruled out from consideration.

Case 3. If (IR-G) is binding while (IR-B) is not, then (IC-B) must be binding in the solution. We have $u(G) = P_{1G}R(Q_U + Q_R) + P_{0G}R(Q_R)$ and $u(B) = u(G) - (P_{1G} - P_{1B})\Delta R(Q_E(G))$. The objective is thus reduced to maximizing

$$\begin{aligned}
V =& P_G\left[P_{1G}R(Q_U + Q_R + Q_E(G)) + P_{0G}R(Q_R + Q_E(E)) - c_R Q_E(G)\right] \\
&+ P_B\left[P_{1B}R(Q_U + Q_R + Q_E(B)) + P_{0B}R(Q_R + Q_E(B)) - c_R Q_E(B) + (P_{1G} - P_{1B})\Delta R(Q_E(G))\right] \\
&- P_{1G}R(Q_U + Q_R) + P_{0G}R(Q_R)
\end{aligned}$$

over $Q_E(G)$ and $Q_E(B)$. We have

$$\begin{aligned}
\frac{\partial V}{\partial Q_E(B)} &= P_B\left[P_{1B}R'(Q_U + Q_R + Q_E(B)) + P_{0B}R'(Q_R + Q_E(B))\right] \\
&= P_B(m - 2Q_R - 2P_{1B}Q_U - 2Q_E(B) - c_R)
\end{aligned} \tag{S.7.9}$$

and

$$\frac{\partial V}{\partial Q_E(G)} = P_G\left[P_{1G}R'(Q_U+Q_R+Q_E(G))+P_{0G}R'(Q_R+Q_E(E))-c_R\right] \\ +P_B(P_{1G}-P_{1B})[R'(Q_U+Q_R+Q_E(G))-R'(Q_R+Q_E(G))] \\ = P_G(m-2Q_R-2P_{1G}Q_U-2Q_E(G)-c_R)-2P_B(P_{1G}-P_{1B})Q_U. \tag{S.7.10}$$

By $P_{1B}=0$, it follows that $Q_E^*(B)=\frac{1}{2}(m-2Q_R-c_R)$, and $Q_E^*(G)=\frac{1}{2}(m-2Q_R-c_R-\frac{2P_{1G}}{P_G}Q_U)$ if $m-2Q_R-2\frac{P_{1G}}{P_G}Q_U>c_R$ while $Q_E^*(G)=0$ otherwise.

Combining this with Case 1 discussed above, we have

(i) $Q_E^*(B)=Q_E^*(G)=0$ if $c_R\geq m-2Q_R$.

(ii) $Q_E^*(B)=\frac{1}{2}(m-2Q_R-c_R)$ and $Q_E^*(G)=0$ if $m-2Q_R-2\frac{P_{1G}}{P_G}Q_U\leq c_R<m-2Q_R$.

(iii) $Q_E^*(B)=\frac{1}{2}(m-2Q_R-c_R)$ and $Q_E^*(G)=\frac{1}{2}(m-2Q_R-c_R-\frac{2P_{1G}}{P_G}Q_U)$ if $c_R<m-2Q_R-2\frac{P_{1G}}{P_G}Q_U$.

The buyer's and supplier R's payoffs can be derived accordingly from the above quantities and the binding constraints. □

Proof of Proposition S.7.2 The algorithm is constructed by analyzing the optimality condition for the two cases separately and then select the global optimal solution. If neither case permits an interior solution, the global optimal is found at the boundary condition $m-2Q_R-(2P_{1G}/P_G)Q_U=c_R$.

Case (B1): $m-2Q_R-(2P_{1G}/P_G)Q_U\leq c_R$ The problem is identical to that without contingent sourcing. The unconstrained optimal solution has been characterized in Proposition S.2.1.

Case (B2): $m-2Q_R-(2P_{1G}/P_G)Q_U>c_R$

LEMMA S.7.1. *π_B is jointly concave in (Q_U,Q_R) for $m-2Q_R-(2P_{1G}/P_G)Q_U>c_R$.*

Proof of Lemma S.7.1 It can be verified that $\frac{\partial^2\pi_B}{\partial Q_U^2}=-\frac{4P_{1G}P_B}{P_G}-2P_{1G}P_G\leq 0$, $\frac{\partial^2\pi_B}{\partial Q_R^2}=-2$, $\frac{\partial^2\pi_B}{\partial Q_U\partial Q_R}=-2P_{1G}$. It follows that

$$\frac{\partial^2\pi_B}{\partial Q_U^2}\frac{\partial^2\pi_B}{\partial Q_R^2}-\left(\frac{\partial^2\pi_B}{\partial Q_U\partial Q_R}\right)^2=\frac{4P_{1G}[P_{1G}(2-3P_G)+P_G^2]}{P_G}.$$

Note that if $P_{1G}\geq 2/3$, $P_{1G}(2-3P_G)+P_G^2$ is decreasing in P_G and so $P_{1G}(2-3P_G)+P_G^2\geq 1-P_{1G}\geq 0$. Thus, for $P_{1G}\geq 2/3$, the Hessian matrix of π_B is negative semi-definite. For $P_{1G}<2/3$, the term $P_{1G}(2-3P_G)+P_G^2$ is minimized at $P_G^*=\frac{3}{2}P_{1G}$. Substituting this, we have

$$P_{1G}(2-3P_G)+P_G^2\geq 2P_{1G}-\frac{9}{4}P_{1G}^2\geq 0,$$

where the last inequality follows as, for any $0\leq P_{1G}<\frac{2}{3}$, $2P_{1G}-\frac{9}{4}P_{1G}^2$ is bounded below by 0. Therefore, the Hessian matrix is also negative semi-definite for $P_{1G}<2/3$. □

The first-order derivatives of π_B are given by

$$\frac{\partial \pi_B}{\partial Q_U} = P_{1G}(m - P_B c_R - 2Q_R) - (2P_{1G}/P_G)Q_U(2P_{1G}P_B + P_G^2) - P1w_U.$$

and

$$\frac{\partial \pi_B}{\partial Q_R} = m - 2Q_R - 2P_{1G}Q_U - w_R.$$

Similar to the analysis in Appendix S.6, we notice that there are four possible cases. (i) $Q_U^* > 0$, $Q_R^* = 0$, $\frac{\partial \pi_B}{\partial Q_U} = 0$ and $\frac{\partial \pi_B}{\partial Q_R} \leq 0$; (ii) $Q_U^*, Q_R^* > 0$, $\frac{\partial \pi_B}{\partial Q_U} = 0$ and $\frac{\partial \pi_B}{\partial Q_R} = 0$; (iii) $Q_U^* = 0$, $Q_R^* > 0$, $\frac{\partial \pi_B}{\partial Q_U} \leq 0$ and $\frac{\partial \pi_B}{\partial Q_R} = 0$; (iv) $Q_U^* = 0$, $Q_R^* = 0$, $\frac{\partial \pi_B}{\partial Q_U} \leq 0$ and $\frac{\partial \pi_B}{\partial Q_R} \leq 0$. The closed-form expressions of Q_U^* and Q_R^*, which are given in Step 2 of Algorithm S.7.1, follow by simplifying the above optimality conditions. Note that the relation $P_{1G}P_G = P_1$ is used to simplify the notation when appropriate.

Overall, the buyer's optimal order quantities can be found by first determining the unconstrained optimal solutions for cases (B1) and (B2), denoted by $(Q_U^{(1)}, Q_R^{(1)})$ and $(Q_U^{(2)}, Q_R^{(2)})$ respectively. If only one of the unconstrained solutions is feasible, then it is the global optimal; if both are feasible, then the optimal solution is determined by comparing $\pi_B(Q_U^{(1)}, Q_R^{(1)})$ and $\pi_B(Q_U^{(2)}, Q_R^{(2)})$; otherwise, the optimal solution must occur at the boundary: $m - 2Q_R - (2P_{1G}/P_G)Q_U = c_R$.

At the boundary, the buyer's problem can be viewed as maximizing $\pi_B(\frac{P_G(m-2Q_R-c_R)}{2P_{1G}}, Q_R)$ over a single variable $0 \leq Q_R \leq \frac{m-c_R}{2}$. Note that $\frac{\partial^2 \pi_B(\frac{P_G(m-2Q_R-c_R)}{2P_{1G}}, Q_R)}{\partial Q_R} = -\frac{2}{P_{1G}}(P_{1G} - 2P_{1G}P_G^2 + P_G^3) \leq -\frac{2}{P_{1G}}(P_{1G}^2 - 2P_{1G}P_G^2 + P_G^4) = -\frac{2}{P_{1G}}(P_{1G} - P_G^2)^2 \leq 0$, where the first inequality follows as $P_{1G} \leq 1$ and $P_G \leq 1$. Thus, the profit function is concave in Q_R. Using its optimality condition, we can obtain the solution at the boundary, denoted by $(Q_U^{(3)}, Q_R^{(3)})$, as given in Step 4 of the algorithm.

□