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Contracts for Changing Times: Sourcing with Raw Material Price Volatility and Information Asymmetry

Wei Zhang
Anderson School of Management, University of California, Los Angeles, Los Angeles, California 90095,
wei.zhang.2014@anderson.ucla.edu

Deke Zhou, Liwen Liu
School of Economics and Management, Tsinghua University, Beijing 100084, China
{zhoudk.06@sem.tsinghua.edu.cn, liulw@sem.tsinghua.edu.cn}

We analyze and compare five contract schemes used in a supply chain: fixed price (FP), cost reimbursement (CR), procurement control (PC), index-linked payment (IL), and relational (RL) contracts. From interviews, we learned that (1) FP and RL are the two most popular schemes; (2) PC is less popular, but it is used more often than CR and IL; and (3) a couple of firms are considering CR and IL and will probably use them in the future. By presenting a two-stage contracting model that incorporates a risk-neutral buyer and a risk-averse supplier under raw material price uncertainty and information asymmetry, we show that overhedging the supplier's risk with an IL contract can be optimal for the buyer in many cases. Using the model to study the effects of price trends, risk attitudes, information asymmetry, and constraints on purchase time, we find that each contract can be optimal in certain situations from certain standpoints. In particular, when a long-term relationship is considered, RL is equivalent to IL as long as the contract is self-enforcing, and RL can replace IL when no index is available. Connecting the analytical results to the interviews, we find that firms' choices and considerations can be well understood.

Key words: raw material price volatility; information asymmetry; supply chain management; contracting; risk aversion; risk sharing
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1. Introduction

Supply chains today face great risks from upstream. Prices for many industrial and agricultural raw materials are changing more frequently than ever before and without any discernible pattern. The world price in U.S. dollars for a barrel of crude oil, for example, surged from approximately $20 in 1998 to nearly $100 by 2008, dropped to $40 in 2009, rose to $100 in 2011, and fell to $80 in 2012.[1] In food markets, prices for corn and wheat rose steadily from 2000 to 2005; soared in 2007 and 2008 because of weather events, food security fears, and trade restrictions; declined in late 2008 and 2009, during the global economic recession; and rose again throughout 2010.[2] Hence, the unit costs of products constitute an unknown factor for supply chain players at the time of contracting, which may complicate the negotiation and contracting processes.

In such an environment, we are particularly interested in a supply chain in which a component or service supplier is "sandwiched" in terms of bargaining power by his downstream buyer (perhaps an assembler or original equipment manufacturer) and his upstream raw material source. Generally, when furnishing components to an assembler downstream, the supplier has to accept a credit period of 60–90 days. By contrast, when purchasing raw materials from his upstream source, he often pays cash or even prepays. Therefore, it is reasonable to assume that suppliers often struggle with stringent cash flows and low profit margins and that they frequently lack the capability to cope with risk. In such a situation, a risk-averse supplier would likely request a high risk premium and tend to make overly conservative inventory decisions. For instance, the risk-averse supplier may enter into a forward or long-term contract that locks the raw material price even when the price is expected to decrease. The resulting bottleneck in the process would undermine the performance of the entire supply chain.

Consequently, the downstream buyer, in most cases a supply chain leader, needs to devise a productive

[1] http://wtrg.com/daily/oilandgasspot.html (accessed in 2010 and 2013).

[2] http://barchart.com/chart.php?sym=ZCY00&t=BAR&size=M&v=0&g=1&p=WN&d=X&qb=l&style=technical&template= (accessed in 2010 and 2013).

mode of cooperation with the supplier and generate a contract that induces him to purchase raw materials efficiently. Complicating the issue is the likelihood that, her (the buyer's) decision processes are hampered by information asymmetry regarding the supplier's raw material prices and consumption. The supplier may regard his raw material purchase price as private. Even when he acquires raw material from a commodity market, the buyer downstream is neither likely to know exactly when the supplier purchased the raw material nor be privy to his mechanism for allocating costs among his clients. Therefore, in decentralized supply chains, the supplier's raw material purchase decision can hardly be verified. Additionally, the supplier has an informational advantage regarding his raw material consumption rate under the following circumstances. (i) The rate may be affected by process or bill-of-material (BOM) complexity and instability. When component design is delegated to the supplier, BOM is generally unstable during early stages of cooperation because of modifications driven by final consumer or supplier feedback, which increases the supplier's familiarity with the usage of raw materials. (ii) Serving multiple clients and running multiple product lines enhance the supplier's information advantage when clients and products share the production or service capacity. This situation is widespread in the logistics services industry. (iii) Technical improvements in supplier efficiency can create a perilous information barrier for the buyer after (ex post) the fact.

Our goal in this research is to find the right contracting scheme for a buyer under a variety of circumstances. To that end, throughout 2008 and 2009, one of the authors interviewed a number of supply chain practitioners from 11 large companies representing various industries. Some interviews involved personal conversations between the author and company managers; others occurred during seminars held at Tsinghua University in Beijing. A detailed list of the companies he interviewed and the contracts they used before, were using at the time, and were considering for the future can be found in the appendix. The first fact we learned is that most companies interviewed deal with small-scale suppliers—mainly producing plastic parts or mechanical components—with a weak capacity for coping with raw material price risk. From the interviews and literature search, we observed five contract schemes industries used to deal with raw material price fluctuation:

1. Fixed-price (FP) contracts are the simplest type of contract, and they prevail in industry practice as well as in the academic literature. Under FP, the buyer and the supplier are responsible for coping with their own risks. Firms using FP contracts include Lenovo and Sany Heavy Industry.

2. Cost reimbursement (CR) contracts put the buyer in the position of shielding the supplier from raw material price risks by separating specific raw material costs (e.g., gasoline) and reimbursing him for them. As studied in this paper, CR contracts have as their prototype the logistics services industry. For example, Volkswagen uses a "gas plus service cost" contract when collaborating with risk-averse logistics services providers. Mutual trust and deep cooperation are usually essential under CR contracts because the supplier must be trusted to report his true cost.

3. Procurement control (PC) contracts also shift risk onto the buyer, who deals directly with the tier 2 raw material supplier and purchases material for her tier 1 component supplier. Normally, company buyers use PC when they exercise superior bargaining power in dealing with raw material suppliers upstream or possess more knowledge about the situation than the tier 1 supplier does. Thus, when upstream price uncertainty exists, PC relieves some of the risk burden on the tier 1 supplier. Haier, a Chinese appliance company, uses PC contracts to purchase steel directly from (tier 2) Baosteel and provide it to its (tier 1) component suppliers. In another example, COFCO Coca-Cola (a joint venture between Chinese food processor COFCO and Coca-Cola) buys raw material, such as polycarbonate for its bottle suppliers. To rule out effects other than risk sharing, we assume in this paper that the buyer and the supplier have equal bargaining power to deal with raw material suppliers further upstream.

4. Index-linked payment (IL) contracts involve the buyer and supplier signing a contract under which the final payment is contingent on the raw material price on a given date. Commonly used in weapons procurement, IL contracts have received increased attention as various raw material prices have become more volatile. Under IL contracts, for example, Foxconn, the world's largest manufacturer of electronic devices, pays its component suppliers according to the raw material price at the time of order placement—not the price on the date when the contract was signed. Even when proposed by the supplier—usually when he is a contract leader—and as long as there is a contractible index, IL contracts are good risk-transferring mechanisms that can benefit the entire supply chain.

5. Relational (RL) contracts are ex post agreements that compensate suppliers when the raw material price deviates substantially from the contracted price. Such negotiations, from our perspective, are not a renegotiation because the original contract is not changed and the compensation transpires after all operational decisions have been finalized. Two modes of RL—named for Chinese electronics firms

Huawei and Konka—emerged among those interviewed. In Huawei mode, no direct compensation is made, but the buyer increases the supplier's market share of new products or new projects at a loss. In Konka mode, the supplier is compensated directly with cash on a quarterly or annual basis.

Although our data set is very limited, our observations are still interesting and useful. We found that FP and RL contracts are the most popular of the five schemes. PC is less popular, but it is used more often than CR and IL. Two of the firms interviewed are considering CR and IL and will probably employ them in the future. Although the choice of contract entails multiple complex considerations, the firms all admitted that raw material price risk is a major concern when dealing with weak suppliers. To understand the contract selections and possibly to obtain some insights, we thoroughly examined each type of contract.

Based on our information, we constructed an analytical model of a two-stage contracting game between a risk-neutral buyer and a risk-averse supplier. The buyer is the contract leader, but she faces information asymmetry, so we assume that screening contracts (revelation principle) are used. The supplier, however, chooses from a menu of contracts and decides whether to buy raw material in advance or later (right before production) and how much to buy, being aware of the fact that raw material prices will change in the next stage according to a normally distributed noise. We then derived the optimal decisions and contract designs, and we compared the efficiency of the contracts in different scenarios.

This paper is organized as follows. In §2, we give a brief literature review. In §3, we state our analytical model in detail. In §4, we investigate each of the first four types of contract schemes under decentralized management, reserving RL for later because it requires us to assume additional structures for the analysis. In §5, we compare the four contracting practices primarily from the buyer's point of view by employing multiple model parameters and modifying assumptions. In §6, we extend the model to incorporate relational contracting and asymmetric raw material price information. In §7, we summarize our findings and conclude the paper.

2. Literature Review

In general, our work belongs to a vast body of literature examining component procurement (or outsourcing) contract design and choice. Our interest is particularly focused on contract design and choice in dealing with raw material price risk, which only recently has become a major concern of supply chain management. Besides interviewing practitioners and accumulating industry facts, we study the complicated issue of contracting in the presence of information asymmetry and risk-averse agents, which offers new insight for optimal contract design and choice.

Information asymmetry, a major concern for firms in service or product outsourcing, can manifest in many dimensions, such as quality, reliability, and cost. Lim (2001) investigated the quality-control contract design problem of a producer when he purchases parts from a supplier who has private information on the quality. Yang et al. (2009) studied a mechanism design problem in which a manufacturer faces a supplier privileged with private information about supply reliability. Compared with quality and reliability, cost information is more popular among researchers that study information asymmetry. Cachon and Zhang (2006) studied a queuing model in which a buyer sources a good or service from a single supplier whose lead time affects the buyer's cost. Assuming the supplier has private information about the production cost, they analyzed several mechanisms such as late fees and fixed lead-time requirements. Kayis et al. (2012) analyzed a problem wherein a manufacturer must choose to delegate or control component procurement when supplier costs are private information. They showed that if the firms implement arbitrarily complex contracts, then delegation and control are equivalent. However, if the firms use price-only contracts, then either delegation or control can be a better choice. In another paper, Guo et al. (2010) considered a three-tier supply chain in which the parties hold their cost information private. They compared three outsourcing structures, one of which resembles the practice of procurement control. Looking at the early stage of the product life cycle, Kim and Netessine (2013) investigated the effects of information asymmetry and contracting strategies on collaboration during the product design stage. Other studies in this category include Li and Debo (2009), Ren and Zhang (2009), and Zhang (2010). Whereas these papers all shed light on outsourcing mechanism design with risk-neutral agents and one-dimensional uncertainty, our paper considers the impact of the supplier's risk attitude and further decomposes the supplier's cost uncertainty into the product of ex ante uncertainty on production (or service) efficiency and ex post uncertainty on raw material price.

The study of risk-averse agents becomes more and more relevant in supply chain management as the volatility of the global economy increases. Among the early papers, Lau and Lau (1999) examined the optimal wholesale price and return policy for a simple supplier–retailer supply chain where both agents have a mean-variance objective. Chen and Federgruen (2000) studied several inventory models with a mean-variance objective. Kim et al. (2007) also used the mean-variance objective to examine performance contracting in after-sales service chains. Using a general utility function, Agrawal and Seshadri (2000) investigated a single-period inventory problem for a risk-averse retailer who optimizes the order quantity and selling price. Gan et al. (2004) studied the class of problem that involves risk-averse agents, defining a coordinating contract at the outset as one that results in a Pareto-optimal solution acceptable to each agent. In a follow-up paper, Gan et al. (2005) investigated the means by which a supply chain involving a risk-neutral supplier and a downside-risk-averse retailer can be coordinated under a risk-sharing contract. Although our model also features risk-averse agent, it is distinguished by the interplay of risk aversion and information asymmetry. We show, in fact, that the Pareto-optimal risk-sharing contract is not the optimal choice for the principal in our setting. Moreover, we explicitly study contract schemes aimed at managing risks associated with raw material prices, which is not the focus of the foregoing papers.

Ways to deal with the risk of raw material or commodity price volatility are explored by an emerging body of operations management literature. A major portion of this stream focused on raw material procurement strategies for single-firm decision making. Li and Kouvelis (1999) studied time and quantity flexible supply contracts between a manufacturer and its raw material provider under price uncertainty and deterministic demand. Secomandi (2010) and Goel and Gutierrez (2011) examined optimal operating policies in presence of the fluctuating commodity prices. Other papers incorporate specific cases of supply chain cooperation between a downstream buyer and an upstream supplier coping with cost uncertainty. Gurnani and Tang (1999) studied the optimal ordering policy for a risk-neutral retailer who has two instants to order a seasonal product from a risk-neutral manufacturer, whose cost in the second instant is uncertain. Nevertheless, the focus of the research was on determining order policy, not on comparing and choosing among different supply chain cooperation mechanisms.

Finally, three of the five contract schemes investigated in this paper—FP, CR, and PC—are relatively common and intuitive in dealing with risk. Papers that address them include Kim et al. (2007), Guo et al. (2010), and Kayis et al. (2012). RL was formally introduced by Levin (2003) in the economics literature and is also a type of contract well-known in supply chain management. However, the ability of RL to deal with supply chain risks has not been fully delineated. Debo and Sun (2004) studied wholesale pricing and order-quantity decisions between a supplier and a buyer under relational contracting. Tunca and Zenios (2006) examined the interplay between supply auctions and relational contracts. Taylor and Plambeck (2007a, b) and Ren et al. (2010) addressed the impact of relational contracting on early capacity investment. In contrast to these papers, we intend to study ways that RL can be used for sharing risk and inducing a risk-averse supplier to make efficient raw material purchasing decisions. As we show by extending the base model in §6, RL can outperform other contracts in certain situations.

3. The Model

A buyer (she) sources a component product or service from a supplier (he) under a single-period contract, which is signed (in period 0) one period before the supplier carries out the production or service (in period 1). The supplier will deliver Q units of component product or service, and the buyer will pay him $T(Q)$ in return. Renegotiation and backlog are not allowed. The supplier is risk averse and seeks to maximize his ex ante mean-variance objective U_S defined as

$$U_S = \mathbf{E}[\pi_S] - \frac{r}{2}\mathbf{V}[\pi_S], \tag{1}$$

where π_S is the supplier's ex post total profit and the constant r is the risk-aversion factor, which can be commonly observed (Kim et al. 2007). In fact, this ex ante objective function is the *certainty equivalent* of the exponential utility (i.e., $u(X) = -e^{-rX}$) as long as the source of uncertainty is normally distributed, and $(r/2)\mathbf{V}[\pi_S]$ is the so-called risk premium. We also assume that the *individual rationality* (IR) constraint for the supplier is $U_S \geq 0$.

The supplier's cost consists of the cost of the raw material c_r and a deterministic part c_d, which includes the cost of other materials, administrative costs, and so on. We have $c_r = q_0 z_0 + q_1 z_1$, where q_t and z_t are the raw material quantity and purchase price in period t $(= 0, 1)$, respectively. In the base model, we assume that the raw material price in each period is publicly known. Let $\epsilon := (z_1 - z_0)/z_0$ follow the (subjective) probability distribution of $N(\mu, \sigma^2)$. Note that the buyer and the supplier should agree on μ and σ after sufficient communication (Aumann 1976). However, other players in the market may have different beliefs. To simplify the analysis, we do not set restrictions on ϵ, and we assume that a positive z_1 can always be observed. Regarding raw material procurement quantities, we require that $q_t \geq 0$ and $q_0 + q_1 = \theta Q$, where θ is the amount of material used to generate one unit of component product or service (i.e., the material consumption rate or efficiency). Note that the supplier in period 0 can either build up his physical inventory of raw material or use forward contract to lock the price. We assume no risk-free arbitrage, so the costs of both methods should be equal. We model them as z_0q_0h, where h stands for the sum of the interest rate and inventory storage cost rate. Finally, without affecting our qualitative results, we normalize c_d to 0.

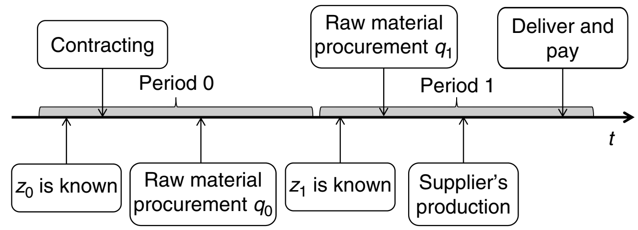
Under the assumptions we have laid out so far, the supplier with a general contract payment $T(Q)$ has the following ex ante objective function:

$$U_S(q_0, q_1 \mid Q, T(Q)) = \mathbf{E}\bigg[T(Q) - \sum_{t=0,1} z_t q_t\bigg] - z_0 h q_0 - \frac{r}{2}\mathbf{V}[T(Q) - z_1 q_1]. \tag{2}$$

The buyer is risk neutral and aims to maximize her expected total profit Π_A. Given Q and $T(Q)$, she will obtain profit $\tilde{R}(Q) - T(Q)$, where $\tilde{R}(Q)$ is the net income without subtracting a contract payment, satisfying $\mathbf{E}[\tilde{R}(Q)] = R(Q)$, $R(0) = 0$, $R'(0) = \infty > T'(0)$, and $R''(Q) < 0$. We assume that the buyer is the contract leader, but she faces an information disadvantage in her dealings with the supplier both ex ante and ex post. On one hand, she is uncertain about the supplier's efficiency θ. We assume that, for the buyer, θ_H is the lowest production efficiency that is acceptable and θ_L is the highest possible efficiency in the industry. The potential supplier's θ is randomly drawn from the finite support $[\theta_L, \theta_H]$, with probability density function $f(\cdot)$ and cumulative distribution function $F(\cdot)$, which is assumed to be log-concave (i.e., $g(\theta) := F(\theta)/f(\theta)$ is increasing in θ). On the other hand, the supplier's raw material procurement decisions q_t are neither observable nor verifiable, which can be caused by the complexity of the supplier's operational process. Therefore, the buyer needs to optimize a screening menu of $\{Q(\theta), T(Q(\theta))\}_{\theta=\theta_L}^{\theta_H}$ to (i) incentivize the supplier to report the true θ, (ii) induce efficient raw material purchasing decisions, (iii) reduce disutility by sharing the supplier's risk, and ultimately (iv) maximize her own expected profit Π_A, which takes the following form:

$$\Pi_A = \int_{\theta_L}^{\theta_H} \big(R(Q(\theta)) - \mathbf{E}[T(Q(\theta))]\big)\, dF(\theta). \tag{3}$$

Figure 1 **Sequence of Events**



To fully explore the impact of the raw material price risk on supply chain performance, we rule out other operational limitations such as capacity constraint, budget constraint, demand forecast, order updating, and so on, which can set restrictions or impose extra risk on inventory decisions. The sequence of events is shown in Figure 1. In the online supplement (available at http://dx.doi.org/10.1287/msom.2013.0454), we analyze a benchmark model with a centralized buyer and supplier.

4. Analysis of Contracts

In the base model, we do not consider the value of long-term relationships; thus, we analyze and compare four contracts in this section. We study relational contracting in §6.

4.1. Fixed-Price Contract

Under an FP contract, the buyer's payment is $T = pQ$. To obtain the optimal contract design, $\{p(\theta), Q(\theta)\}_{\theta=\theta_L}^{\theta_H}$, we start from the supplier's problem. Given any (p, Q), the supplier's ex post profit is $\pi_S = pQ - z_0q_0(1+h) - z_1(\theta Q - q_0)$ and expected utility is

$$U_S = [p - z_0\theta(1+\mu)]Q + z_0q_0(\mu - h) - \frac{r}{2}\sigma^2 z_0^2 (q_0 - \theta Q)^2. \tag{4}$$

It is easy to verify that $\partial^2 U_S/\partial q_0^2 < 0$ so that the optimal raw material buying decision for the supplier in period 0 is $q_0^* = \max\{0, \theta Q - (h - \mu \wedge h)/(rz_0\sigma^2)\}$. Applying the standard procedure of designing a screening contract (Laffont and Tirole 1993), we obtain the FP results summarized in Tables 1 and 2. We can

Table 1 **Summary of Optimal Operations Decisions and Information Rent**

	$Q^*(\theta)$	$q_0^*(\theta)$	$U_S(\theta)$
CM	$R'^{-1}(z_0\theta(1+\mu\wedge h))$	$\theta Q^*(\theta)\mathbb{1}\{\mu > h\}$	—
FP	$R'^{-1}(z_0(1+h)A(\theta))$	$\theta Q^*(\theta) - \dfrac{h-\mu\wedge h}{rz_0\sigma^2}$	$\int_\theta^{\theta_H} z_0(1+h)Q^*(x)\,dx$
CR	$R'^{-1}(z_0(1+\mu)\Gamma(\theta))$	$\dfrac{\mathbf{E}[\epsilon\vee h]-h}{rz_0\mathbf{V}[\epsilon\vee h]}$	$\int_\theta^{\theta_H} z_0\bigg(1+\mu-\dfrac{(\mathbf{E}[\epsilon\vee h]-h)\mathbf{Cov}(\epsilon\vee h,\epsilon)}{\mathbf{V}[\epsilon\vee h]}\bigg)Q^*(x)\,dx$
PC	$R'^{-1}[z_0(1+\mu)B(\theta,\mu)]$	$\theta Q^*(\theta)\mathbb{1}\{\mu > h\}$	$\int_\theta^{\theta_H} z_0(1+\mu)Q^*(x)\,dx$
IL	$R'^{-1}(z_0(1+\mu)G(\theta))$	$\bigg[\dfrac{\mu-h}{rz_0\sigma^2} - \dfrac{F(\theta)}{f(\theta)}Q^*(\theta)\bigg]^+$	$\int_\theta^{\theta_H} z_0(1+\mu)[G(x)-x]\dfrac{f(x)}{F(x)}Q^*(x)\,dx$

Table 2 The Buyer's Expected Profit

	Π_A
FP	$\int_{\theta_L}^{\theta_H}\int_{z_0(1+h)A(\theta)}^{R'(0)} R'^{-1}(x)\,dx\,dF(\theta)+\dfrac{(h-\mu\wedge h)^2}{2r\sigma^2}$
CR	$\int_{\theta_L}^{\theta_H}\int_{z_0(1+\mu)\Gamma(\theta)}^{R'(0)} R'^{-1}(x)\,dx\,dF(\theta)-\dfrac{(\mathbf{E}[\epsilon\vee h]-\mu)^2-(h-\mu)^2}{2r\mathbf{V}[\epsilon\vee h]}$
PC	$\int_{\theta_L}^{\theta_H}\int_{z_0(1+\mu)B(\theta,\mu)}^{R'(0)} R'^{-1}(x)\,dx\,dF(\theta)$
ILP	$\int_{\theta_L}^{\theta_H}\int_{z_0[(1+\mu)A(\theta)-(\mu-h)^+ +g(\theta)]}^{R'(0)} R'^{-1}(x)\,dx\,dF(\theta)-\dfrac{(\mu-h\wedge\mu)^2}{2r\sigma^2}$

see that, given the supplier's type θ, the buyer's effective marginal production cost is $z_0(1+h)A(\theta)$, where $A(\theta):=\theta+F(\theta)/f(\theta)$ and her order quantity is smaller than the first-best (because $(1+h)A(\theta)>\theta(1+h\wedge\mu)$). The supplier deviates from first-best by buying some raw materials in advance, even when the holding cost outweighs the expected cost fluctuation, which is driven by the supplier's risk-averse attitude.

4.2. Cost-Reimbursement Contract

Under CR contracts, the buyer seeks to protect the supplier from the risk of raw material price increases by reimbursing the cost incurred in raw material procurement. Hence, the contract payment is $T(Q)=pQ+(1+h)z_0\hat{q}_0+z_1\hat{q}_1$, where p is a fixed price and $\hat{q}_t$ is the claimed amount of raw material purchased in period t by the supplier. Note that $\{\hat{q}_t\}$ may not be the true information because the supplier's raw material procurement decisions are not observable or verifiable ex post. To prevent the supplier from cheating, the buyer would require that the supplier pick a $\hat{\theta}$ ex ante from a menu of $\{\theta,p(\theta),Q(\theta)\}_{\theta=\theta_L}^{\theta_H}$ and require that $\hat{q}_0+\hat{q}_1=\hat{\theta}Q$ be satisfied ex post. Of course, $\{\hat{q}_t\}$ cannot be arbitrary, and reimbursement is based on purchasing records that must be real. Supposing that q_0 is the real quantity purchased in period 0, the supplier can only report $\hat{q}_0\in[0,q_0]$ and $\hat{q}_1=\hat{\theta}Q-\hat{q}_0$. By manipulating his procurement records, the supplier can get extra reimbursement if $z_1>z_0$. We assume excessive raw material can be sold on the spot market or used for other purposes.

Because the reimbursement is linear in $\hat{q}_0$, the supplier's action set can be reduced to $\{0,q_0\}$. Given that the supplier reports $\hat{\theta}=b$ and buys q_0 in period 0, his ex post profit is

$$\pi_S(b\,|\,\theta)=\max\{z_1bQ(b),(1+h)z_0q_0+z_1(bQ(b)-q_0)\}+pQ(b)-(1+h)z_0q_0-z_1(\theta Q(b)-q_0),\qquad(5)$$

where the first item (the maximum) is the reimbursement from the buyer, the second item is the fixed payment, and the last two items are the actual raw material procurement costs. By maximizing $U_S(\pi_S\cdot(b\,|\,\theta))$, we get

$$q_0^*=\max\left\{0,\frac{\mathbf{E}[\epsilon\vee h]-h-rz_0^2(b-\theta)Q(b)\mathbf{Cov}(\epsilon\vee h,\epsilon)}{rz_0\mathbf{V}[\epsilon\vee h]}\right\}.$$

Hence, when $b=\theta$ (i.e., when the revelation principle holds), we have $q_0^*>0$, so the supplier would always buy some raw material in advance. By doing so, he can create some room to manipulate the reported purchasing records. On the other hand, if $rz_0\mathbf{V}[\epsilon\vee h]$ is large enough, he would never buy all the raw material in advance, even if the price is expected to rise because the buyer would reimburse the cost anyway. The moral hazard problem therefore makes the CR contract a very risky game for both the buyer and the supplier. Following the same process of analysis, we obtain the CR results summarized in Tables 1 and 2. We can see that, given the supplier's efficiency θ, the buyer's effective marginal production cost under CR is $z_0(1+\mu)\Gamma(\theta)$, where

$$\Gamma(\theta):=\theta+\left(1-\frac{(\mathbf{E}[\epsilon\vee h]-h)\mathbf{Cov}(\epsilon\vee h,\epsilon)}{(1+\mu)\mathbf{V}[\epsilon\vee h]}\right)\frac{F(\theta)}{f(\theta)}<A(\theta).$$

If there is no ex ante information asymmetry, then $\Gamma(\theta)=\theta$. Hence, under a CR contract, the buyer's expected cost would always increase with μ.

4.3. Procurement Control Contract

Now we consider the practice through which the buyer takes charge of raw material procurement. For our purposes, we will assume that the buyer incurs no administrative cost. Although a moral hazard issue is no longer present, the supplier retains an incentive to misreport his cost efficiency because we assume he can benefit from any excess raw material he obtains from the buyer. Given that the buyer uses a contract menu consisting of $\{P(\theta),Q(\theta)\}_{\theta=\theta_L}^{\theta_H}$ and the supplier reports $\hat{\theta}=b$, the supplier's ex post profit is $\pi_S(b\,|\,\theta)=P(b)+z_1Q(b)(b-\theta)$, where the second term is a possible gain or loss in period 1 resulting from misreporting. However, note that we will have $b=\theta$ in equilibrium by the Revelation Principle, so the second term will be zero and the supplier will not be exposed to z_1. Following the same analytical procedure, we obtain the PC results summarized in Tables 1 and 2. The only difference from previous contracts is that q_0 is now decided by the buyer. We find that the buyer's effective marginal production cost is $z_0((1+\mu)B(\theta,\mu))$, where $B(\theta,\mu)=A(\theta)-((\mu-h)^+/(1+\mu))\theta$. If there is no ex ante information asymmetry (i.e., if $A(\theta)=\theta$), then a PC contract is equivalent to centralized management. In general, the effective marginal cost increases with μ because the larger μ is, the greater the supplier's incentive to misreport his production efficiency.

4.4. Index-Linked Payment Contract

Finally, let us look at the contract that was least often encountered in the interviews but is, indeed, the most interesting. Under an IL contract, the payment $T(z_1, Q)$ is contingent on the raw material price. We have assumed that the supplier's raw material purchase prices, $\{z_t\colon t=0,1\}$, are public information, which naturally makes z_1 a perfect index for the contract payment. Again, we assume that the buyer uses a screening menu, $\{Q(\theta), T(z_1, Q(\theta))\}_{\theta=\theta_L}^{\theta_H}$, which could take various forms, although we assume a general linear form $T(z_1, Q(\theta)) = P(\theta) + \beta(\theta)z_1$. Essentially, everything in an IL contract is prespecified, as opposed to a CR contract, under which the contract payment depends on the supplier's ex post behavior. Given the supplier's type θ, if he chooses $\{Q(b), P(b), \beta(b)\}$ and makes raw material procurement decision $q_0 \in [0, \theta Q(b)]$ in period 0, then his ex post total profit is $\pi_S = P(b) + \beta(b)z_1 - z_0(1+h)q_0 - z_1(\theta Q(b) - q_0)$, and his ex ante objective function is

$$U_S = P(b) - z_0(1+h)q_0 - z_0(1+\mu)(\theta Q(b) - \beta(b) - q_0) - \frac{r}{2}z_0^2(\theta Q(b) - \beta(b) - q_0)^2\sigma^2. \quad (6)$$

We can check that $\partial^2 U_S/\partial q_0^2 < 0$, so that by applying the first-order condition, we get

$$q_0^* = \theta Q(b) \wedge \left[\theta Q(b) - \beta(b) - \frac{h-\mu}{rz_0\sigma^2}\right]^+. \quad (7)$$

It can be seen that the value of q_0^* is bound from both above and below, producing three cases for q_0^*. Checking each possible case of q_0^*, we can derive the following theorem given $\{Q(\theta)\}$.

Theorem 1. *If $\mu \gg h$, then $\beta^*(\theta) = 0$, $q_0^* = \theta Q(\theta)$, and the supplier has information rent*

$$U_S(\theta) = z_0(1+h)\int_\theta^{\theta_H} Q(x)\,dx.$$

If $\mu \le h$, then $\beta^*(\theta) = A(\theta)Q(\theta)$, $q_0^* = 0$, and the supplier has information rent

$$U_S(\theta) = \int_\theta^{\theta_H} \big[z_0(1+\mu) - rz_0^2\sigma^2 Q(x)g(x)\big]Q(x)\,dx.$$

Therefore, we can see that it is optimal for the buyer to overhedge the supplier's risk under an IL contract when $\mu \le h$ because $A(\theta) > \theta$. The intuition behind overhedging is that if the supplier reports a larger raw material consumption rate then he faces even greater risk from the buyer's contract payment because $A(\theta)$ is an increasing function of θ. Given that the supplier is risk averse, the incentive to misreport his cost efficiency is reduced and thus his information rent is squeezed. It might not be intuitive that the supplier gets averse when his cost is overestimated. Note that it does not necessarily mean the supplier is overpaid because the payment consists of two parts and the fixed part P will be reduced as β increases.

Another direct insight from Theorem 1 is that an FP contract ($\beta^*(\theta) = 0$) dominates the IL contract ($\beta^*(\theta) = A(\theta)Q(\theta)$) if $\mu \gg h$. (The sign $\gg$ means "much greater than.") Hereafter, we define the IL contract payment as $T(z_1, Q(\theta)) = P(\theta) + z_1 A(\theta)Q(\theta)$. It is obvious that, for the benefit of the supply chain, the two parties should purchase all the raw material in period 0 if $\mu > h$, in which case an FP contract gives the supplier the right incentive. However, it is possible that the buyer benefits from overhedging the supplier when μ is just slightly greater than h.

The use of IL contracts is technically complicated when $\mu > h$. As seen from (7), certain highest-efficiency suppliers will still purchase some raw material in advance while less-efficient others will not. This will lead to different contract designs for different types of supplier. Let $\Theta(\mu)$ denote the set such that for $\theta \in \Theta(\mu)$, $q_0^*(\theta) > 0$ under an IL contract. We can check that $U_S(\theta) = z_0(1+h)\int_\theta^{\theta_H} Q(x)\,dx$ for $\theta \in \Theta(\mu)$, and $U_S(\theta)$ for $\theta \in \bar{\Theta}(\mu) := [\theta_L, \theta_H]\backslash\Theta(\mu)$ takes the same form as for $h \ge \mu$ in Theorem 1. Moreover, we have $\Theta(\mu) = \varnothing$ if $\mu \le h$ and $\Theta(\mu) \ne \varnothing$ if $\mu > h$.

Next, we proceed to characterize the rest of the contract. An effective screening contract should satisfy both the IC and IR conditions. Under an IL contract, according to Theorem 1, the design of $Q(\theta)$ may affect the sign of $U_S(\theta)$ and thus the IR condition, especially for $\theta \in \bar{\Theta}(\mu)$. Hence, we characterize the feasible range for $Q(\theta)$ in the following lemma.

Lemma 1. *Under IL contract, the IR condition is satisfied if $Q(\theta) \le ((1+\mu)f(\theta))/(rz_0\sigma^2 F(\theta))$ for any $\theta \in \bar{\Theta}(\mu)$.*

Hence, we denote $\bar{Q}(\theta) := ((1+\mu)f(\theta))/(rz_0\sigma^2 F(\theta))$ as the upper bound of the buyer's order quantity for the supplier with type $\theta \in \bar{\Theta}(\mu)$, and in deriving the optimal contract, we need to impose this constraint on the design of $Q^*(\theta)$ for $\theta \in \bar{\Theta}(\mu)$. For $\theta \in \Theta(\mu)$, however, we have $Q^*(\theta) < ((\mu - h)f(\theta))/(rz_0\sigma^2 F(\theta)) < \bar{Q}(\theta)$ by definition. Therefore, we can actually impose the constraint $Q(\theta) \le \bar{Q}(\theta)$ for every θ and simplify our analysis. Also, to guarantee a unique $Q^*(\theta)$, we assume the revenue function R is concave enough so that $R''[Q] < -rz_0^2\sigma^2 g(\theta_H)^2$ for a reasonably large range of Q. Thus, we can derive the optimal menu of contract (note that $P^*(\theta)$ is given by (6) once we have $Q^*(\theta)$) and the buyer's maximal expected profit as follows.

Proposition 1. *Under an IL contract, the optimal order for the buyer and her expected profit are*

$$Q^*(\theta) = \min\{\bar{Q}(\theta), R'^{-1}[z_0(1+\mu)A(\theta) - rz_0^2\sigma^2 g(\theta)^2 Q^*(\theta)]\},$$

$$\Pi_A^{\mathrm{IL}} = \int_{\theta_L}^{\theta_H}\left[R(Q^*(\theta)) - z_0(1+\mu)A(\theta)Q^*(\theta) + \max\left\{\frac{(\mu-\mu\wedge h)^2}{2r\sigma^2}, \frac{rz_0^2\sigma^2 g(\theta)^2 Q^*(\theta)^2}{2}\right\}\right] dF(\theta). \quad (8)$$

The buyer's optimal order quantity can be written as $Q^*(\theta) = R'^{-1}(z_0(1+\mu)G(\theta))$, where

$$G(\theta) := \max\left\{\frac{R'(\bar{Q}(\theta))}{z_0(1+\mu)}, A(\theta) - \frac{rz_0^2\sigma^2 g(\theta)^2 Q^*(\theta)}{z_0(1+\mu)}\right\}.$$

Thus, her effective marginal production cost with a type θ supplier is $z_0(1+\mu)G(\theta)$. We have

$$G(\theta) \geq A(\theta) - \frac{rz_0^2\sigma^2 g(\theta)^2 Q^*(\theta)}{z_0(1+\mu)} \geq A(\theta) - \frac{rz_0^2\sigma^2 g(\theta)^2 \bar{Q}(\theta,\mu)}{z_0(1+\mu)} = \theta \quad \text{for any } \theta.$$

To guarantee the IC condition, we need $Q^*(\theta)$ to be decreasing in θ. Note that $A(\theta) > g(\theta)$ and $z_0(1+\mu) \geq rz_0^2\sigma^2 g(\theta)Q^*(\theta)$ according to the definition of $\bar{Q}(\theta)$. It is plausible to assume $z_0(1+\mu)A(\theta) - rz_0^2\sigma^2 g(\theta)^2 Q^*(\theta)$ is increasing in θ since $z_0(1+\mu)A(\theta)$ is the dominant term.

Note that another possible design for an IL contract is $\beta(\theta) = \theta Q(\theta)$, which is aimed to hedge the risk perfectly, so we call it ILP. The buyer's expected profit under ILP is given in Table 2, and there is no bound for $Q(\theta)$. As we can see, the risk is perfectly hedged when $\mu \leq h$ but is not hedged when $\mu > h$ (because $-(\mu - h\wedge\mu)^2/(2r\sigma^2)$ is a loss of utility caused by risk aversion). Furthermore, as Theorem 1 shows, given $\{Q(\theta)\}$, we have $\Pi_A^{\mathrm{ILP}} \leq \Pi_A^{\mathrm{IL}}$ if $\mu \leq h$ (by the optimality of IL) and $\Pi_A^{\mathrm{ILP}} \leq \Pi_A^{\mathrm{FP}}$ if $\mu > h$ (by the optimality of FP). Hence, ILP seems not to be the optimal choice, although ILP is important when we compare other contracts because $\Pi_A^{\mathrm{ILP}} = \Pi_A^{\mathrm{PC}}$ if $\mu \leq h$.

5. Contract Comparison and Selection

So far, we have analyzed FP, CR, PC, and IL contracts. In this section, we try to answer the essential question: Which contract is the best among the four, given different model parameters and assumptions?

Let us start by summarizing the optimal decisions of the two parties as well as the supplier's expected utility (i.e., information rent), as shown in Table 1. First, $Q_{\mathrm{CR}}^*(\theta) > Q_{\mathrm{FP}}^*(\theta) \vee Q_{\mathrm{PC}}^*(\theta)$ when $\mu \leq h$ because $\Gamma(\theta) < A(\theta) = B(\theta,\mu)$. If the bound for IL is high enough such that $R'(\bar{Q}(\theta)) < z_0(1+\mu)A(\theta)$, then we also have $Q_{\mathrm{IL}}^*(\theta) > Q_{\mathrm{FP}}^*(\theta) \vee Q_{\mathrm{PC}}^*(\theta)$. However, it is hard to compare $Q^*(\theta)$ when $\mu > h$. Second, the supplier's raw material purchase decision q_0^* is efficient under PC and is efficient under FP when $\mu > h$. Third, the information rents under different contracts are different and hard to compare, but one thing to note is that U_S is not affected by μ under FP. Last, the raw material price risk (σ) has no impact on the supplier's utility (U_S) under FP and PC, its impact on U_S under CR decreases as μ decreases, and its impact under IL depends on q_0^*. (It has impact only when $q_0^* = 0$, although not explicitly.)

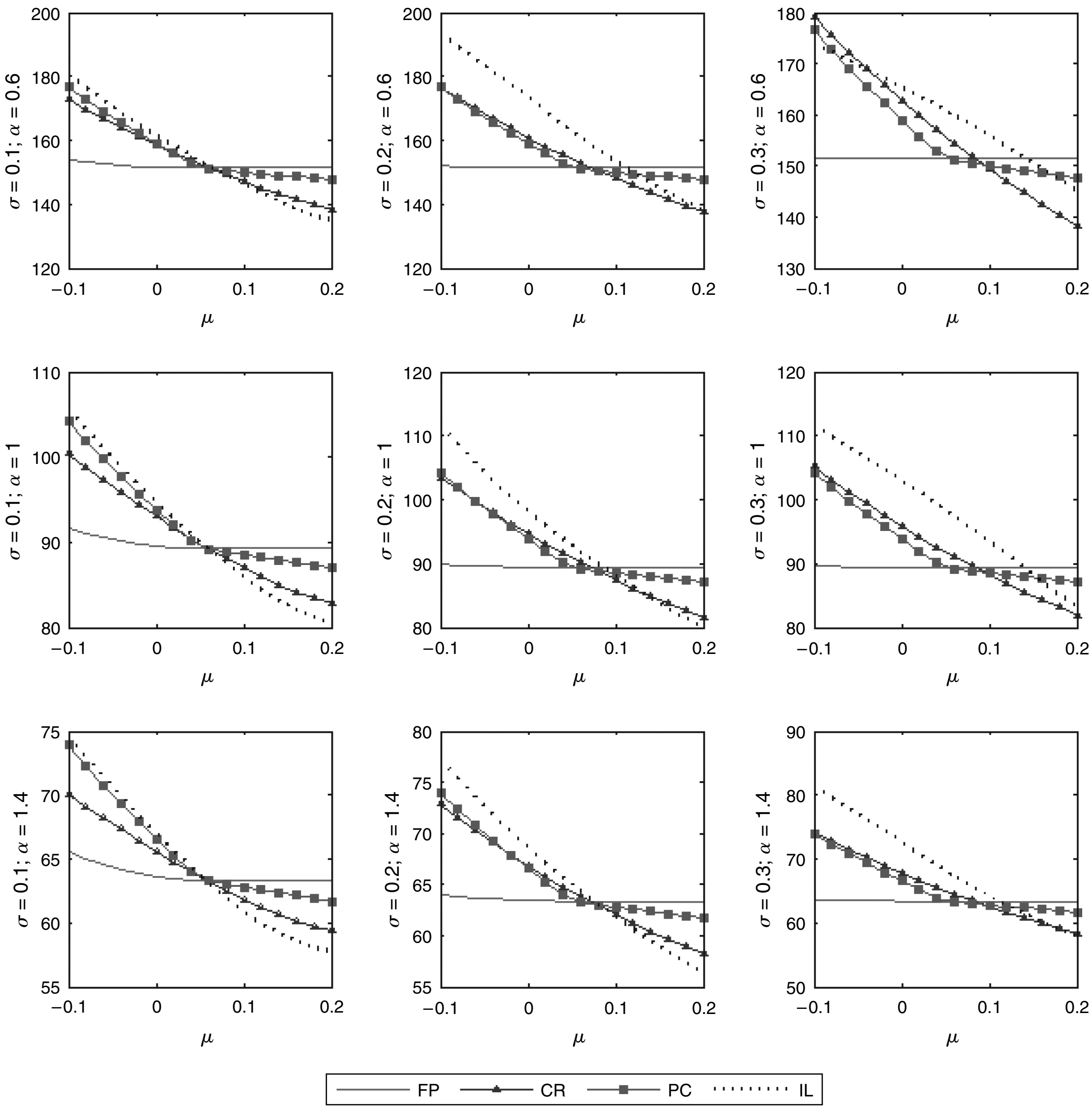
By and large, the underlying rationale for these results is twofold: (i) how the raw material price risk is allocated between the two parties and (ii) whether the contract payment depends on the supplier's post-contracting behavior. Under FP, the buyer's contract payment is fixed from the very beginning; thus, her order quantity and the supplier's information rent are independent of the raw material price trend and the supplier's ex post behavior. Under CR, the buyer aims to take all the risk from the supplier by granting him the right to make an ex post claim, but the supplier would take advantage of the right, which is risky and inefficient from a centralized perspective. Under PC, the buyer takes charge of raw material procurement; thus, the contract payment is not affected by any after-contracting behavior. However, the supplier has an incentive to claim to be less efficient when the raw material price is expected to rise. Under IL, the buyer can optimize the level of risk sharing and introduce additional risk by overestimating the supplier's material consumption rate, which deters the supplier from misreporting. Nevertheless, we have made a critical assumption for using an IL contract: the buyer has perfect knowledge about the supplier's raw material purchase price. (The assumption is relaxed and discussed in §6.) In the following, we discuss in detail the best contract choice in different situations. Note that administrative costs may be taken into account when a choice is made in practice.

5.1. Raw Material Price Trend

Obviously, the buyer's contract choice is closely linked to the expected (perceived) raw material price in period 1. The holding cost rate h is a critical value for investigating the impact of μ because in the centralized case h is a threshold value for deciding whether or not to purchase raw material in advance (i.e., buy earlier if $\mu > h$ and later if $\mu \leq h$). After we obtain expressions for Π_A under different contracts (see Table 2), we can conveniently compare FP, PC, and ILP contracts and get the following result:

Proposition 2. *If $\mu \leq h$ and $Q_{\mathrm{IL}}^*(\theta) < \bar{Q}(\theta)$, then $\Pi_A^{\mathrm{IL}} \geq \max\{\Pi_A^{\mathrm{FP}}, \Pi_A^{\mathrm{PC}}\}$; if $\mu > h$, then $\Pi_A^{\mathrm{FP}} > \Pi_A^{\mathrm{PC}}$; and if $\mu \gg h$, then $\Pi_A^{\mathrm{FP}} > \Pi_A^{\mathrm{IL}}$.*

Figure 2 Numerical Examples of the Buyer's Expected Profit



We use $\gg$ because, as we mentioned, IL contracts generate slightly higher expected profit than FP contracts when μ is very close to h, but Π_A^{IL} drops below Π_A^{FP} quickly as μ increases. Missing in the comparison is the CR contract. Because of the complex expression of Π_A^{CR}, it is hard to compare CR with other contracts analytically. If $\mu \le h$ and σ is smaller such that $((\mathbf{E}[\epsilon \vee h] - h)\mathbf{Cov}(\epsilon \vee h, \epsilon))/(\mathbf{Var}[\epsilon \vee h]) \approx 0$, then it can be checked that $\Pi_A^{\mathrm{CR}} < \Pi_A^{\mathrm{PC}} \le \Pi_A^{\mathrm{IL}}$. However, $((\mathbf{E}[\epsilon \vee h] - h)\mathbf{Cov}(\epsilon \vee h, \epsilon))/(\mathbf{Var}[\epsilon \vee h]) \neq 0$ in general. Moreover, if $\mu > h$, we sense that $\Pi_A^{\mathrm{FP}} > \Pi_A^{\mathrm{CR}}$ because Π_A^{FP} is not affected by μ, whereas Π_A^{CR} is decreasing in μ. As a result, we expect that an IL contract is the best for the buyer when μ is below h, but an FP contract is the best when μ is above h.

To test our intuition, we construct nine numerical examples to illustrate the buyer's expected profit under four types of contract change with μ (see Figure 2). In our examples, revenue function $R(Q) = 10\sqrt{Q}$, and θ is a uniformly distributed random variable with bounds $\theta_L = 0.05\alpha$ and $\theta_H = 0.1\alpha$, where α controls the degree of information asymmetry and the proportion of raw material cost in total cost. Note that these two factors are positively correlated in nature, so we use a common parameter α for them. Because we focus on the impacts of information asymmetry and raw material price risk, we use three different values of α as well as σ to construct our nine examples, where $\alpha \in \{0.6, 1, 1.4\}$ and $\sigma \in \{0.1, 0.2, 0.3\}$. Other parameters are fixed at $z_0 = 3$, $h = 0.05$, and $r = 0.5$.

Based on the numerical examples in Figure 2, we can make the following observations:

1. When $\mu \le h$, an IL contract is the best for the buyer in most cases, which is consistent with our analysis. An exception appears when σ is large (0.3), α is small (0.6), and μ is far below h. Recall that an IL contract has a constraint that $Q(\theta) \le (1+\mu)/(rz_0\sigma^2 g(\theta))$, and the constraint is tight when σ is large and μ is low. Moreover, information asymmetry is not very significant when α is small, so overhedging cannot significantly help the IL contract reduce information rent. When all these conditions are met, CR and PC outperform an IL contract.
2. The relative performance of IL increases with σ. This is because when σ gets larger, overhedging introduces greater additional risk introduced and squeezes the information rent.
3. Whereas an IL contract has the greatest sensitivity to μ, an FP contract has the least sensitivity and is optimal when μ is high, which strengthens the result from our model and partly explains the prevalence of FP contracts in industry when steel and oil prices are increasing. The intuition behind this result is not that the buyer should avoid upstream risk but that risk-averse suppliers would make efficient procurement decisions under an FP contract when μ is high. (It is efficient to buy the raw material early if they expect the price to increase, and early purchase protects the supplier from price risks.)
4. PC approximates IL very well when σ is small and $\mu \le h$. This is because PC is equivalent to ILP ($\beta(\theta) = \theta Q$) and ILP is close to IL when overhedging does not work well.

In the second step, we investigate the supplier's expected utility U_S. (Because of its length, we place the figure in the online supplement.) We find that U_S under PC is always the highest, and it is almost always the lowest under IL. The result for IL is attributed to overhedging and easy to understand. The result for PC may initially seem counterintuitive, but the key turns out to be that the supplier does not face any risk from purchasing raw material under PC. Last, his expected utility is always decreasing in μ under CR; although the incentive of misreporting is greater when μ is higher, the game also becomes riskier because the buyer would take the moral hazard issue into account.

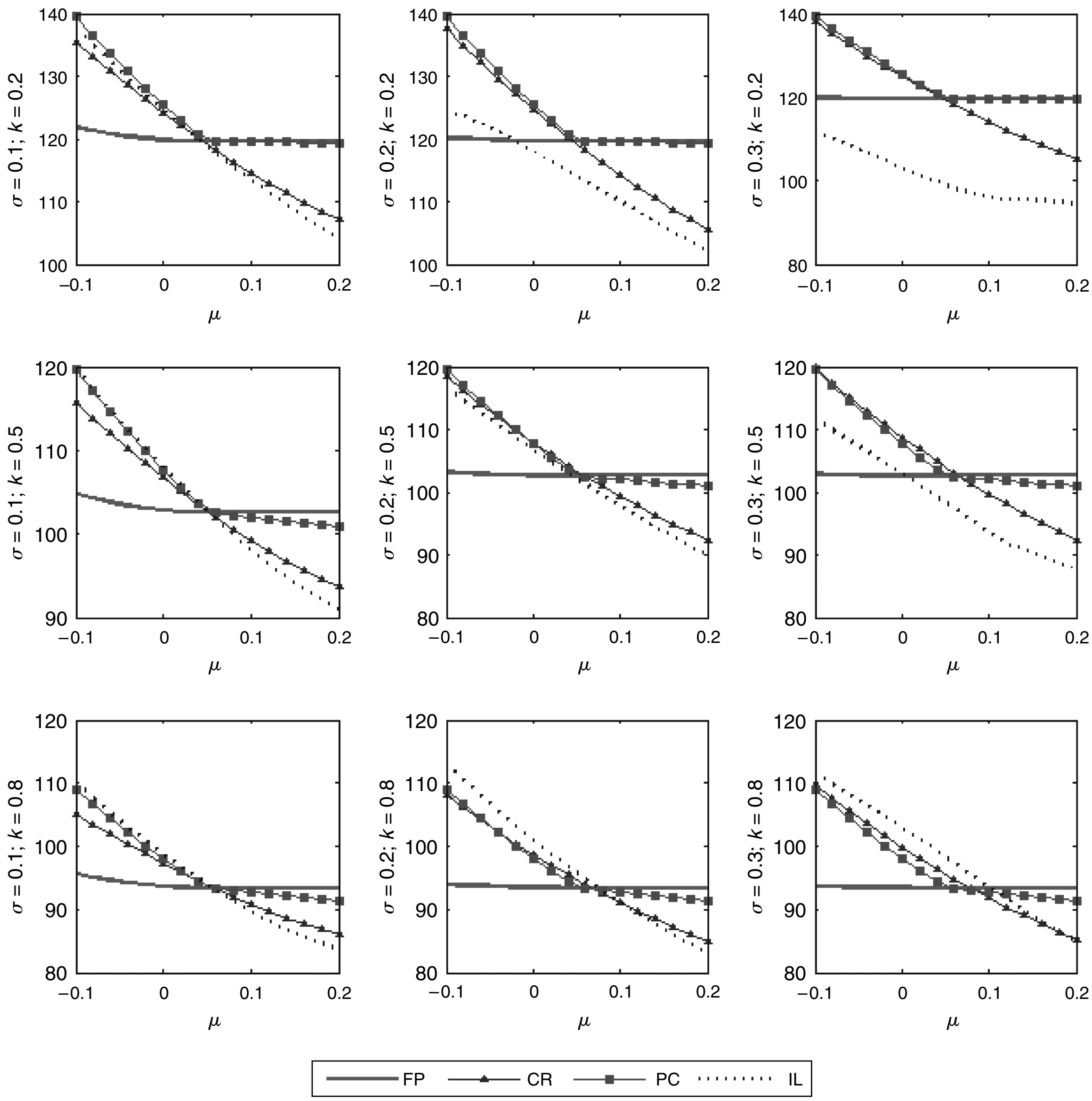
Next, it is of interest to examine the optimal contract choice when we consider both parties' preferences. To this end, we sum up the buyer's expected profit and the supplier's expected utility and define the sum as systemwide expected utility. We can do the summation because the supplier's utility is measured in monetary units, and we assume the utilities of the two can be reallocated by a side payment. Hence, the contract that generates the highest total utility is *Pareto dominant* among the four types. From such a perspective, we obtain some new results, as shown in Figure 3. This time we fix $\alpha = 1$ because α does not greatly impact the contract choice from either the buyer's or the supplier's perspective. Instead, we let $\theta = \theta_L + k(\theta_H - \theta_L)$ and examine the impact of k, the supplier's relative cost efficiency with the following observations:

1. FP always generates the highest system utility when μ is high. This observation adds to the superiority of FP.
2. The system utility under IL drops with σ and is more sensitive to the risk when the supplier is more efficient. Moreover, IL is never the optimal choice when the supplier is very efficient. The intuition is that overhedging is a good tactic for rent reduction for the buyer, but it can greatly hurt the supplier. This may be a reason why IL is not widely used even if it gives the buyer the highest expected profit in most cases.
3. If the supplier's efficiency is high ($k = 0.2$) or moderate ($k = 0.5$), PC generates the highest system utility when $\mu \le h$, which to a certain extent explains the empirical observation from our interviews that PC is the second most popular among the four contracts studied so far. The reason is twofold. First, the raw material purchase is always efficient under PC. Second, the supplier is isolated from raw material price risk in equilibrium. However, because the information rent increases with μ under PC, it is dominated by FP when $\mu > h$.
4. In certain cases, CR can be optimal from a systemwide point of view. According to our numerical examples, this is the case when k is moderate, risk is high ($\sigma = 0.3$), and μ is low. This is because, when μ is low, the inefficient raw material purchase is reduced; therefore, much of the raw material price risk will be eliminated by the reimbursement.

5.2. Risk-Neutral Supplier

Now we consider the case where $r \to 0$, which means the supplier is risk neutral. Plugging this into the original model, we re-solve the problem under four types of contract and then summarize the results in Table 3. We find that, if the supplier is risk neutral, FP and IL are exactly equivalent ex ante, although the final contract payment can be very different. This is surprising at first glance, but it is actually intuitive because from a risk-neutral point of view the expected payment is fixed under both FP and IL once the contract is signed. Hence, the design of the contingent payment (i.e., the design of β) is not important for a risk-neutral supplier who only cares about the expected value. In addition, the supplier's procurement decision under a CR contract is not efficient when $\mu < h$ because he would always buy all raw material early

Figure 3 **Systemwide Expected Utility**



to exercise the greatest flexibility in manipulating the reimbursement. Under a PC contract, although the contract payment is also fixed and not affected by the supplier's ex post behavior, the incentive to misreport cost efficiency is slightly different than under FP and IL. Such a difference is rooted in the independence of his payoff on the raw material purchase cost, which is incurred by the buyer under PC.

Now let us look at the buyer's decision. It is easy to compare and see that, among the four types of contract, the buyer's order quantity under FP and IL is always the largest and closest to the first-best level. PC generates the largest order when $\mu \le h$, and the order quantity under CR is always the lowest. Thus, from the buyer's perspective, we sense that both FP and IL are the optimal choice in all circumstances and PC is optimal when $\mu \le h$, as stated in the following proposition. We can find that FP and IL are optimal for both parties in many cases and are thus Pareto dominant.

Proposition 3. *Suppose the supplier is risk neutral. If $\mu \le h$, then FP, PC, and IL are equivalent ex ante and are optimal choices for both the buyer and the supplier. If $\mu > h$, then FP and IL are equivalent and optimal for the buyer, and CR and PC are equivalent and optimal for the supplier if the degree of information asymmetry is not too high.*

5.3. Symmetric Information on Cost Efficiency

In this case, we assume that the buyer knows the supplier's cost efficiency or type θ, eliminating the need for a screening menu. However, the buyer cannot observe or verify the supplier's inventory decisions,

Table 3 Summary of Model Results with a Risk-Neutral Supplier

	$Q^*(\theta)$	$q_0^*(\theta)$	$U_S(\theta)$
FP, IL	$R'^{-1}[z_0 A(\theta)(1+\mu\wedge h)]$	$\theta Q^*(\theta)\cdot \mathbb{I}\{\mu>h\}$	$\int_\theta^{\theta_H} z_0(1+\mu\wedge h)Q^*(x)\,dx$
CR	$R'^{-1}\left[z_0\left((1+\mu)\frac{F(\theta)}{f(\theta)}+(1+h)\theta\right)\right]$	$\theta Q^*(\theta)$	$\int_\theta^{\theta_H} z_0(1+\mu)Q^*(x)\,dx$
PC	$R'^{-1}\left[z_0\left((1+\mu)\frac{F(\theta)}{f(\theta)}+(1+\mu\wedge h)\theta\right)\right]$	$\theta Q^*(\theta)\cdot \mathbb{I}\{\mu>h\}$	$\int_\theta^{\theta_H} z_0(1+\mu)Q^*(x)\,dx$

which creates ex post information asymmetry and a moral hazard issue. By fixing $b=\theta$ in the original model, we can again solve the supplier's and buyer's problems and get the results summarized in Table 4. Note that because the information rent is zero, in this case, we have $U_S=U_0=0$.

According to the results in Table 4, we see that both the order size and the raw material procurement are the first-best under PC. Thus, without any proof, we can claim that the PC contract is a dominant strategy for the buyer, regardless of μ, and it is Pareto dominant ex ante because $U_S=0$. We also find that without ex ante information asymmetry, IL and PC are equivalent if $\mu\le h$, whereas FP and PC are equivalent if $\mu\ge h$. CR is never optimal, however, because the supplier's raw material procurement decision is not efficient. One thing worth mentioning is that without ex ante information asymmetry it is no longer optimal for the buyer to overhedge the supplier; instead, we have $\beta^*(\theta)=\theta Q^*(\theta)$. Consequently, we put forth the following proposition:

Proposition 4. *If there is no ex ante information asymmetry, then PC and IL are ex ante optimal when $\mu\le h$, whereas PC and FP are ex ante optimal when $\mu\ge h$.*

5.4. Restricted Raw Material Purchase Time

In this section, we examine the situation where $q_0=0$ is forced. This is reasonable in industries such as logistics services wherein the raw material, gasoline or diesel fuel, can neither be stored in large amounts by a service provider nor be purchased in advance with a forward contract, thus eliminating the moral hazard issue. In the following, we impose this constraint, re-solve the buyer's and the supplier's problems, and obtain results summarized in Table 5. Under an FP contract, it is routine to check that the optimal order quantity for the buyer is $Q^*(\theta)$ that satisfies

$$R'(Q^*(\theta))-z_0(1+\mu)A(\theta)-2rz_0^2\sigma^2\theta\left(\frac{F(\theta)}{f(\theta)}+\frac{\theta}{2}\right)Q^*(\theta)=0. \tag{9}$$

Let $H(\theta):=(R'[Q^*(\theta)])/(z_0(1+\mu))>A(\theta)$ so that we can write $Q^*(\theta)=R'^{-1}(z_0(1+\mu)H(\theta))$. The analysis for CR and PC is easier, and the two contracts are completely equivalent. Note that the supplier has no room to manipulate the reimbursement when the window of opportunity for purchasing raw material is restricted. Hence, the supplier would face no risk under both CR and PC in equilibrium. Last, an IL contract is not affected much by this time restriction because in the original model $q_0=0$ holds under IL contracts in most cases.

It is easy to see that the relative sizes of $Q^*(\theta)$ are determined by $H(\theta)$, $A(\theta)$, and $G(\theta)$. If $R'((1+\mu)f(\theta)/(rz_0\sigma^2F(\theta)))\le z_0(1+\mu)A(\theta)$, i.e., $\bar{Q}(\theta)$ under IL is large enough or the risk ($r\sigma^2$) is not too high, we will have $H(\theta)>A(\theta)\ge G(\theta)$; thus, $Q^{\mathrm{FP}}(\theta)<Q^{\mathrm{CR}}(\theta)=Q^{\mathrm{PC}}(\theta)\le Q^{\mathrm{IL}}(\theta)$. This result is helpful for comparing systemwide total utilities because Q is the only operational decision given that $q_0=0$ is fixed. Under

Table 4 Summary of Model Results Without Ex Ante Information Asymmetry

	$Q^*(\theta)$	q_0^*	Π_A
FP	$R'^{-1}(z_0(1+h)\theta)$	$\theta Q^*-\frac{h-\mu\wedge h}{rz_0\sigma^2}$	$\int_{z_0(1+h)\theta}^{R'(0)} R'^{-1}(x)\,dx+\frac{[h-\mu\wedge h]^2}{2r\sigma^2}$
CR	$R'^{-1}(z_0(1+\mu)\theta)$	$\frac{\mathbf{E}[\epsilon\vee h]-h}{rz_0\mathbf{V}[\epsilon\vee h]}$	$\int_{z_0(1+\mu)\theta}^{R'(0)} R'^{-1}(x)\,dx-\frac{(\mathbf{E}[\epsilon\vee h]-\mu)^2-(h-\mu)^2}{2r\mathbf{V}[\epsilon\vee h]}$
PC	$R'^{-1}(z_0(1+\mu\wedge h)\theta)$	$\theta Q(\theta)\cdot\mathbb{I}\{\mu>h\}$	$\int_{z_0(1+\mu\wedge h)\theta}^{R'(0)} R'^{-1}(x)\,dx$
IL	$R'^{-1}(z_0(1+\mu)\theta)$	$\frac{\mu-\mu\wedge h}{rz_0\sigma^2}$	$\int_{z_0(1+\mu)\theta}^{R'(0)} R'^{-1}(x)\,dx+\frac{[\mu-\mu\wedge h]^2}{2r\sigma^2}$

Table 5 **Summary of Model Results When Raw Material Procurement Is Restricted to Period 1**

	$Q^*(\theta)$	$U_S(\theta)$
FP	$R'^{-1}[z_0(1+\mu)H(\theta)]$	$z_0(1+\mu)\int_\theta^{\theta_H}\frac{H(x)+g(x)}{A(x)+g(x)}Q^*(x)\,dx$
CR and PC	$R'^{-1}[z_0(1+\mu)A(\theta)]$	$z_0(1+\mu)\int_\theta^{\theta_H}Q^*(x)\,dx$
IL	$R'^{-1}[z_0(1+\mu)G(\theta)]$	$z_0(1+\mu)\int_\theta^{\theta_H}[G(x)-x]\frac{f(x)}{F(x)}Q^*(x)\,dx$

centralized management, the first-best order quantity is $Q^{\mathrm{FB}}(\theta) = R'^{-1}[z_0(1+\mu)\theta]$; hence, $Q^{\mathrm{FP}}(\theta)$ is least efficient in most cases. This is because the supplier faces the greatest risk under FP. Also, the following proposition shows that, from the buyer's perspective, $\Pi_A^{\mathrm{FP}} < \Pi_A^{\mathrm{CR}} = \Pi_A^{\mathrm{PC}} \le \Pi_A^{\mathrm{IL}}$. The supplier's expected utility is not clear from the analytical results. Thus, we need numerical examples to further explore U_S as well as the relative performance of IL contracts in general.

Proposition 5. *If $q_0 = 0$ is fixed, then CR and PC are equivalent and better than FP for the buyer, but if $q_0 = 0$ and $R'((1+\mu)f(\theta)/(rz_0\sigma^2 F(\theta))) \le z_0(1+\mu)A(\theta)$, then IL is optimal for the buyer.*

On the left side of Figure 4, we can see that IL is indeed the optimal choice for the buyer except when the constraint $R'(\bar{Q}(\theta)) \le z_0(1+\mu)A(\theta)$ is tight. In our example, this condition is binding when risk is high ($\sigma = 0.4$) and information asymmetry is not significant ($\alpha = 0.6$); thus, CR and PC give the buyer the highest expected profit. In any case, FP is the worst. From the supplier's perspective, the right side of Figure 4 shows that FP is still the worst, and CR and PC are the best in most cases. Hence, we can conclude that, when the raw material purchase occur in conjunction with the service or production activity, the FP contract is Pareto dominated by other contracts. Moreover, from a system perspective (in the online supplement), CR and PC dominate IL when risk is lower and the supplier is efficient. This is because the effectiveness of overhedging under IL is low when the risk is low and the supplier is "hurt" too much when he is efficient.

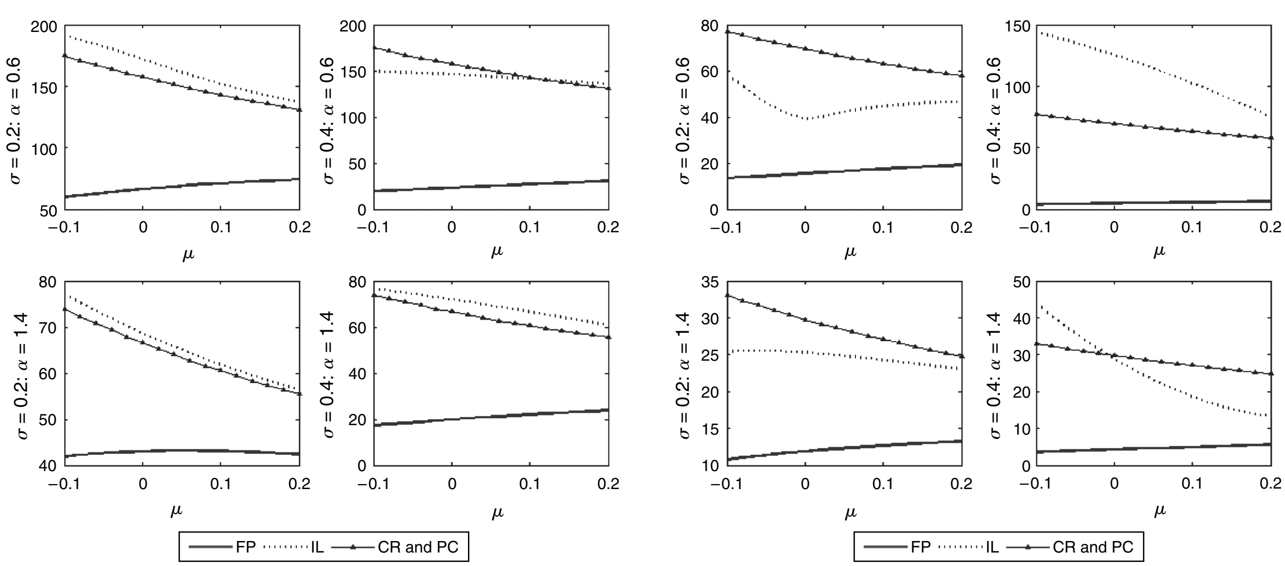
Table 6 **Impacts of Information and Risk-Attitude on the Buyer's Optimal Contract Choice**

q_0 is not fixed	Risk averse	Risk neutral
Asymmetric information	Depends	FP and IL
Symmetric information	PC	PC, FP, and IL

5.5. Summary

In this section, we compared four types of contract in a general setting as well as three restricted settings from the buyer's point of view, the supplier's point of view, and the system point of view, respectively. In the general setting, we studied the impact of the perceived raw material price trend and showed how it is related to the optimal contract choice. Next, we studied the impacts of the perceived risk by the supplier and ex ante information asymmetry separately as well as the optimal contract choices for the buyer under different scenarios are summarized in Table 6. Last, we checked the impact of raw material purchase time and showed the equivalence between CR and PC as well as the optimality of IL when the purchase time is restricted. It is interesting to note that, when there are both information symmetry and risk neutrality, FP, PC, and IL are equivalent. Moreover, if all three conditions are imposed, we obtain equivalence among

Figure 4 **The Buyer's (Left) and the Supplier's (Right) Expected Utility Given $q_0 = 0$**



the four contracts, which we formalize in the following corollary. Here, equivalence is defined as leading to identical consequence in every aspect. When all four contracts are equivalent in our model, the simplest contract dominates in practice. Beyond all question, FP is the simplest. Hence, the following corollary enhances our understanding on the prevalence of FP in industry.

Corollary 1. *If information is symmetric ex ante, both buyer and supplier are risk neutral, and raw material cannot be purchased early, then FP, CR, PC, and IL are completely equivalent.*

So far, our model has been able to explain most contracting practices observed in interviews except for the IL contract. The results on IL are all based on the availability of a perfect price index, which may not be true in many cases. However, those results are still useful in explaining why relational contracting (RL) is popular in practice. In the extension, we establish the connection between IL and RL, and we consider a scenario wherein the buyer has imperfect information about z_t. When z_1 is not contractible, IL is not feasible and RL can be used.

6. Base Model Extensions

6.1. Relational Contract

Informal agreements in addition to contracts are widely observed, and the reason varies. It might be because the contract objective (product or service) is ill defined at the time of contracting (Taylor and Plambeck 2007b), it is too costly to specify contract terms in all contingencies, or there is information asymmetry between the contracting parties. In such situations, companies can write a simple payment contract ex ante to compensate each other ex post once the uncertainty is resolved. All these behaviors are built on mutual trust and long-term relationships.

Note that the original contract terms are not modified or renegotiated, and what usually happens is just a transfer payment. Theoretically, renegotiation will never happen, given that it would require both parties to agree. The reason is clear: the size of the pie is not changed when the transfer payment is made in period 1 because all decisions are finalized. For simple profit reallocation, it is impossible to have both parties reach a consensus without factoring in a long-term relationship. In the online supplement, we show that RL is equivalent to IL as long as RL is self-enforcing.

6.2. Raw Material Price Information Asymmetry

In many cases, the buyer can obtain only an imperfect signal regarding the supplier's period 1 raw material price z_1, which is $s = z_1 + \omega$. Even when the supplier purchases raw material from a commodity market, the buyer may not know the exact date of the purchase. In such cases, z_1 is not contractible, so an IL contract is not warranted, and RL becomes a good substitute. Regarding z_0, we first assume it is publicly known, which is true in a commodity market. Also, we assume the relationship is productive and RL is self-enforcing. We finish this discussion by considering the situation wherein z_0 is not known by the buyer.

First of all, note that FP, CR, and PC are not affected by the assumption of an imperfect signal because z_1 is not written into these contracts. Hence, we do not need to repeat the analysis on them and can focus on RL. We are interested in a linear form of payment, $w = a(\theta) + b(\theta) \cdot s$, and the optimal $b(\theta)$. In particular, we are interested in the case when $\mu \le h$ because according to Theorem 1 we will get $b^*(\theta) = 0$ when $\mu \gg h$. To begin, we assume ω follows $N(0, \tau^2)$, $\mathrm{Cov}(\varepsilon, \omega) = 0$, and let $\kappa(\theta) := (rz_0\sigma^2 g(\theta)Q(\theta) + h - \mu)/(rz_0\sigma^2\theta Q(\theta) - (h - \mu))$.

Proposition 6. *If $\mu \le h$ and $Q(\theta)$ is given, the optimal contingent payment is*

$$b^*(\theta) = \begin{cases} \dfrac{z_0(h-\mu)^+}{r\tau^2}, & \tau^2 > \kappa(\theta) z_0^2\sigma^2; \\[2ex] \dfrac{z_0^2\sigma^2}{z_0^2\sigma^2 + \tau^2} \cdot A(\theta)Q(\theta), & \tau^2 \le \kappa(\theta) z_0^2\sigma^2. \end{cases} \tag{10}$$

Therefore, when the signal is precise enough, the contingent payment is proportional to the transaction size (Q)—both overhedging and underhedging are possible. However, if τ^2 is large, the optimal contingent payment becomes irrelevant to Q and decreases with τ^2. As τ^2 increases, $b^*(\theta) \to 0$, and RL will finally be reduced to FP. Hence, the performance of RL for the buyer is bounded below by that of FP when $\mu \le h$.

Finally, if z_0 is not known by the buyer, she can just take $\vartheta := z_0\theta$ as the type of the supplier, meaning the cost per unit of the component product or service. The raw material purchase decision q_0 will be replaced by m_0, the production cost to be fixed. Hence, the supplier's realized profit will be $\pi_S = T(Q) - m_0(1+h) - (1+\epsilon)(\vartheta Q - m_0)$. Furthermore, we assume that the benefit the supplier gets from excess raw material supply under PC is determined by the buyer's material purchase price. Then, by following the same analysis as for the original model, we will obtain the same qualitative results, except that the degree of information asymmetry will be relatively lower under PC.

7. Concluding Remarks

We have analyzed and compared five sourcing contracts that we abstracted from interviews with industry practitioners and the supply chain contracting literature. As we connected the model results to observations from interviews, we found that firms' choices and considerations in large part can be explained. Thus our model insights were grounded to guide contract choice in practice.

First of all, FP contracts were used by most companies, which is consistent with our model implications. According to our model, FP is optimal for the buyer and the system when the supplier is risk neutral, or when the supplier is risk averse and the raw material price is expected to rise significantly. In the latter case, FP is optimal, not because the buyer should avoid the risk, but because risk-averse suppliers will make efficient material purchase decisions. This result also explains our observation that, of the seven firms that used or are using FP, four have turned to other contracts and one is considering PC. Given that our interviews were conducted between 2008 and 2009, such a transition from FP to other contracts can be explained as a reaction to a change in the expected trend for raw material prices, driven by the global economic recession. Before the recession began in 2008, most raw material prices worldwide demonstrated an upward trend, so according to our model, FP was undoubtedly the optimal choice. However, starting in 2008, prices fluctuated more dramatically and were not expected to rise much, so the companies need to make changes.

RL but not IL was the most popular among the five schemes at the time of the interviews. According to our model, IL is optimal for the buyer when the supplier is risk neutral, or when the supplier is risk averse and raw material price is not expected to rise much, or raw materials cannot be purchased early. However, using IL requires a perfect price index that can be written into the contract. When such an index is not available, RL is a close approximation of IL when the business relationship is productive and the signal for contingent payment is sufficiently relevant. Moreover, the optimal IL for the buyer is not Pareto optimal but intended to overhedge the supplier, which is certainly not welcomed by a risk-averse supplier. In contrast, the risk hedging of RL is milder. Hence, it is reasonable in hindsight that IL would not be employed frequently in practice.

We found PC to be less popular than FP and RL but more popular than CR and IL. According to our model, PC is optimal when there is no ex ante information asymmetry. Hence, PC can be implemented only when the two parties are engaged in a deep cooperation or close relationship. In addition, the administrative cost of PC can be significant because it is usually implemented along with the integration of information systems and the welding of production or service processes.

CR is only observed in the U.S. logistics service industry, but it was being considered by two firms in China for logistics services. According to our analysis, CR is optimal from the system perspective when the raw material price risk is high and the supplier's efficiency is close to the mean. This condition is restrictive, but it helps explain why CR is considered in China when the government regulation of gas prices is expected to relax. Also, CR is equivalent to all other contracts in the combined presence of information symmetry, risk neutrality, and an inability to purchase raw materials early. This result explains why CR is used for logistics service; gas cannot be stored by the logistics service provider.

Last, we find the overall predictions on contract choice from the systemwide perspective in the general model are more consistent with our empirical observations than from other angles. Such a coincidence is reasonable because the contract could be jointly chosen by both parties and the pie could be evenly split to develop long-term cooperation.

In a nutshell, based on the assumptions and model results in this paper, we have provided some partial explanations for different contracting practices observed in our interviews and have provided a number of suggestions for contract choice in various environments. Nevertheless, the topic of optimum cooperation in times of raw material price volatility, as we mentioned, is far from being completely investigated. Future research can incorporate the interaction between the buyer and the raw material provider (tier 2 supplier). Also, if the supplier can dynamically improve his production efficiency and his effort is affected by contract, it would be interesting to examine the optimal contract choice along the timeline.

Supplemental Material

Supplemental material to this paper is available at http://dx.doi.org/10.1287/msom.2013.0454.

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Appendix. Industry Interviews

In the first part of our research, one of us visited a number of famous companies in China and interviewed them about the mechanisms they used to cope with raw material price uncertainty. The list of firms and their practices are summarized in Table A.1. Note the following observations: (1) COFCO Coca-Cola uses PC with plastic bottle suppliers and takes charge of the raw material procurement and supplies the bottle supplier for free. (2) Haier centralizes the raw material procurement among its suppliers and sells the material to its suppliers with a fixed price. (3) Huawei compensates component suppliers for new orders, but current

Table A.1 Companies and Their Contracting Practices

Company	Fixed price	Cost reimbursement	Index-linked payment	Procurement control	Relational contract
CIMC	Used previously	—	—	—	Used now
COFCO Coca-Cola	Used previously	—	—	Used now	—
First Automobile	Used previously	Under consideration	Under consideration	—	Used previously
Foxconn	Used in most cases	—	Used for U.S. supplier	—	—
Haier	—	—	—	Used now	—
Huawei	—	—	—	—	Used now
Konka	Used previously	Under consideration	—	—	Used now
Lenovo	Used now	—	—	Under consideration	Used previously
Li-Ning	—	—	—	Used now	Used now
Sany Heavy	Used now	—	—	—	—
Volkswagen	—	Used now	—	—	—

orders are not affected. (4) Konka compensates logistics service suppliers with cash for the current order at the end of the period. (5) Li-Ning is only involved in the price and quantity bargaining with upstream raw material provider but is not involved in the actual purchase. Li-Ning compensates its supplier when a raw material price jumps more than 20%.

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