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# Managing Supply Uncertainty with an Information Market

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**Abstract.** We propose a market-based information aggregation mechanism to manage the supply side uncertainty in the supply chain. In our analytical model, a simple supply chain consists of a group of retailers who order a homogeneous product from two suppliers. The two suppliers differ in their ability to fulfill orders – one always delivers orders and the other fulfills orders probabilistically. We model the supply chain decisions as a Stackelberg game where the supplier who has uncertain reliability decides a wholesale price before the retailers who independently receive signals about the supplier's reliability determine their sourcing strategies. We then propose an information market to trade binary contracts with payoffs contingent on the supplier's true reliability. Using a simple uniform demand distribution, we demonstrate that the market-based information aggregation mechanism improves the overall supply chain efficiency.

**Keywords:** Information market, Supply chain, Uncertainty, Game theory.

## 1 Introduction

Information market, also known as prediction market, is a powerful information acquisition mechanism to elicit and aggregate information from a variety of sources. For years, public prediction markets have been used for politics (Iowa Electronic Market), video game (simExchange) or movie box-office (Hollywood Stock Exchange) sales. Prediction markets focusing on economic statistics such as employment rates, retail sales, industrial production, and private sector returns have been launched by Goldman Sachs, Deutsche Bank, and the Chicago Mercantile Exchange. Economic Derivatives and Hedgestreet are two prediction markets that offer trading of innovative futures contracts.

In addition to predicting public events and macroeconomic indicators, many leading companies have experimented with internal prediction markets to forecast corporate events. For example, Google has designed quite a few internal markets to provide estimates by collecting intelligence from the wisdom of employees. These markets are designed to forecast both demand for its own products, such as Gmail, as well as the performance of competitive products, such as the Apple iPhone. It is also well known that Hewlett Packard (HP) is among the first businesses to strategically deploy prediction markets. McAdams and Malone [7] proposed an internal futures market to allow plant managers learn information about which products are most profitable from sales people. Usually predictions about possible future events can be designed as tradable contracts whose payoffs depend on the future realization of certain events. Prices of these contracts can be interpreted as a market-generated forecast of uncertain future events.

Guo et al. [4] extend the internal, corporate use of prediction market to an external, supply chain environment. They propose a macro prediction market to manage the systematic demand risk in a supply chain. Fang et al. [3] discussed alternative market mechanisms to separate the information flow from the physical product flow in supply chain optimization. They demonstrate the potential of using properly designed market mechanisms to yield accurate demand forecasts among supply chain partners. They suggest that market mechanisms outperform other traditional methods of demand forecasting in several aspects. When being asked to back up predictions with real money, the performance-dependent reward mechanism well aligns supply chain partners' incentives to share useful information with the goal of improving overall forecast accuracy. Additionally, market mechanisms aggregate useful demand-related information from both within and outside the supply chain. The ability to crowd-sourcing the forecast information contributes to improved forecast accuracy and better business planning.

Though promising, the integration of prediction market with supply chain optimization and business decision making is still in an early stage. Prior work has demonstrated the usefulness of prediction market in supply chain demand forecasting. In this paper, we try to extend the scope of supply chain applications to manage supply side uncertainty. For example, a retailer may run a prediction market in its procurement team about the future delivery of a key component. If the same market can be opened to other retailers who are interested in knowing the reliability of the component supplier, the collective forecasting outcome in the large supply network could outperform that in the internal market.

Supply side uncertainty is a well recognized problem in the supply chain literature [1]. It is quite common in the semiconductor industry that the production process has yield variations. With random yield, firms often receive a random portion of the order placed with a supplier. In other cases, supply uncertainty is binary in nature. An order placed with a supplier either arrives in full or not at all. Natural disasters and equipment failures are common reasons to cause such supply disruption. To better manage uncertain yield, firms usually source from two or more suppliers. Operational issues of quantity allocation between competing suppliers and its effects on the inventory policies have practical significance. Additionally, supply chain partners have asymmetric information about the supplier's reliability. Yang et al. [10] adopts a mechanism design approach to characterize the optimal menu of contracts. Tomlin [8] studies sourcing strategies when a firm can update its forecast of a supplier's yield distribution. A central question addressed in the literature is how uncertainty about a supplier's reliability influences a firm's optimal sourcing and inventory decisions. In general, it is shown that reducing such uncertainty can improve supply chain efficiency.

This study aims to explore the potential of using an information market mechanism to crowd-source a supplier's reliability forecast in a supply chain setting. The paper is organized as follows. We present a simple supply chain game theoretical model in Section 2. The supply chain information structure and our information market mechanism design are discussed in Section 3. Using a simple example based on uniform demand distribution in Section 4, we demonstrate the benefit of market-based information aggregation in improving the overall supply chain profit. We conclude our paper with future research directions in Section 5.

# 2 The Base Model

In this section, we consider a stylized model in which a retailer determines a sourcing strategy from two potential suppliers to satisfy an uncertain market demand. We investigate how the supplier's reliability uncertainty and pricing decision influence the sourcing strategy used by the retailer to mitigate the supply risk. In the next section, we extend our model to a supply network of $N$ retailers.

We assume that the two suppliers differ in their ability to fulfill orders. Supplier 1 guarantees delivery of orders from the retailer so she is always reliable. Supplier 2 delivers orders with probability $\theta$. We interpret $\theta$ as the reliability measure of supplier 2. In case that supplier 2 fails to deliver, she pays the retailer a non-delivery penalty cost (compensation cost) $c$ per unit. To simplify our analysis, we assume supplier 1's wholesale price $v$ is exogenously given. We model the supply chain as a Stackelberg game where supplier 2 determines a wholesale price $w$, and the retailer decides the order quantity pair ($Q$, $q$), where $Q$ and $q$ represent the retailer's order quantities from supplier 2 and supplier 1, respectively. Moreover, the retailer only pays supplier 2 for the quantity that she actually delivers.

The retailer sells the product at an exogenous retail price $r$. We assume the market demand is random with density $f(x)$ and cumulative distribution function $F(x)$ on the interval $[\underline{x}, \overline{x}]$. Demand not filled in a period is lost. Suppose the lost sales cost is $h$ per unit. Inventory left over at the end of the period is salvaged at the value of $g$ per unit. We further assume supplier 2's unit production cost is $c_s$ regardless of whether it is successful or not. Without loss of generality, we assume $v > h > c_s$, $v > g$, $r > v$, $w > h \geq c$, $r > w > g$. Note that these conditions do not put additional constraints to our model, but are used to avoid discussion of trivial cases. A complete list of notations is provided in the Appendix.

## 2.1 The Retailer's Sourcing Strategy

To mitigate the supply risk, the retailer has to determine her sourcing strategy based on her belief about supplier 2's reliability and announced wholesale price. Denote $\tilde{\theta}$ as the retailer's belief about the supplier's reliability. It may or may not be the same as supplier 2's true reliability $\theta$, as shown later in Section 3.

Define $w_1 = \frac{v-(1-\tilde{\theta})(r+h-c)}{\tilde{\theta}}$ and $w_2 = v + \frac{c(1-\tilde{\theta})}{\tilde{\theta}}$. We have the following results about the retailer's optimal sourcing strategy and order quantities.

**Proposition 1:** *Given supplier 2's wholesale price* $w$*, the retailer's sourcing strategy can be characterized by:*

*1. If* $w \le w_1$ *, the retailer single sources from supplier 2 with order quantity determined by*

$$Q^* = F^{-1}\left[\frac{\tilde{\theta}(r+h-w)+(1-\tilde{\theta})c}{\tilde{\theta}(r+h-g)}\right] \tag{1}$$

*2. If* $w_1 < w \le w_2$*, the retailer dual source from both supplies with order quantities determined by*

$$q^* = F^{-1}\left[\frac{r+h-v-\tilde{\theta}(r+h-w)-(1-\tilde{\theta})c}{(1-\tilde{\theta})(r+h-g)}\right] \tag{2}$$

$$Q^* = F^{-1}\left[\frac{\tilde{\theta}(r+h-w)+(1-\tilde{\theta})c}{\tilde{\theta}(r+h-g)}\right] - q^* \tag{3}$$

*3. If* $w > w_2$ *, the retailer single sources from supplier 1with order quantity determined by*

$$q^* = F^{-1}\left[\frac{r+h-v}{r+h-g}\right] \tag{4}$$

The following figure illustrates the effect of wholesale price on sourcing strategies using a uniform demand distribution with parameter values chosen according to Table 1 in Section 4. Under other types of demand distribution such as the normal demand distribution, the shape may not be piecewise linear. But the qualitative insights remain the same.

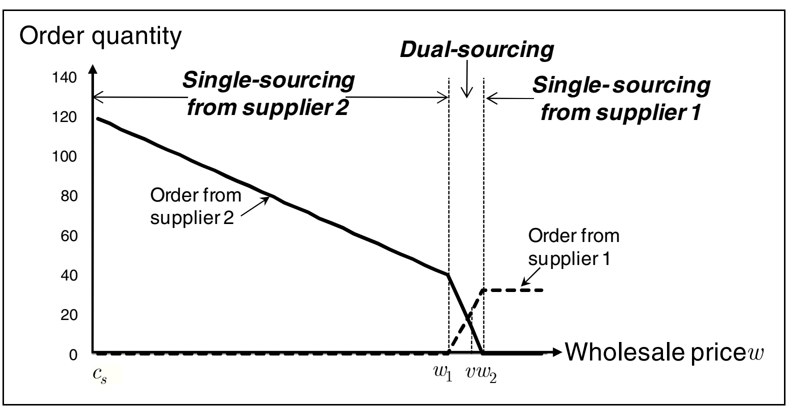


**Fig. 1.** Effect of Wholesale Price on Sourcing Strategies

We see that the retailer's order quantity from supplier 2 decreases as supplier 2's wholesale price increases. In addition, the total order quantity decreases in supplier 2's wholesale price as well. Not surprisingly, when supplier 2's wholesale price is significantly lower than supplier 1's, the retailer is interested in ordering from supplier 2 due to the lower price discount. Note that when $w = v$, the retailer would order more from supplier 1 than that from supplier 2. This is because, all else equal, supplier 2 is less reliable than supplier 1 so supplier 1 is more attractive. On the other hand, due to the compensation supplier 2 agrees to pay in case of delivery failure, it is equivalent that supplier 2 signs an option contract with the retailer. Supplier 2 pays $c$ as a premium to elicit order from the retailer. The option contract is exercised at strike price $w - c$ if supplier 2 delivers the order, and the option contract is not exercised if supplier 2 fails to deliver the order. This flexible contract attracts the retailer to partially order from supplier 2 as a secondary souring channel even under the case that supplier 2's wholesale price is greater than or equal to supplier 1's.

## 2.2 Supplier 2's Pricing Game

Given the retailer's sourcing strategy characterized in Proposition 1, supplier 2's problem is to choose the wholesale price $w$ to maximize the expected profit. The optimization problem can be expressed as:

$$\underset{w}{Max}\ \pi\left(Q^*, w\right) = \left[\theta w - (1-\theta)c - c_s\right]Q^* \tag{5}$$

Differentiating the supplier's objective function, we have

$$\frac{\partial \pi\left(Q^*, w\right)}{\partial w} = \theta Q^* + \left[\theta w - (1-\theta)c - c_s\right]\frac{\partial Q^*}{\partial w} = 0 \tag{6}$$

If the retailer sources solely from supplier 2, then under the condition $w \le w_1$, differentiating $Q^*$ from (1) we have $\frac{\partial Q^*}{\partial w} = -\frac{1}{(r+h-g)f\left(Q^*\right)}$. Substituting $\frac{\partial Q^*}{\partial w}$ into (6) we derive the optimality condition for the supplier's pricing game under the single-sourcing strategy.

If the retailer sources from both suppliers, then under the condition $w_1 < w \le w_2$, differentiating $Q^*$ from (3) yields $\frac{\partial Q^*}{\partial w} = -\frac{1}{(r+h-g)f\left(q^*+Q^*\right)} + \frac{\tilde{\theta}}{\left(1-\tilde{\theta}\right)(r+h-g)f\left(q^*\right)}$. Substituting $\frac{\partial Q^*}{\partial w}$ into (6) we derive the optimality condition for the supplier's pricing game under single-sourcing.

We assume that demand distribution has an increasing generalized failure rate (IGFR). Lariviere and Porteus [6] showed that if the demand distribution is IGFR with a finite mean, the supplier's problem is pseudo-concave. Therefore, we can characterize the equilibrium in the following proposition.

**Proposition 2:** *Let the pair $\left(w^*, Q^*\right)$ be the solution to the following system of equations:*

$$\theta Q^{*}-\frac{\theta w^{*}-(1-\theta)c-c_{s}}{(r+h-g)f\left(Q^{*}\right)}=0 \tag{7}$$

$$F\left(Q^{*}\right)=\frac{\tilde{\theta}\left(r+h-w^{*}\right)+\left(1-\tilde{\theta}\right)c}{\tilde{\theta}(r+h-g)} \tag{8}$$

*If* $w^{*}\leq w_{1}$ *, then* $\left(w^{*},Q^{*}\right)$ *constitutes a Stackelberg equilibrium of the inventory game in which the retailer chooses a single-sourcing strategy. Otherwise, let the triple* $\left(w^{**},q^{**},Q^{**}\right)$ *be the solution to the following system of equations:*

$$\theta Q^{**}+\left(\theta w^{**}-(1-\theta)c-c_{s}\right)\left[-\frac{1}{(r+h-g)f\left(q^{**}+Q^{**}\right)}+\frac{\tilde{\theta}}{\left(1-\tilde{\theta}\right)(r+h-g)f\left(q^{**}\right)}\right]=0 \tag{9}$$

$$Q^{**}=F^{-1}\left[\frac{\tilde{\theta}\left(r+h-w^{**}\right)+\left(1-\tilde{\theta}\right)c}{\tilde{\theta}(r+h-g)}\right]-q^{**} \tag{10}$$

$$q^{**}=F^{-1}\left[\frac{r+h-v-\tilde{\theta}\left(r+h-w^{**}\right)-\left(1-\tilde{\theta}\right)c}{\left(1-\tilde{\theta}\right)(r+h-g)}\right] \tag{11}$$

*If* $w_{1}<w\leq w_{2}$*, then the pair* $\left(w^{**},Q^{**}\right)$ *constitutes a Stackelberg equilibrium of the inventory game in which the retailer chooses a dual-sourcing strategy. Otherwise, supplier 2 prices* $w^{***}=w_{1}$ *, and the retailer is indifferent between the single-sourcing and dual-sourcing strategies.*

# 3 The Information Structure

In this section, we extend our Stackelberg supply chain game to a supply chain network of $N$ retailers. We assume the retailers only differ in their ability to observe signals about supplier 2's true reliability. For simplicity, we assume that the true reliability $\theta$ is unknown but can take two possible values: $\theta_{L}$ and $\theta_{H}$ , where $\theta_{L}<\theta_{H}$ .

Before ordering, we assume each retailer obtains a signal $s$ correlated to the supplier 2's reliability $\theta$ . We further assume that $s$ takes two possible values: 0 and 1. One can consider receiving a signal 1 or 0 as receiving good news or bad news. Denote the total number of retailers who receive signal $s=1$ is $\alpha$ and the total number of retailers who receive signal $s=0$ is $\beta$ . So $\alpha+\beta=N$ .

Assume that $P\left(s=1\mid\theta=\theta_{H}\right)=P\left(s=0\mid\theta=\theta_{L}\right)=\lambda>1/2$ . That is, a retailer is more likely to receive a piece of good (bad) news when the true reliability $\theta=\theta_{H}$ ($\theta=\theta_{L}$). In addition, we assume that the prior belief that $P\left(\theta=\theta_{H}\right)=p$ . In the following, we characterize the belief update under different supply chain information structures.

### 3.1 Decentralized Information Framework

For those retailers who receive $s=1$, the posterior belief of $\tilde{\theta}$ will be updated as $\tilde{\theta}_h$, where:

$$P\left(\theta=\theta_H \mid s=1\right)=\frac{p\lambda}{p\lambda+(1-p)(1-\lambda)}$$
$$\tilde{\theta}_h \triangleq E\left(\theta \mid s=1\right)=\theta_L+\frac{p\lambda\left(\theta_H-\theta_L\right)}{p\lambda+(1-p)(1-\lambda)} \tag{12}$$

For those retailers who receive $s=0$, the posterior belief of $\tilde{\theta}$ will be updated as $\tilde{\theta}_\ell$, where:

$$P\left(\theta=\theta_H \mid s=0\right)=\frac{p(1-\lambda)}{p(1-\lambda)+(1-p)\lambda}$$
$$\tilde{\theta}_\ell \triangleq E\left(\theta \mid s=0\right)=\theta_L+\frac{p(1-\lambda)\left(\theta_H-\theta_L\right)}{p(1-\lambda)+(1-p)\lambda} \tag{13}$$

Based on the posterior belief $\tilde{\theta}_j$, for $j=h,\ell$, the order quantities will have the same expression as described in Proposition 1 by simply substituting $\tilde{\theta}$ with $\tilde{\theta}_j$, depending on the received signals. Since we assume two types of signals, for given supplier 2's wholesale price, the order quantities are of two types. Denote $Q_h^*$ and $Q_\ell^*$ as the order quantities when retailers receive signal 1 and 0, respectively. The total order quantity to supplier 2 will be $\alpha Q_h^*+\beta Q_\ell^*$. Accordingly, the total order quantities to supplier 1 will be $\alpha q_h^*+\beta q_\ell^*$.

#### 3.1.1 Effect of Perceived Reliability on Sourcing Strategies

Based on different signals received, the retailer's sourcing strategies are described as follows.

**Proposition 3:** *Based on the received signal $s=1$ or 0 and the perceived reliability (i.e., the corresponding posterior belief $\tilde{\theta}_j$, for $j=h,\ell$), the retailer's sourcing strategies are characterized by:*

1. *If $w<v$, the retailer dual source from both suppliers if $\tilde{\theta}_j<\overline{\theta}$, where $\overline{\theta}=\frac{r+h-c-v}{r+h-c-w}$; otherwise, the retailer will single source from supplier 2.*
2. *If $w>v$, the retailer dual source from both suppliers if $\tilde{\theta}_j\le\underline{\theta}$, where $\underline{\theta}=\frac{c}{c+w-v}$; otherwise, the retailer will single source from supplier 1.*

The following figure illustrates how the sourcing strategy is affected by both the perceived reliability and the wholesale price. Again, the figure is plotted based on a uniform demand distribution with parameter values chosen according to Table 1 in Section 4.

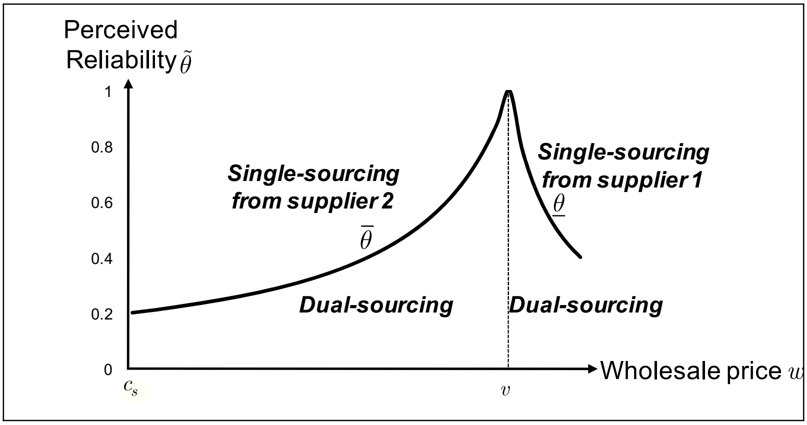


**Fig. 2.** Effect of Perceived Reliability on Sourcing Strategies

In Figure 2, $\overline{\theta}$ and $\underline{\theta}$ represent the threshold levels where the retailer changes her sourcing strategy. When supplier 2's wholesale price is lower than supplier 1's, retailers whose perceived reliability is above the curve would prefer a single-sourcing strategy. In this case, retailers prefer lower price, more reliable supplier. In contrast, when supplier 2's wholesale price is higher than supplier 1's, retailers whose perceived reliability is lower than the curve would be interested in ordering from supplier 2. This is due to the expected compensation from supplier 2.

For any given perceived reliability, we can draw a parallel line to cross over the threshold curve. We can see that the wholesale price range for dual-sourcing decreases as the retailer's perceived reliability increases. This implies that a dual sourcing strategy is more likely used by a retailer if the supply base is more differentiated.

### 3.1.2 Supplier 2's Incentive for Information Disclosure

In order to analyze supplier 2's incentive for information disclosure, we first characterize the effect of the perceived reliability on the retailer's order quantity. Figure 3 illustrates such effect.

In Figure 3, we denote the wholesale price corresponding to $\overline{\theta}$ and $\underline{\theta}$ as $\overline{w}$ and $\underline{w}$ respectively. We further use subscripts *H*, *L*, *N* to denote the scenarios where the perceived reliabilities are High ($s = 1$), Low ($s = 0$), or No information (under the prior probability). The No information case is equivalent to no information update so the prior belief is used to determine order quantity.

Corresponding to Figures 1 & 2, the kinks occur when the retailer changes from single-sourcing to dual-sourcing strategy. We see that, if the retailer single sources from supplier 2, then the order quantity decreases in the perceived reliability. If the retailer sources from both suppliers, then the order quantity for supplier 2 decreases faster when the perceived reliability is high than that when the perceived reliability is low as supplier 2's wholesale price increases. Additionally, when supplier 2's wholesale price is greater than supplier 1's, the retailer's order quantity for supplier 2 decreases in the perceived reliability.

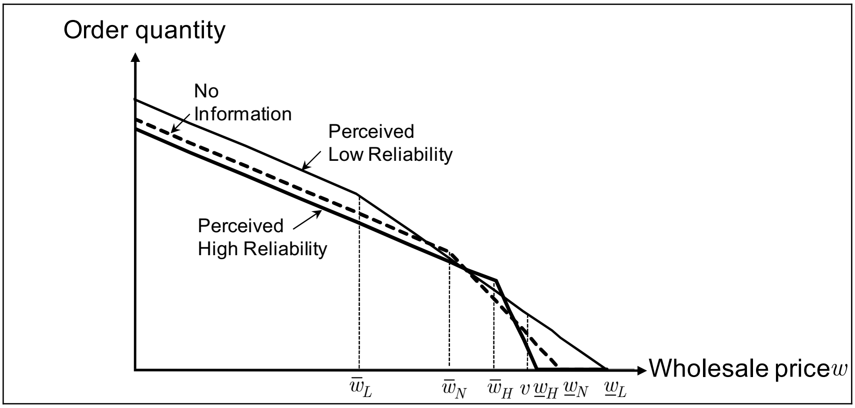


**Fig. 3.** Effect of Perceived Reliability on Order Quantity

Based on this observation, we can analyze the supplier's incentive for information disclosure as follows.

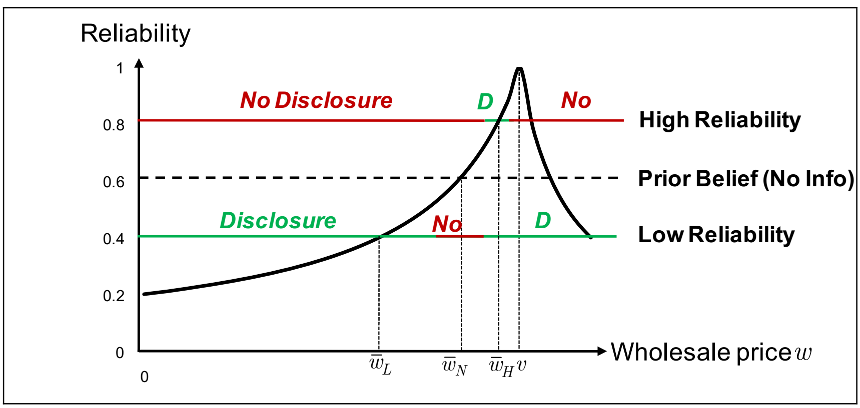


**Fig. 4.** Supplier 2's Incentive for Information Disclosure

From Figure 4, it is clear that a high reliability supplier has no incentive to disclose her reliability information most of the time. A high reliability supplier is only willing to disclose her reliability information when she decides to price around $\overline{w}_H$ . In contrast, a low reliability supplier has incentive to disclose its reliability information most of the time. A low reliability supplier would not disclose its reliability when she decides to price around $\overline{w}_N$ . In general, incentives for information sharing are not well aligned in this supply chain game. Supplier 2 cannot credibly signal her type to the retailers, and the retailers have no means to better forecast supplier 2's reliability. In the following section, we propose a market-based information aggregation mechanism to align retailers' incentives for information sharing.

### 3.2 Market-Based Collaborative Forecasting

We propose an information market to elicit and aggregate the retailers' private signals. Presumably the aggregate signals could yield a more reliable forecast of supplier 2's reliability, closer to the true reliability $\theta$. Additionally, the market mechanism should provide adequate incentive for the retailers to "tell the truth." For this purpose, we design two binary contracts: the "High_Reliability" contract pays off \$1 if the future realized reliability is $\theta_H$ and \$0 if $\theta = \theta_L$; the "Low_Reliability" pays off \$1 if the future realized reliability is $\theta_L$ and \$0 if $\theta = \theta_H$. Similar types of binary contracts have been used in IEM trading, among others.

Based on their observed signals, the retailers decide which types of contract to trade in the market. According to [9], the equilibrium market prices will efficiently aggregate all the initially dispersed information and can be interpreted as the probabilities (or market beliefs) about supplier 2's reliability. Denote such equilibrium prices for the contracts "High_Reliability" and "Low_Reliability" as $\phi_H^*$ and $\phi_L^*$. We can derive that:

$$\begin{cases} \phi_H^* \triangleq P(\theta = \theta_H \mid \alpha, \beta) = \frac{p\lambda^\alpha (1-\lambda)^\beta}{p\lambda^\alpha (1-\lambda)^\beta + (1-p)(1-\lambda)^\alpha \lambda^\beta} \\ \phi_L^* \triangleq P(\theta = \theta_L \mid \alpha, \beta) = \frac{p(1-\lambda)^\alpha \lambda^\beta}{p(1-\lambda)^\alpha \lambda^\beta + (1-p)\lambda^\alpha (1-\lambda)^\beta} \end{cases} \tag{14}$$

Therefore, the market-based belief (expected reliability) is expressed as

$$\tilde{\theta}^m \triangleq E(\theta \mid \alpha, \beta) = \phi_H^* \theta_H + \phi_L^* \theta_L \tag{15}$$

which is known to all retailers and supplier 2. Based on the aggregated information, the total order quantity is $NQ^*\left(\tilde{\theta}^m\right)$. One can justify that $\tilde{\theta}^m \to \theta$ when $N \to \infty$. So the market prediction of $\theta$ will be reliable and close to true value when the number of market participants is large.

## 4 An Illustration with Uniform Demand

Assume that the uncertain demand is characterized by a uniform distribution. The density function is expressed as:

$$f(x) = \begin{cases} 1/A & \text{if } 0 \le x \le A \\ 0 & \text{otherwise} \end{cases} \tag{16}$$

So, $F(x) = \frac{x}{A}$, for $0 \le x \le A$. We can easily verify that supplier 2's objective function is strictly concave. So a unique equilibrium solution exists. In this numerical example, we set $A = 100$.

We assume that the supplier 2's reliability is either high or low with equal probabilities. So $p = 0.5$. Since supplier 2 cannot creditably signal her true type (high or low), retailers use our market mechanism to aggregate information and form a collaborative forecast of supplier 2's reliability. We further assume there are 10 retailers. All parameter values are summarized in Table 1.

**Table 1.** Summary of Parameter Values

| Parameter Interpretation | Parameter Value |
|---|---|
| True probability of supplier 2 | $\theta_H = 0.8$ or $\theta_L = 0.4$ |
| Number of retailers | $N = 10$ |
| Demand distribution | $A = 100$ |
| Unit retail price | $r = 1$ |
| Unit opportunity cost of lost sales | $h = 0.1$ |
| Unit salvage cost of overstock | $g = 0.15$ |
| Unit production cost of supplier 2 | $c_s = 0.05$ |
| Unit compensation cost from supplier 2 | $c = \{0.05, 0.06, 0.07, 0.08, 0.09, 0.1\}$ |
| Supplier 1's wholesale price | $v = \{0.6, 0.7, 0.8, 0.9\}$ |
| Prior probability | $p = 0.5$ |
| Conditional probability | $P(s = 1 \mid \theta = \theta_H) = P(s = 0 \mid \theta = \theta_L) = \lambda = 0.75$ |

To demonstrate the benefit of market-based information sharing, we use the decentralized supply chain information structure as benchmark. In the decentralized supply chain, each retailer independently receives a private signal 1 or 0, which is observable by neither the other retailers nor supplier 2. Retailers who receive signals valued 1 and 0 would update their beliefs about supplier 2's reliability as $\tilde{\theta}_h = 0.7$ and $\tilde{\theta}_\ell = 0.5$, respectively. Based on this updated belief, retailers determine their order strategies and best response order quantities corresponding to supplier 2's wholesale price.

Supplier 2 does not have information about the retailers' signals. However, she knows that retailers' signal distribution follows a binomial distribution, contingent on its reliability. The probability mass function with N = 10 and $P(s = 1 \mid \theta = \theta_H) = P(s = 0 \mid \theta = \theta_L) = \lambda$ can be characterized by the following binomial distribution:

$$\Pr(\alpha = k) = \binom{N}{k} \lambda^k (1 - \lambda)^{N-k} \tag{17}$$

where $k = 0, 1, \ldots, 10$. According to this probability distribution, supplier 2 can fully anticipate the expected retailers' orders. Supplier 2 then determines a wholesale price $w^{d*}$ that maximizes her expected profit.

Under the market-based information aggregation, the market efficiently aggregates all available information and the final equilibrium market prices are observed by both the supplier and the retailers. Correspondingly, the market belief $\tilde{\theta}^m$ is formed and is known to all supply chain members. Supplier 2 can fully anticipate the retailers'

**Table 2.** Supply Chain Profits under Market-Based (M) and Decentralized (D) Inforamtion Structure

| $v$ | $c$ | Retailers (Aggregated) | | | | | | Supplier 2 | | | | Supplier 1 | | Chain | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $TQ^d$ | $TQ^m$ | $Tq^d$ | $Tq^m$ | $PR^d$ | $PR^m$ | $w^d$ | $w^m$ | $P2^d$ | $P2^m$ | $P1^d$ | $P1^m$ | $PC^d$ | $PC^m$ | Eff. Improvement |
| 0.9 | 0.00 | 530.00 | 534.11 | 0.00 | 0.00 | 163.34 | 163.32 | 0.600 | 0.593 | 31.78 | 32.59 | 0.00 | 0.00 | 195.11 | 195.91 | 0.41% |
| | 0.02 | 528.20 | 533.85 | 0.00 | 0.00 | 163.44 | 163.34 | 0.613 | 0.610 | 31.71 | 32.58 | 0.00 | 0.00 | 195.14 | 195.92 | 0.40% |
| | 0.04 | 525.86 | 533.56 | 0.00 | 0.00 | 163.56 | 163.36 | 0.629 | 0.627 | 31.37 | 32.55 | 0.00 | 0.00 | 194.93 | 195.91 | 0.50% |
| | 0.06 | 524.59 | 533.25 | 0.00 | 0.00 | 163.71 | 163.39 | 0.645 | 0.644 | 31.30 | 32.54 | 0.00 | 0.00 | 195.01 | 195.93 | 0.47% |
| | 0.08 | 522.78 | 532.98 | 0.00 | 0.00 | 163.89 | 163.43 | 0.661 | 0.661 | 31.06 | 32.47 | 0.00 | 0.00 | 194.95 | 195.90 | 0.49% |
| | 0.1 | 521.50 | 532.60 | 0.00 | 0.00 | 164.09 | 163.47 | 0.676 | 0.679 | 30.88 | 32.41 | 0.00 | 0.00 | 194.97 | 195.87 | 0.46% |
| 0.8 | 0.00 | 617.76 | 571.73 | 2.76 | 32.77 | 158.13 | 154.33 | 0.511 | 0.526 | 58.02 | 49.66 | 2.07 | 24.58 | 218.22 | 228.57 | 4.74% |
| | 0.02 | 618.98 | 571.84 | 1.32 | 32.75 | 158.62 | 154.35 | 0.525 | 0.543 | 58.53 | 49.75 | 0.99 | 24.56 | 218.14 | 228.67 | 4.83% |
| | 0.04 | 619.55 | 571.43 | 0.00 | 32.94 | 159.15 | 154.37 | 0.540 | 0.560 | 58.73 | 49.73 | 0.00 | 24.71 | 217.87 | 228.81 | 5.02% |
| | 0.06 | 613.53 | 571.09 | 0.00 | 33.14 | 159.63 | 154.40 | 0.560 | 0.577 | 56.32 | 49.73 | 0.00 | 24.85 | 215.95 | 228.98 | 6.04% |
| | 0.08 | 606.60 | 570.93 | 0.39 | 33.19 | 160.01 | 154.43 | 0.581 | 0.594 | 53.85 | 49.69 | 0.30 | 24.89 | 214.15 | 229.01 | 6.94% |
| | 0.1 | 596.90 | 570.53 | 1.97 | 33.39 | 160.31 | 154.47 | 0.603 | 0.611 | 51.05 | 49.65 | 1.48 | 25.04 | 212.84 | 229.16 | 7.67% |
| 0.7 | 0.00 | 580.00 | 540.52 | 82.11 | 99.44 | 138.12 | 142.63 | 0.471 | 0.492 | 73.86 | 65.32 | 53.37 | 64.64 | 265.35 | 272.58 | 2.73% |
| | 0.02 | 577.54 | 540.42 | 82.24 | 99.47 | 138.67 | 142.64 | 0.488 | 0.509 | 73.85 | 65.32 | 53.45 | 64.66 | 265.98 | 272.62 | 2.50% |
| | 0.04 | 575.08 | 540.20 | 82.37 | 99.58 | 139.26 | 142.66 | 0.504 | 0.526 | 73.77 | 65.34 | 53.54 | 64.73 | 266.56 | 272.73 | 2.31% |
| | 0.06 | 571.69 | 539.60 | 82.89 | 99.92 | 139.89 | 142.68 | 0.521 | 0.543 | 73.50 | 65.34 | 53.88 | 64.95 | 267.27 | 272.97 | 2.13% |
| | 0.08 | 568.57 | 538.94 | 83.16 | 100.27 | 140.56 | 142.71 | 0.538 | 0.560 | 73.01 | 65.28 | 54.05 | 65.18 | 267.63 | 273.17 | 2.07% |
| | 0.1 | 566.11 | 537.97 | 83.29 | 100.78 | 141.28 | 142.75 | 0.555 | 0.578 | 72.69 | 65.21 | 54.14 | 65.51 | 268.11 | 273.47 | 2.00% |
| 0.6 | 0.00 | 600.70 | 552.19 | 150.88 | 173.40 | 114.88 | 126.06 | 0.386 | 0.411 | 121.75 | 111.10 | 82.98 | 95.37 | 319.62 | 332.52 | 4.04% |
| | 0.02 | 613.98 | 551.65 | 144.21 | 173.71 | 115.26 | 126.08 | 0.394 | 0.428 | 123.29 | 111.19 | 79.32 | 95.54 | 317.86 | 332.81 | 4.70% |
| | 0.04 | 619.02 | 550.95 | 142.11 | 174.10 | 115.51 | 126.11 | 0.406 | 0.445 | 124.31 | 111.23 | 78.16 | 95.75 | 317.98 | 333.09 | 4.75% |
| | 0.06 | 613.84 | 550.38 | 146.01 | 174.37 | 115.75 | 126.17 | 0.421 | 0.462 | 125.17 | 111.25 | 80.30 | 95.91 | 321.23 | 333.32 | 3.76% |
| | 0.08 | 607.87 | 550.15 | 150.18 | 174.55 | 116.13 | 126.22 | 0.437 | 0.479 | 125.55 | 111.32 | 82.60 | 96.00 | 324.27 | 333.54 | 2.86% |
| | 0.1 | 602.56 | 549.38 | 154.21 | 174.92 | 116.47 | 126.30 | 0.453 | 0.497 | 126.02 | 111.27 | 84.82 | 96.21 | 327.31 | 333.78 | 1.98% |

orders based on $\tilde{\theta}^m$ . Supplier 2 then determines a wholesale price $w^{m*}$ that maximizes her expected profit. This optimal wholesale price $w^{m*}$ can be adjusted according to the actual number of retailers who receives high/low signals.

Table 2 reports expected values of the supply chain game outcome under both the decentralized and market-based information structure. We use superscript d and m to denote the decentralized, no information sharing case and the market-based, collaborative forecasting case side by side. We report the wholesale price w and the expected aggregated order quantities TQ and Tq from all the retailers to supplier 1 and supplier 2, respectively. We also present supplier 1, supplier 2, and retailers' expected profits, as well as the total supply chain profit (denoted as PS1, PS2, and PC). We then perform sensitivity analysis based on two key parameters: the compensation $c$ and supplier 1's wholesale price $v$ .

We see that, under all cases, the expected supply chain efficiency increases under the market-based collaborative forecasting framework in comparison with the decentralized framework. The last column in Table 2 presents the percentage improvement of the total supply chain profit. We measure the total supply chain profit as the sum of profits from all supply chain members including all retailers, supplier 1 and supplier 2. We measure the supply chain efficiency improvement as the ratio of the supply chain profit difference between the market-based framework and the decentralized framework to the decentralized supply chain profit, i.e., $(PC^m\text{-}PC^d)/PC^d$.

We further observe that the degree of supply chain efficiency improvement varies when $v$ and $c$ changes. Interestingly, the improvement is the highest when $v$ values around 0.8. At this value, supplier 2 manipulates the wholesale price in the decentralized framework so that all the retailers single source from her in most of the cases. However, in the market-based framework, the market information aggregation helps reveal supplier 2's true type to all the retailers so it greatly reduce the room for supplier 2 to manipulate the market. As a result, the retailers choose to dual source from both suppliers in most of the cases. Since supplier 2's reliability is either 0.8 or 0.4 with equal probability, from the supply chain perspective, it is more beneficial if retailers order from the perfectly reliable supplier 1. This is because all price related parameters such as the wholesale price and compensation cost only affect the division of profit among supply chain members rather than the total supply chain profit. Sourcing from the more reliable supplier 1 can eliminate the supply chain inefficiency caused by lost sales opportunity due to the less reliable supplier's inability to fulfill orders. In the case that $v$ = 0.8, we observe significantly higher order quantity $(Tq^m - Tq^d)$ from supplier 1. Hence the supply chain efficiency improves the most.

Another interesting observation is that increasing the compensation value $c$ may or may not improve the degree of supply chain efficiency. When $v$ is relatively high (e.g. $v$ =0.8 or 0.9), the degree of improvement increases as $c$ increases. However, when $v$ is relatively low (e.g. $v$ =0.6), the degree of improvement moves towards the other direction. This result is not too surprising. Even though supplier 2 agrees a fixed compensation to retailers in the case of non-delivery, she can adjust the wholesale price to incorporate the effect of compensation on her profitability. Hence an increase of compensation may not always make supplier 2 more attractive, but depend on how supplier 2 is actually adjusting the wholesale price. This intuition is confirmed with the observation that the higher compensation, the higher the average wholesale price. When $v$ is relatively high, supplier 1 is less competitive in comparison with supplier

2. So supplier 2 can offer a relatively high compensation but effectively adjust the wholesale price upwards and still attract retailers to single source from her. As a result, supplier 2's profits increase and retailers' profits decrease as $c$ increases (as seen when $v$ = 0.9). On the other hand, when $v$ is relatively low, supplier 1 becomes very competitive in comparison with supplier 2. Supplier 2 cannot increase the wholesale price aggressively when the compensation is high. Although supplier 2 would not worse off when she offers higher compensation, retailers benefit from the competition between the two suppliers and their profits increase (as seen when $v$ = 0.6).

## 5 Concluding Remarks

An extensive body of work in the literature has shown that information market is a promising mechanism to effectively predict uncertain outcomes [2, 9]. However, existing applications of such markets have been limited to predict public events such as presidential election or internal corporate use such as the prediction of future sales. We aim to explore the potential application of information markets in a broader decision making environment including the management of supply side uncertainty in the supply chain.

In this paper, we demonstrate the benefit of a market-based information aggregation mechanism in improving the overall supply chain efficiency. We choose the uniform demand distribution as a simple illustration. In fact, similar qualitative insights can be extended to other demand distributions. In addition to fully analyze the game structure in equilibrium analysis, future work should formally characterize conditions under which the information market improves supply chain performance.

To better coordinate the supply chain and manage the supply-side uncertainty, we assume a compensation scheme is offered by supplier 2 as a form of risk sharing contract. However, we assume the unit compensation is predetermined and the supplier only needs to decide the wholesale price. Other forms of coordination contracts, including the options contract, could be studied in future work. Please refer to [5] for more general discussion on the distribution function and the coordination mechanisms.

Although we propose to trade simple binary contracts in this research, we expect more sophisticated trading contracts such as those with continuous payoffs could also be considered in future market mechanism design. Moreover, dynamic models might be an alternative modeling tool to study repeated interactions and market dynamics in multi-period supply chain coordination. We leave all these interesting explorations to future research.

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# Appendix

**Table 3.** Table of Notations

| | |
|---|---|
| Uncertainty | |
| $\theta$ | Supplier 2's true reliability, $\theta = \theta_H$ or $\theta_L$ |
| $\tilde{\theta}$ | The retailer's belief about supplier 2's reliability |
| $x \in [\underline{x}, \overline{x}]$ | Random demand with lower bound $\underline{x}$ and upper bound $\overline{x}$ |
| $f(x)$ | Probability density function of demand |
| $F(x)$ | Cumulative density function of demand |
| Supply Chain Parameters | |
| $i = 1,\ldots N$ | $N$ retailers |
| $v$ | Unit wholesale price charged by supplier 1 |
| $w$ | Unit wholesale price charged by supplier 2 |
| $q$ | The retailer's order from supplier 1 |
| $Q$ | The retailer's order from supplier 2 |
| $c$ | Supplier 2's unit compensation cost in case of non-delivery |
| $c_s$ | Supplier 2's unit production cost |
| $r$ | The retailer's unit retail price |
| $h$ | Unit lost sales cost |
| $g$ | Unit salvage value |
| Information Structure | |
| D | Denote decentralized information structure |
| M | Denote market-based information structure |
| $P(\theta = \theta_H) = p$ | Prior belief that supplier 2's reliability is high |
| $P(\theta = \theta_L) = 1 - p$ | Prior belief that supplier 2's reliability is low |

**Table 3.** (*continued*)

| | |
|---|---|
| $s = \{1, 0\}$ | The value of binary signal |
| $\alpha$ | Number of retailers who receive $s = 1$ |
| $\beta$ | Number of retailers who receive $s = 0$, $\alpha + \beta = N$ |
| $P(s = 1 \mid \theta = \theta_H) = \lambda$ | Conditional probability, $P(s = 0 \mid \theta = \theta_H) = 1 - \lambda$, $\lambda > 1/2$ |
| $P(s = 0 \mid \theta = \theta_L) = \lambda$ | Conditional probability, $P(s = 1 \mid \theta = \theta_L) = 1 - \lambda$, $\lambda > 1/2$ |
| $\tilde{\theta}_h$ ( $\tilde{\theta}_\ell$ ) | The retailer's perceived reliability if she receives signal $s = 1$ ( $s = 0$ ) |
| $\tilde{\theta}^m$ | Updated market belief based on market prices |
| $\phi_H^*$ ( $\phi_L^*$ ) | Equilibrium market prices for contracts "High_Reliability" ( "Low_Reliability") |
| Threshold Values | |
| $w_1$ | Wholesale price threshold value below which the retailer single-sourcing from supplier 2 |
| $w_2$ | Wholesale price threshold value above which the retailer single-sourcing from supplier 1 |
| $\overline{\theta}$ | Reliability threshold value above which the retailer single-sourcing from supplier 2 |
| $\underline{\theta}$ | Reliability threshold value above which the retailer single-sourcing from supplier 1 |
| $\overline{w}$ | Wholesale price threshold value corresponding to $\overline{\theta}$ |
| $\underline{w}$ | Wholesale price threshold value corresponding to $\underline{\theta}$ |