Outsourcing structures and information flow in a three-tier supply chain

Pengfei Guo, Jing-Sheng Song, Yulan Wang

Department of Logistics and Maritime Studies, Hong Kong Polytechnic University, Hong Kong
Fuqua School of Business, Duke University, Durham, NC 27708, USA
Institute of Textiles and Clothing, Hong Kong Polytechnic University, Hong Kong

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A B S T R A C T

We consider a three-tier supply chain consisting of an original equipment manufacturer (OEM), a contract manufacturer (CM) and a supplier. We analyze and compare three outsourcing structures that are currently implemented by top-tier OEMs: (1) inhouse consignment, under which the OEM signs independent contracts with the CM and the supplier; (2) turnkey with integration, under which the OEM contracts with an alliance of the CM and the supplier; and (3) turnkey, under which the OEM contracts with the CM, and the CM then subcontracts with the supplier. The OEM is a Stackelberg leader who decides how much of the end product to produce. All parties use take-it-or-leave-it wholesale-price contracts. Both the CM and the supplier have private information about their own production costs. The OEM has prior information about these costs, but this prior information depends on the specific outsourcing structure. Each party's optimal decision is characterized. We then compare each party's profits across the three outsourcing structures and identify which benefits and when.

1. Introduction

Today's advanced information, communication and transportation technologies, as well as the increasingly open global economy, are providing unprecedented opportunities for companies to outsource more of their traditional business activities. For example, computer makers and other original equipment manufacturers (OEMs), such as Motorola, IBM Corp., Hewlett-Packard Co. (HP) and Dell Computers, which traditionally produced inhouse, now often outsource their production to contract manufacturers (CMs). By so doing, these OEMs hope to better focus on their core competencies, such as product design and marketing. They also expect to enjoy cost savings due to the CMs' economies of scale and flexibility. However, production outsourcing is also risky: what is being outsourced also involves tacit knowledge and supplier relationships, which may eventually hurt the competitive advantage of the OEM. Many OEMs have learned this lesson the hard way and have started to restructure their outsourcing arrangements so as to have more control over supplier relationships. According to Carbone (2004), Wolfgang Zenger, vice president of HP's global procurement services group, said that in the 1990s HP outsourced a lot of its strategic purchasing and manufacturing to electronics manufacturing services (EMS), which proved to be a mistake: “We had given too much control to contract manufacturers”, he said. HP lost a lot of visibility in the supply chain because its relationships with suppliers were not as tight as they should have been. “So we took some control back in house through the buy-sell process”, he said. For more examples of different outsourcing arrangements, see Amaral et al. (2006).

Although a great deal of research has been carried out on the coordination of decentralized supply chains under a given outsourcing structure, little attention has been paid to a comparison of the effectiveness of different structures (e.g., which party carries out material purchasing, the OEM or the CM). This paper takes a first step in this direction and investigates several commonly seen outsourcing arrangements. Our focus is on how different structures may affect the information flow in the supply chain and thus affect the chain partners' decision making. We further examine the consequent impact on the performance of each player and that of the entire chain.

We consider a three-tier supply chain consisting of an OEM, a CM and a supplier. The OEM owns the brand and outsources production, but retains contracting power. Consider the following three outsourcing structures.

- Turnkey (T for the superscript). In this structure, the CM is responsible not only for manufacturing, but also for managing the upstream supply chain, including material purchasing from the supplier. For example, such consumer electronic companies as Ericsson and Palm outsource the entire
manufacturing of their products from CMs such as Flextronics (Huckn and Pisano, 2004).

- Turnkey with integration (integration for short; I for the superscript). In this structure, the CM and the supplier form an alliance. The OEM contracts with the integrated party through the CM.

- Inhouse consignment (consignment for short; C for the superscript). In this structure, the OEM contracts separately with the CM and the supplier. The CM is responsible only for manufacturing. The OEM negotiates and purchases materials from the supplier directly; once purchases are completed, the ordered components are shipped from the supplier to the CM (Carbone, 2004). This arrangement is often facilitated by the evolution of online auctions and e-purchasing, and has been employed by many top-tier OEMs in recent years. For example, HP has established an automated global e-procurement system to handle instantaneous buy-sell transactions with its suppliers.

These three outsourcing structures have different material, information and cash flows. We assume that the end product has price-dependent deterministic demand. The OEM is a Stackelberg leader who sets a price point ("target price") at which the end-product will be sold. A good example is the retail furniture chain IKEA, which first sets the target price for its product, and then chooses a manufacturer to produce that product (Margonelli, 2002). As a result, it also determines the production quantity of the end-product. Under consignment, the OEM offers wholesale prices to the CM and the supplier; under integration, the OEM offers a wholesale price to the alliance of the CM and the supplier (alliance for short); and under turnkey, the OEM offers a wholesale price to the CM, which subsequently offers another wholesale price to the supplier.

The unit production costs of the CM and the supplier constitute private information, and the OEM has only prior knowledge of them. However, the prior knowledge of the supplier's cost depends on the specific outsourcing structure. For example, under turnkey, the outsourcing supply chain management activities (procurement, control and the allocation of product availability) to the CM loosen the relationship between the OEM and the supplier. Thus, the former has little information about the latter's cost. Switching from turnkey to consignment, in contrast, allows the OEM to obtain more information about material costs. In other words, the OEM has vague information about the supplier's costs under turnkey or integration than it does under consignment.

Our primary interest in this research is to better understand how cost information asymmetry affects supply chain performance under the different outsourcing models.

We first consider one-period contracts. We find that under all outsourcing structures considered, it is not possible to achieve credible information sharing between the OEM and the CM without a suitable mechanism because the CM always has the motivation to provide stochastically larger prior information (in the sense of the reverse hazard rate order) when it is asked for it. We find that when the OEM is able to obtain the same level of information on the other parties' costs across the three structures, it is always better off under integration than under consignment or turnkey. We argue that integration mitigates double marginalization in the supply chain. However, there is no certain answer for the comparison result between consignment and turnkey. Consignment offers an information advantage and reduces the middle party for the OEM; however, under turnkey, the decision rights are delegated to the more reasonable party, the CM, as it has private information on its own production costs and can make a more reasonable decision on the wholesale price.

We then investigate a two-period model. The setting for each period is similar to the single-period model. However, the players can update their prior information at the end of period 1, and a wholesale price contract can be renegotiated at the beginning of period 2. We derive the subgame perfect Nash equilibriums under consignment and turnkey. One of the major findings here is that, even when the OEM's prior information on the supplier's cost under turnkey is in the best interests of the CM, the OEM can now be better off under turnkey than under consignment. Therefore, the OEM's and CM's objectives can be aligned under turnkey. One possible explanation is that when the game lasts for two periods, the CM or the supplier may pretend to have high costs in the first period in expectation of a higher wholesale price in the second period. Such gaming behavior results in losses for the OEM. Turnkey helps to mitigate this gaming effect, whereas consignment strengthens it.

Given that production contracts usually last more than one period in practice, the findings presented here can be summarized in one word: Caution. The choice between turnkey and consignment depends on specific situations: to what extent the cost information can be observed, how many periods the contract lasts, etc.

The remainder of the paper is organized as follows. Section 2 reviews the related literature. Section 3 considers one-period contracts, and Section 4 considers two-period contracts. Section 5 presents our numerical results, and Section 6 concludes the paper.

2. Related literature

Our work is mainly related to two streams of the supply chain literature. The first considers contract design with asymmetric information. The other addresses dynamic games with renegotiable contracts. As detailed in the following, our model setting and focus are quite different from those of previous work.

Many researchers have investigated supply chain contracting issues under demand information asymmetry. A typical setting consists of a supplier and a manufacturer. The latter can observe real demand, but the former knows only the demand distribution. The main thrust of those research is that the supplier design a contract to induce the manufacturer to reveal the demand information truthfully. Representative studies include those of Blair and Lewis (1994), Porteus and Whang (1999), Cachon and Lariviere (2001), Özer and Wei (2006) and Burnetas et al. (2007) and the references therein. See Cachon (2003) and Chen (2003) for reviews. Recently, Ülkü et al. (2007) consider a situation in which the CM and the OEM differ in their forecast accuracy and resource pooling capabilities, and investigate the effectiveness of premium-based schemes in inducing the best party to bear the demand risk. In contrast, we consider a deterministic price-sensitive demand. Once the OEM decides what wholesale prices to contract with the upstream players, the market selling price and the production quantity are determined. Therefore, demand information is not an issue here.

Instead, our work is more closely related to contract design issues under asymmetric cost information. One of the earliest studies along this line was that carried out by Corbett and Tang (1998). They assume a linear price-sensitive deterministic demand and consider a supplier that offers a contract to a buyer, but knows the buyer's marginal cost only through prior distribution. They show that by designing a two-part menu of nonlinear contracts, the supplier can induce the buyer to reveal its true cost. Corbett and de Groote (2000) and Corbett (2001) study the cost information asymmetry issue in the context of EOQ and \((r, q)\) inventory models, respectively. Ha (2001) extends Corbett and Tang's (1998) model to a price-sensitive stochastic demand
setting. Kaya and Özer (2009) consider a two-tier supply chain consisting of an OEM and a CM and assume that the OEM outsources design, manufacturing and procurement functions to the CM. Their focus is to study how the OEM’s pricing strategy affects quality risk in outsourcing. In contrast, we consider a three-tier supply chain and allow procurement function to be either outsourced to the CM or kept in-house.

There are two main distinctions between our model and those summarized above. First, the previous studies focus on a two-stage buyer-supplier supply chain. Second, they assume prior belief is not related to an outsourcing structure. Under these settings, these authors focus on mechanisms by which one party designs a menu based on the prior distribution so that the other party’s information can be truthfully revealed through menu selection. Here, we consider (1) a three-tier supply chain and due to the existence of an intermediate player (the CM) between the OEM and the supplier, we can investigate a situation in which (2) the OEM’s prior information about the supplier’s cost differs according to the outsourcing structure.

We are aware of two studies in the supply chain literature that analyze different supply chain structures similar to our turnkey and consignment. Kayis et al. (2007) consider delegation (similar to our turnkey) and control (similar to our consignment) in procurement in a three-tier supply chain assuming the News-vendor formulation. They compare the optimal contract (menu contract) with the price-only contract and find that either delegation or control may be preferable, depending on the degree of manufacturer’s prior information on the suppliers’ costs. They assume prior belief is not related to an outsourcing structure while we assume it is related. Chen et al. (2006) consider a situation in which a manufacturer must decide how to allocate its capacity among multiple retailers or whether to delegate this duty to a distributor.

We note that Chen (2007) considers supply chain contracts under asymmetric cost information in an auction setting. Different from his many-to-one supply chain, however, we investigate a serial chain.

Finally, our two-period dynamic game follows some researchers’ early efforts to model renegotiation and multi-period supply chain contracts. For example, Taylor and Plambeck (2007) study an infinitely repeated game between a manufacturer and a supplier. They show that multi-period relational contracts can build up trust between these firms and enhance the supplier’s investment in capacity. They also show that a perfect Bayesian equilibrium will be a self-enforcing contract in this setting. Plambeck and Taylor (2007) consider a one-period game between a manufacturer and N buyers. The manufacturer builds capacity based on the buyers’ initial contracts before they see their demands. After demand realization, the capacity allocation can be renegotiated. Lutze and Özer (2008) quantify the renegotiation incentives under a multi-period promised leadtime contract to induce buyer participation and the truthful reporting of changes in processing leadtime.

3. One-period model

3.1. Model setting and preliminaries

We use subscript o to label the OEM, m to label the CM, s to label the supplier and a to label the alliance (between the CM and the supplier). Customer demand for the end-product is price-dependent and represented by \( p = \kappa - \theta q \), where \( \kappa \) and \( \theta \) are non-negative parameters, \( p \) is the market price and \( q \) is the end-product production quantity. Assume that this demand function is common knowledge. The supplier incurs a cost, \( c_a \), to produce one unit of component, and the CM incurs a cost, \( c_m \), to produce one unit of this component into one unit of semi-product. Assume that the OEM’s production cost is normalized to zero. Then, to guarantee a positive production quantity, \( K > c_m + c_s \) is required. Also assume that all three parties have infinite production capacity and that the related fixed costs are sunk. Denote the wholesale price offered to player i by \( w_i, i = m, s, a \).

Each player holds private information about its own costs. The other players are unable to fully observe this information, but are endowed with a prior distribution. One critical assumption in this paper is that this incomplete information (prior distribution) is dampened by the “distance” between two parties in the supply chain. For example, if party \( i \) directly interacts with upstream party \( j \) through a buy-sell process, then party \( i \)'s prior information can be denoted with a random variable \( \text{r.v.} X_j \); however, if party \( i \) deals indirectly with party \( j \) through intermediary party \( k \), then party \( i \)'s prior information is denoted with the r.v. \( X_k \), under consignment, the OEM’s prior belief about the CM’s cost is \( X_m \), and both the OEM’s and CM’s prior belief about the supplier’s cost is \( X_s \); under turnkey, the OEM’s prior belief about the total cost is \( X_m + X_s \); under turnkey, the OEM’s prior belief about the CM’s cost is \( X_m \), but that about the supplier is \( X_s \), and the CM’s prior belief about the supplier’s cost is \( X_s \).

Assume continuous r.v. \( X_i, i = m, s \), has cumulative distribution function \( \text{cdf} \Phi_i(x) \) and probability density function \( \text{pdf} \phi_i(x) \). Similarly, \( X_s \) has \( \text{cdf} \Phi_s(x) \) and pdf \( \phi_s(x) \). Assume that the domains of all distributions are strictly positive. We also assume that cost distributions are log-concave and thus have an increasing failure rate (IFR). Many commonly used probability distributions are log-concave, e.g., uniform, normal, logistic, extreme-value, chi-square, chi, exponential and Laplace. Other examples include Weibull, gamma and beta with certain parameter ranges; see Bagnoli and Bergstrom (2005). In addition, we assume \( X_i = q \), for \( i = s, m \), where \( q \) is the reverse hazard rate order, which means \( \phi(x)/\Phi(x) \leq \phi(x)/\Phi(x) \) for all \( x \) (see Shaked and Shanthikumar, 1994).

3.2. Consignment

Under consignment, the probability of the CM accepting the contract is \( P[X_m \leq w_m] = \Phi_m(w_m) \) and that of the supplier is \( P[X_s \leq w_s] = \Phi_s(w_s) \). Only when both the CM and the supplier accept will the contract succeed. The problem for the OEM is choosing a vector \( \{ q, w_m, w_s \} \) that maximizes its expected profit, \( \Pi_s(q, w_m, w_s) \), as follows:

\[
\text{OEM : Max } \Pi_s(q, w_m, w_s) = (K - \theta q - w_m - w_s)q\Phi_m(w_m)\Phi_s(w_s).
\]

Denote the optimum by \( \{ q^*, w_m^*, w_s^* \} \).

The foregoing objective function is the product of three terms \( p(q, w_m, w_s)q\Phi_m(w_m)\Phi_s(w_s) \). The first term is jointly concave and thus also log-concave in \( q, w_m, w_s \). By assumption, the second and third terms are log-concave in \( w_m \) and \( w_s \), respectively. The entire objective function is therefore log-concave (the product of log-concave functions is log-concave). Hence, the optimum is unique.

Given \( w_m \) and \( w_s \), the first-order condition of (1) with respect to \( q \) is

\[
q = \frac{K - w_m - w_s}{\theta}.
\]

Substituting (2) back into \( \Pi_s(q, w_m, w_s) \), the problem becomes

\[
\text{Max } (K - w_m - w_s)^2\Phi_m(w_m)\Phi_s(w_s).
\]
Then, the first-order conditions with respect to $w_m$ and $w_s$ are,

$$
\frac{K-w_m-w_s}{2} = \frac{\phi_m(w_m)}{\phi_m(w_m)}
$$

(4)

and

$$
\frac{K-w_m-w_s}{2} = \frac{\phi_s(w_s)}{\phi_s(w_s)}.
$$

(5)

Suppose the OEM’s prior belief about the CM’s (supplier’s) cost is instead $\hat{X}_j$, $j=m$ or $s$. Denote the corresponding wholesale prices by $\hat{w}_j^i$, $i=m$, $s$. We have the following proposition.

**Proposition 1.** If $\hat{X}_j \geq \hat{w}_j^i$, then $\hat{w}_j^C \geq \hat{w}_j^i$ and $\hat{w}_m^C \leq \hat{w}_m^C$. Similarly, if $\hat{X}_m \geq \hat{w}_m^i$, then $\hat{w}_m^C \geq \hat{w}_m^i$ and $\hat{w}_s^C \leq \hat{w}_s^C$.

Thus, under consignment, if the OEM makes a larger estimation of the supplier’s cost in the sense of the reversed hazard rate order, then it will offer a higher wholesale price to the supplier and a lower wholesale price to the CM. (Throughout this paper, “higher and lower” and “increasing and decreasing” are not used in the strict sense, i.e., they include equality.)

### 3.3. Integration

Under integration, the OEM has priors $X_m$ and $\hat{X}_s$, and offers a contract pair $(w_m, q)$ to the integration party. The alliance then decides whether to accept or reject. Suppose that the OEM offers $w_m$ to the alliance. Then, the latter’s best response is accept if $w_m \geq c_m + c_i$ and reject otherwise. Because the OEM’s prior about the total cost incurred by the alliance is $X_m + \hat{X}_s$, its contract success probability is $P(X_m + \hat{X}_s \leq w_m) = \int_{w_m}^{\infty} \phi_m(w_m-x_i) d\phi_s(x_s)$. The OEM chooses $w_m$ and $q$ that maximizes its expected profit $\Pi_m(q,w_m)$, as follows:

**OEM : Max $\Pi_m(q,w_m) = (K-q-w_m)qP(X_m \leq w_m)\hat{X}_i \leq \hat{w}_s(w_m,X_m))$.**

(6)

Note that $\int_{w_m}^{\infty} \phi_m(w_m-x_i) d\phi_s(x_s)$ is the convolution of $\phi_m$ and $\phi_s$. According to Lemma 3, it is log-concave. The overall objective function is also log-concave in $(q, w_m)$, and the optimum is unique.

For fixed $w_m$, (6) is concave in $q$, and the first-order condition is

$$
q = \frac{K-w_m}{2\theta}.
$$

(7)

Substitute (7) back into (6), and we obtain the first-order condition for $w_m$:

$$
\frac{K-w_m}{2} = \int_{0}^{w_m} \phi_m(w_m-x_i) d\phi_s(x_s)
$$

(8)

Denote the solution of (8) by $\hat{w}_m^i$.

Suppose the OEM’s prior belief about the supplier’s cost is instead $X_s$. Denote the corresponding wholesale price offered to the alliance by $\hat{w}_s$. Then, we have the following proposition.

**Proposition 2.** If $\hat{X}_s \geq \hat{w}_s^i$, then $\hat{w}_s^C \geq \hat{w}_s^i$.

Proposition 2 shows that under integration, the CM has the motivation to provide a stochastically larger prior in the sense of the reversed hazard rate order to the OEM when it is asked for. Therefore, credible information sharing cannot be achieved without a valid mechanism.

### 3.4. Turnkey

Under this structure, the sequence of events is: (1) the OEM offers a contract consisting of wholesale price $w_m$ and production quantity $q$ to the CM; (2) if the CM accepts, then it offers wholesale price $w_s$ and production quantity $q$ to the supplier; and (3) the supplier decides to accept or reject. This can also be analyzed in reverse order. First, we derive the CM’s best response given the OEM’s offer. Then, we analyze the OEM’s decision in anticipation of the CM’s best response.

Given the OEM’s offer $(w_m, q)$, the CM chooses $w_s$ to maximize its expected profit,

**CM : Max $\Pi_m(q,w_m, q) = (w_m - w_s - c_m)q\phi_s(q,w_s)$.**

(9)

This is log-concave in $w_s$, and the first-order condition for $w_s$ is

$$
w_m - c_m = w_s + \frac{\phi_s(q,w_s)}{\phi_s(q,w_s)}.
$$

Denote the optimal solution to the above equation by $\hat{w}_s(w_m,X_m)$. Then, the CM chooses $w_m$ and $q$ to maximize its expected profit, as follows:

**OEM : Max $\Pi_m(q,w_m) = (K-q-w_m)qP(X_m \leq w_m, \hat{X}_s \leq \hat{w}_s(w_m,X_m))$.**

(10)

The two events $(X_m \leq w_m)$ and $(\hat{X}_s \leq \hat{w}_s(w_m,X_m))$ are not independent. Note that if $X_m > w_m$, then the CM’s profit margin, $w_m - X_m - w_s$, is negative. Therefore, the optimal pricing strategy for the CM is to set $\hat{w}_s(w_m,X_m) = 0$. Because the domain is positive, i.e., $\hat{X}_s > 0$, event $\hat{X}_s \leq \hat{w}_s(w_m,X_m)$ implies $\hat{w}_s(w_m,X_m) > 0$, and thus $X_m > w_m$ is impossible. As a result, a positive price paid to the supplier by the CM implies that the latter accepts the contract offered by the OEM. Thus,

$$
P(X_m \leq w_m, \hat{X}_s \leq \hat{w}_s(w_m,X_m)) = P(\hat{X}_s \leq \hat{w}_s(w_m,X_m))$$

$$
= \int_{0}^{w_m} \phi_s(w_s(w_m,X_m)) d\phi_m(w_m,X_m).
$$

(11)

Then, (12) reduces to

$$
\text{Max}_{w_m} \Pi_m(w_m) = (K-q-w_m)q \int_{0}^{w_m} \phi_s(w_s(w_m,X_m)) d\phi_m(w_m,X_m).
$$

(13)

Again, given $w_m$, (13) is concave in $q$. Thus, maximization over $q$ yields

$$
q = \frac{K-w_m}{2\theta}.
$$

(14)

Substituting (14) back into (13) gives

$$
\text{Max}_{w_m} \Pi_m(w_m) = \frac{(K-w_m)^2}{4\theta} \int_{0}^{w_m} \phi_s(w_s(w_m,X_m)) d\phi_m(w_m,X_m).
$$

(15)

**Lemma 1.** If $\phi_s(x)/\phi_s(x)$ is convex in $x$, the objective function in (15) is log-concave and the optimal $w_m$ satisfies the first order condition of (15):

$$
\frac{K-w_m}{2} = \frac{\int_{0}^{w_m} \phi_s(w_s(w_m,X_m)) d\phi_m(w_m,X_m)}{\int_{0}^{w_m} \partial w_s(w_s(w_m,X_m))/\partial w_m d\phi_m(w_m,X_m)}.
$$

(16)

where $\hat{w}_s(w_m,X_m)$ and $\partial \hat{w}_s(w_m,X_m)/\partial w_m$ can be derived from (11).
Note that if \( \Phi_i \) is a power function distribution, the convexity of \( \Phi_i(x)/\Phi_i(x) \) in the above lemma holds. Denote the solution to (16) by \( w_{m}^{T} \).

Suppose the OEM's prior belief about the supplier's cost is instead \( X_c \). Denote the corresponding wholesale price offered to the CM by \( w_{m}^{C} \). Then, we have the following proposition.

**Proposition 3.** Assuming \( \Phi_{i}(x)/\Phi_{i}(x) \) and \( \Phi_{i}(x)/\Phi_{i}(x) \) are both convex in \( x \), if \( \tilde{X}_i \geq nX_c \) and \( (\Phi_{i}(x)/\Phi_{i}(x))' \leq (\Phi_{i}(x)/\Phi_{i}(x))' \) for all \( x \geq 0 \), then \( w_{m}^{T} \geq w_{m}^{C} \).

In comparison with Propositions 2 and 3 shows that besides the reverse hazard rate order, an additional condition is needed for the OEM to offer a higher wholesale price to the CM. Suppose that \( X_i (\tilde{X}_i) \) has a power function distribution on interval (0,1] with parameter \( \beta_i (\tilde{\beta}_i) \). Then the condition \( (\Phi_{i}(x)/\Phi_{i}(x))' \leq (\Phi_{i}(x)/\Phi_{i}(x))' \) for all \( x \geq 0 \) is equivalent to \( \tilde{\beta}_i \geq \beta_i \), which is also the condition for \( \tilde{X}_i \geq nX_c \). Thus, in the case of power function prior distributions, condition \( \tilde{X}_i \geq nX_c \) and condition \( (\Phi_{i}(x)/\Phi_{i}(x))' \leq (\Phi_{i}(x)/\Phi_{i}(x))' \) for all \( x \geq 0 \) are equivalent. However, this is not true in general. The additional condition under turnkey adds more restrictions on the prior distribution. The additional condition requires that increasing one unit of the wholesale price leads to a more significant increase in the success probability of the contract under \( \Phi_i \) than under \( \Phi_{i} \).

Proposition 3 implies that under turnkey the CM has the motivation to provide even more distorted prior information to the OEM when it is asked for. The need for this more aggressive information distortion under turnkey can be explained by the structural difference between integration and turnkey. Under integration, the OEM ensures that a higher wholesale price guarantees a higher success probability of the contract; however, under turnkey, the CM retains the partial extra rents obtained from this larger wholesale price and passes only the leftover to the supplier. Thus, under turnkey, the OEM has less incentive to offer a high wholesale price to the CM. To induce the OEM to pay a high wholesale price, the CM needs to distort the prior information more aggressively under turnkey than the alliance does under integration if it has an opportunity to do so.

### 3.5. Comparison without information difference across three structures

As described in the foregoing section, the prior information is different across the three structures. In this subsection, we compare the three structures under the benchmark scenario, where there is no information difference, i.e., \( \Phi_{i} = \Phi_{i} \).

A general comparison of the wholesale prices across the three structures is complicated, as \( (w_{m}^{C}, w_{m}^{T}) \) under consignment and \( w_{m}^{C} \) under turnkey depend jointly on \( (X_{m}, X_{c}) \), whereas \( w_{m}^{T} \) under integration depends solely on the additive marginal cost \( X_{m} + X_{c} \). For this reason, we focus on power-function prior distributions. This type of distribution allows us to obtain the optimal wholesale prices in closed-form, and thus to conduct analytical comparisons.

**Proposition 4.** Assume there is no information difference across the three structures and the cost priors have power function distributions with parameters \( \beta_i, i = m,s \).

(a) If \( \beta_m + \beta_s \leq 2/(\kappa - 1) \), then the total wholesale price paid by the OEM to purchase one unit of the semi-product is the same under consignment as that under integration, i.e., \( w_{m}^{C} + w_{m}^{T} = w_{s}^{C} \). Otherwise, the total wholesale price paid by the OEM to purchase one unit of the semi-product is higher under consignment than that under integration, i.e., \( w_{m}^{C} + w_{m}^{T} > w_{s}^{C} \).

(b) The OEM pays the same wholesale price for one unit of the semi-product under integration as that under turnkey, i.e., \( w_{m}^{I} = w_{m}^{T} \).

The OEM's expected profits under the three structures take the same form, that is, the product of \( (k - w_{m}^{C}I) \) and the contract success probability, where \( w \) is the total wholesale price that the OEM pays to obtain one unit of the semi-product. In particular, \( w = w_{m}^{C} \) under consignment, \( w = w_{m}^{T} \) under integration, and \( w = w_{m}^{I} \) under turnkey. The contract success probability equals \( P(w_{m}^{C} > X_{m} + X_{c}) \) under consignment, \( \int_{0}^{w_{m}^{C}} \Phi_{m}(w_{m}^{C})d\Phi_{m}(X_{m}) \) under turnkey, and \( \Phi_{m}(w_{m}^{C})\Phi_{m}(w_{m}^{C}) = P(w_{m}^{C} > X_{m})P(w_{m}^{C} > X_{c}) \) under consignment.

**Proposition 5.** Assume no information difference across three structures. Then,

(a) the OEM is always better off under integration than under consignment;
(b) the OEM is always better off under integration than under turnkey; and
(c) the OEM may be better or worse off under consignment than under turnkey.

Parts a and b of Proposition 5 can be explained by double marginalization. Integration mitigates the effect of double marginalization by integrating the CM and the supplier, whereas under consignment and turnkey, given the same payment to the alliance, the redistribution of rents between the CM and the supplier may not be socially optimal. Our explanation for Part c is as follows. Consignment provides the OEM an information advantage on the supplier's cost; however, under turnkey, the decision rights are delegated to the CM, who has private information on its own production cost and may make a more reasonable decision about the wholesale price offered to the supplier. Hence, each structure has its own advantages and disadvantages.

### 4. Two-period model

In Section 3, we focused on one-period contracts between the supply chain parties. In reality, however, the trade among these parties may last for many periods. To investigate whether our conclusions from the single-period model hold in a multi-period environment, in this section, we consider a two-period model. The setting for each period is similar to the single-period model. What is different here is that the players can update their prior information at the end of period 1, and a wholesale price contract can be renegotiated at the beginning of period 2. More specifically, we assume the following.

1. **Commitment:** If two players agree on a contract in period 1, then the same contract is repeated in period 2.
2. **Renegotiation:** If two players disagree on a contract in period 1, then they update their beliefs about the cost information and renegotiate in the next period.
3. **Rational expectation:** If a contract is rejected in the first period, then the contracting player will offer a higher wholesale price in the next period.

We assume the OEM makes its wholesale pricing decisions myopically in each period: it maximizes its current period profits based on the information it has. In particular, the wholesale prices offered by the OEM in the first period are the same as those in the one-period model, provided that the initial prior information is the same.

Note that under such two-period renegotiable contracts, the "ratchet effect" (Freixas et al., 1985) may occur: Both the CM and
the supplier may pretend to have very high costs in the first period in the expectation of higher wholesale prices in the next period. In other words, they may intentionally reject the contract in the first period even though the wholesale prices offered are high enough to cover their costs. In contrast, intentional rejection is never optimal under a one-period contract scenario. As a result, our focus in this section is on comparing the significance of the ratchet effect between the two outsourcing structures, consignment and turnkey. We omit the integration structure in this section as we want to focus on the discussion of the ratchet effect among the three parties.

For any \( t = 1, 2 \), denote \( w_{it} \) as the wholesale price offered to party \( i \), \( i = m, s \), at the beginning of time period \( t \). The production quantity in each period is determined by the corresponding first-order conditions in the one-period setting (a function of the wholesale prices). Let \( x_t \) be the action of party \( i \) in period \( t \), \( i = m, s \). Then, \( x_t = a \) means the action is reject; and \( x_t = a \) means it is accept. We use \( x_t = (x_{mt}, x_{st}) \) to denote the joint action of the CM and the supplier; then, \( x_t \in S(m,s) = \{(a,a),(r,a),(a,r),(r,r)\} \). Let \( h_t \) be the action history up to the end of period \( t \), i.e., \( h_t = (x_1, x_2) \). Denote by \( PI_t(x_t) \) and \( PI_t(h_t) \) the profit of party \( i \) at the end of periods 1 and 2, respectively, \( i = a, m, s \). We assume that there is a discount factor: \( \gamma(0 < \gamma \leq 1) \).

4.1. Consignment

Under two-period consignment: (i) at the beginning of period 1, the OEM offers take-it-or-leave-it wholesale prices \( w_{1m} \) and \( w_{1s} \) to the CM and the supplier, respectively, based on its initial prior information, \( \Phi_m(\cdot) \) and \( \Phi_s(\cdot) \). (ii) Then, the CM and the supplier decide whether to accept the contract with the objective of maximizing their own discounted two-period profits. (iii) After their response, the OEM updates its knowledge about the upstream cost structures based on its current information set: the original prior beliefs about costs and the observed history of actions \( h_t \) according to Bayes rule. (iv) With this updated knowledge, the OEM then makes the second-round pricing decisions, \( w_{2m}(h_1) \) and \( w_{2s}(h_1) \), at the beginning of period 2 to maximize its expected profit in that period. Let \( q(h_1) \) denote the resulting optimal ordering quantity at the beginning of period 2. (v) Then, the CM and the supplier decide whether to accept or reject the contract with the objective of maximizing their own profits in period 2, given the other player's strategy fixed.

Assumptions (i), (ii), (iv) and (v) mean “perfection,” namely optimization by each player for any history of the game. An equilibrium satisfying the foregoing five conditions is said to be a perfect Bayesian equilibrium (PBE). A perfect Bayesian equilibrium represents a strategy profile and a belief system, such that the strategies are sequentially rational given the particular belief system and that the belief system is consistent, wherever possible, given the strategy profile. In the remainder of this section, we show that the two-period consignment game has a PBE.

We first establish a key observation. Note that the intentional rejection has a cost: the CM (supplier) sacrifices its first-period positive profit. The following lemma shows that only when the CM’s (supplier’s) cost is larger than a certain threshold will it reject the contract.

**Lemma 2.** In period 1, given wholesale prices \( w_{1i} \), \( i = m, s \), and under the rational expectation assumption, there exists the cutoff level \( \bar{c}_m(\bar{c}_s) \) such that if \( c_m > \bar{c}_m(> \bar{c}_s) \), the CM’s (supplier’s) optimal decision is to reject. Otherwise, it is to accept. When \( c_m = \bar{c}_m(= \bar{c}_s) \), the CM (supplier) is indifferent between accepting and rejecting.

Anticipating this threshold-type strategy, if party \( i \) rejects contract \( w_{1i} \) in period 1, then the OEM knows that its cost must be at least higher than some value \( \hat{c}_i \). Then, the OEM updates its belief as follows.

\[
\phi^*_i(x_t | r) = \begin{cases} 
\phi_i(x_t) / (1 - \Phi_i(\hat{c}_i)) & \text{for } x_t \geq \hat{c}_i \\
0 & \text{for } x_t < \hat{c}_i.
\end{cases}
\]

(17)

Thus, the posterior distribution is a left-truncation of the prior. Correspondingly, we have

\[
\phi^*_i(x_t | r) = \int_{\hat{c}_i}^{x_t} \phi_i(x_t) / (1 - \Phi_i(\hat{c}_i)) dx_t = \frac{\phi_i(x_t) - \Phi_i(\hat{c}_i)}{\phi_i(\hat{c}_i)} < \frac{\phi_i(x_t)}{\phi_i(x_t)}.
\]

(18)

In other words, conditional updated belief \( X_j | r \) satisfies \( X_j | r \geq \gamma X_j \). According to Proposition 1, we must have \( \omega_{2i}(h_1) > \omega_{1i} \). Thus, this information-updating mechanism is consistent with party \( i \)’s rational expectation.

If party \( i \) accepts \( w_{1i} \), then the same contract is repeated in period 2, according to the commitment assumption.

We now derive the profit functions of the CM and the supplier assuming their costs are at the cutoff levels (\( \bar{c}_m, \bar{c}_s \)) in Lemma 2. Because of their indifference at these threshold points, we obtain a number of simultaneous equations to solve for the equilibrium.

**Proposition 6.** 1. The CM’s indifference between reject and accept when \( c_m = \bar{c}_m \) leads to

\[
\gamma \Phi_m(\bar{c}_m)(K - \omega_{2m}(r,a) - \omega_{2s}(r,a) - \bar{c}_m) + \gamma \Phi_s(\bar{c}_m) \Phi_m(\bar{c}_m)(K - \omega_{2s}(r,a) - \omega_{2s}(r,a) - \bar{c}_m) + \omega_{2m}(r,a) - \omega_{2s}(r,a) - \bar{c}_m
\]

(19)

where the left-hand side is the expected profit for the CM when it chooses to reject the offer; the right-hand side is that it accepts. Similarly, the supplier’s indifference when \( c_s = \bar{c}_s \) leads to

\[
\gamma \Phi_m(\bar{c}_m)(K - \omega_{2m}(r,a) - \omega_{2s}(r,a) - \bar{c}_s) + \gamma \Phi_s(\bar{c}_s) \Phi_m(\bar{c}_s)(K - \omega_{2s}(r,a) - \omega_{2s}(r,a) - \bar{c}_s) + \omega_{2m}(r,a) - \omega_{2s}(r,a) - \bar{c}_s
\]

(20)

Solving (19) and (20) yields the equilibrium solution to \( \bar{c}_m \) and \( \bar{c}_s \).

2. If condition

\[
(1 + \gamma) \Pi_m((a,a), \bar{c}_m) + \gamma \Pi_m((r,a), (a,a), \bar{c}_m) + \gamma \Pi_m((a,r), (a,a), \bar{c}_m)
\]

(21)

holds, then \( \bar{c}_m \) is increasing with \( \bar{c}_s \). A similar result holds for the supplier when the condition is

\[
(1 + \gamma) \Pi_s((a,a), \bar{c}_s) + \gamma \Pi_s((r,r), (a,a), \bar{c}_s) + \gamma \Pi_s((a,r), (a,a), \bar{c}_s)
\]

(22)

3. Given that conditions (21) and (22) are satisfied, there exists a unique solution for \( (\bar{c}_m, \bar{c}_s) \).

Condition (21) means that the sum of the discounted profits for the CM when it and the supplier take the same action in the first period (both accept or both reject) should be greater than that when the CM and the supplier take different actions in the first period. Under this condition, when the supplier chooses a larger \( \bar{c}_s \), the CM also chooses a larger \( \bar{c}_m \). Similar interpretation applies to (22).
The CM's and the supplier's best response in period 1 can be characterized by \( \hat{c_s}, \hat{\ell}_s \), and takes the following form: \( x_1 = (a, r) \) if \( c_m \leq c_s, \hat{c}_s \leq \hat{c}_m \); \( x_1 = (a, \theta) \) if \( c_m \leq \hat{c}_m, c_s > \hat{c}_s \); \( x_1 = (r, a) \) if \( c_m > \hat{c}_m, c_s < \hat{c}_s \); and \( x_1 = (r, r) \) if \( c_m > c_s, c_s > \hat{c}_s \). (When a player is indifferent between accepting and rejecting, we assume it chooses to accept.) The action taken in period 2 depends on the order between wholesale price \( w_2(h_1) \) and cost \( c_i, i = m, s \). If \( w_2(h_1) \geq c_i \), then party \( i \) chooses to accept the offer. Otherwise, it chooses to reject it.

The OEM's decisions about the wholesale prices in period 1, \((w_{m1}, w_s1)\), can then be obtained by solving its two-period discounted profit function with a numerical exclusive search.

### 4.2. Turnkey

In the two-period turnkey setting, we assume that as long as the OEM offers a wholesale price that is greater than the CM's cost, the CM will always accept the contract offer. One argument is that the CM can always maximize its profit by deciding the price offered to the supplier. Even though the CM wants to reject the offer, it can instead offer a low price to the supplier and let the supplier reject the contract. Hence, we can concentrate on analyzing the supplier's behavior.

Here, the supplier may intentionally reject the CM's offer in anticipation of a higher price in the next period. Similar to our analysis of the two-period consignment, there exists a cutoff level \( \hat{c}_s \). If the supplier's cost \( c_s \) falls at this point, then it is indifferent between rejecting and accepting the contract. If \( c_s > \hat{c}_s \), then the optimal decision for the supplier is to reject it.

Now consider indifferent point \( c_s = \hat{c}_s \). Suppose the supplier chooses to accept in period 1; then, the CM must accept the contract (as argued in the single-period turnkey). Thus, \( x_1 = (a, a) \). According to our commitment assumption, the contract in the second period remains the same. As a result, \( x_2 = (a, a) \) and

\[
\Pi_2((a, a)|\hat{c}_s) = \Pi_2((a, a), (a, a)|\hat{c}_s) = \frac{(K - w_{m1})}{2\theta}(w_{s1} - c_s). 
\]

Hence, the supplier's total discounted profit is

\[
\Pi_1(a|\hat{c}_s) = (1 + \gamma)(K - w_{m2})/2\theta(w_{s2} - c_s). 
\]

If the supplier rejects the contract in period 1, then, at the end of period 1, both the OEM and the CM update their prior information about the supplier's cost. The analysis of this game is similar to that for the one-period turnkey, but with updated prior information.

The OEM updates prior \( \hat{\Phi}_2 \) according to (17) and offers updated wholesale price \( w_{m2}(a, r) \) to the CM, which solves

\[
\frac{K - w_{m2}}{2\theta} = \int_{0}^{w_{m2}} \left[ \Phi_1(\hat{w}_1)(w_{m2} - \hat{w}_1) \right] d\Phi_0(\hat{w}_1). 
\]

where \( \hat{w}_1(w_{m2} - \hat{w}_1) \) is the solution to

\[
w_{m2} - \hat{w}_1 = \frac{\Phi_1(\hat{w}_1) - \Phi_0(\hat{w}_1)}{\Phi_1(\hat{w}_1)}. 
\]

The CM also updates its belief about the supplier's cost and offers the supplier \( w_{s2}(a, r) \), which is the solution to

\[
w_{s2}(a, r) - c_m = w_{s2} + \frac{\Phi_1(\hat{w}_1) - \Phi_0(\hat{w}_1)}{\Phi_1(\hat{w}_1)}. 
\]

In this case, the supplier's total discounted profit is

\[
\Pi_1(r|\hat{c}_s) = \gamma \frac{(K - w_{m2})}{2\theta}(w_{s2} - c_s). 
\]

Solving equation \( \Pi_1(a|\hat{c}_s) = \Pi_1(r|\hat{c}_s) \) generates the solution for \( \hat{c}_s \). We summarize the foregoing conclusions in the following proposition.

### 5. Numerical experiments

In this section, we compare the significance of the ratchet effect under consignment and turnkey through a numerical study. We examine each party's best response, profit and resulting chain performance by varying the production costs, prior distributions and discount factors. In all of our experiments, the market demand parameters are \( \kappa = 30 \) and \( \theta = 1 \). Production costs \( c_m \) and \( c_s \) are drawn from the following set: \( \{1, 3, 5, 7, 9, 11, 13\} \). We assume the cost priors are independent random variables with normal distributions. The means are unbiased, that is, \( m_i = c_i, i = m, s \), and the standard deviation \( \sigma_i \in \{0.1m_i, 0.2m_i, 0.3m_i\} \). The discount factors are set at \( \gamma \in \{0.35, 0.55, 0.75, 0.95\} \). In total, there are 1764 combinations for the two-period model. In choosing the OEM's prior on the supplier's cost \( \hat{X}_s \), under turnkey, we consider an extreme case where \( \hat{X}_s \) is in the best interests of the CM, that is, the CM's profit is maximized with \( \hat{X}_s \). In this way, we can eliminate the CM's self-interested behavior under turnkey and focus on investigating the impact of the ratchet effect in the three-tier supply chain.

We observe that in the one-period setting, when \( \hat{X}_s \) is most desirable for the supplier, the OEM always prefers consignment to turnkey, and the CM always prefers turnkey to consignment. This is not surprising. However, when the outsourcing contract lasts for two periods, in contrast, the OEM may prefer turnkey to consignment, and the CM may prefer consignment to turnkey.

Table 1 illustrates the profits of each player under certain prior information structures, where the bold number means either that the OEM prefers turnkey or that the CM prefers consignment. Also, the outcome for each player under two-period renegotiation outsourcing may be worse than that under one-period outsourcing when intentional rejection (by the CM or the supplier) occurs in the first period.

We then find that the profits of the OEM and the entire supply chain decrease when intentional rejection occurs. Table 2 compares the profits of each player under one- and two-period consignment, where intentional rejection occurs, and Table 3 compares similar behavior under one- and two-period turnkey. We observe that when the CM (supplier) intentionally rejects the offer while the supplier (CM) does not, then the supplier's (CM's) expected profits are lower. Therefore, the ratchet effect brings inefficiency to two-period outsourcing.

By comparing the behavior of the CM and the supplier in 1764 combinations, we find that, as the variances of the prior distributions increase, more intentional rejections occur, either by the CM, or the supplier or by both. Thus, the ratchet effect is reinforced by prior information uncertainty.

In addition, we find that the ratchet effect is more severe under consignment than under turnkey. Intentional rejection occurs more frequently under consignment than under turnkey. Among
the 1741 cases, we observed 114 cases of intentional rejection under two-period consignment and 99 cases of it under two-period turnkey. This is because of the non-cooperative game between the CM and the supplier under consignment: that is, consignment's success depends on the participation of both the CM and the supplier. If one player accepts the contract and the other rejects it, then the former gets zero in the current period and the same price in the next period; however, if instead, they both reject it, then that player is better off with a higher price in the next period. Thus, the non-cooperative game between the CM

Table 1
Two-period outsourcing performance (γ = 0.75).

<table>
<thead>
<tr>
<th>Input parameters</th>
<th>Consignment</th>
<th>Turnkey</th>
</tr>
</thead>
<tbody>
<tr>
<td>μ₁</td>
<td>σ₁</td>
<td>μ₂</td>
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<tr>
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<td>0.90</td>
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Table 2
Ratchet effect on inhouse consignment (γ = 0.75).

<table>
<thead>
<tr>
<th>Input parameters</th>
<th>One period consignment</th>
<th>Two period consignment</th>
</tr>
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<tbody>
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<td>μ₁</td>
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and the supplier may diminish the profits of both, as well as those of the entire supply chain. In contrast, the CM has no incentives to intentionally reject the contract under turnkey, which mitigates the non-cooperative game’s inefficiency.

Lastly, we explore the effect of the discount factor on the ratchet effect. We observe that, as this factor increases, the failure of the outsourcing contract in the first period occurs more frequently. That is, as $\gamma$ increases, the profits in the second period become more important, which stimulates rejection in the first period. Hence, increasing the discount factor enhances the ratchet effect. Table 4 lists the total incidence of outsourcing failure as well as that of intentional rejection (from the CM, the supplier and both) in the first period under each discount factor. It also shows that consignment has more outsourcing failure and intentional rejection than does turnkey.

6. Summary

In this paper, we investigate three outsourcing structures in a three-tier supply chain consisting of an OEM, a CM and a supplier: consignment, integration and turnkey. We first obtain the equilibrium wholesale prices under the one-period setting and examine the impact of the OEM’s prior information about other parties’ costs on those wholesale prices. We then extend the study to a two-period scenario. We discuss how to update the cost information between the periods and demonstrate how to derive the corresponding perfect Bayesian equilibria. Finally, we conduct a numerical study to explore the ratchet effects under different structures.

Without information difference, and with an example of the power function distributions of costs, we illustrate that the wholesale price offered by the OEM for each semi-product is the same under integration and turnkey. When the OEM has a low estimation of the CM’s and supplier’s costs, the wholesale price it offers for each semi-product is also the same under consignment. However, when this estimation is high, the OEM tends to offer a lower wholesale price under integration than under consignment. We show that the OEM is always better off under integration than under consignment or turnkey. This is because integration mitigates double marginalization.

We then characterize the sensitivity of the prior information on wholesale prices. We find that, under integration, as long as...
the OEM has stochastically larger prior in the reversed hazard rate order, the wholesale price it offers will be higher. However, under turnkey, the conditions prompting the OEM to offer a higher price are stronger. From this analysis, we conclude that credible information sharing between the OEM and the CM is not possible without a suitable mechanism. We note that there exist several research work along this direction such as Kaya and Özær (2009) and Kayis et al. (2007).

We find that when outsourcing contracts last more than one period, even though the OEM’s indirect prior about the supplier’s cost under turnkey is in alignment with the CM’s best interests, it may be better off under this structure than under consignment even though it possesses more information under the latter. One possible reason for this is the inefficiency that arises from the ratchet effect. Through our numerical studies, we find that consignment results in a larger ratchet effect than does turnkey, a difference that is caused by the non-cooperative game between the CM and the supplier. Under turnkey, the CM has no incentives to reject an offer intentionally, and the system’s success depends solely on the supplier’s optimal decision. Under consignment, the contract’s success depends on the participation of both the CM and the supplier. As one player’s rejection tends to induce the other’s rejection, this strengthens the ratchet effect and renders supply chain coordination more difficult. We also find that the ratchet effect is strengthened by a high degree of variance in the cost priors and a larger discount factor.

Our study shows that the choice between turnkey and consignment depends on such situational factors as the priors about costs and the length of contracts. Our research also demonstrates the importance of coordination under consignment and turnkey to achieve contract success, an issue worth further exploration in the future.

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We would like to thank the editor and two anonymous referees for their helpful comments and good suggestions. Guo’s research was supported in part by Hong Kong RGC Research Grant (no. B-Q11F). Song’s research was supported in part by National Natural Science Foundation of China (no. 70731003). Wang’s research was supported in part by the Hong Kong Polytechnic University Departmental Grant (G-U639).

Appendix

To prove the propositions in this paper, we first introduce the following lemmas and definitions.

**Lemma 3** [Bagnoli and Bergstrom, 2005]. Suppose random variable \( Y_i \) has a log-concave distribution function \( G_i \) and pdf \( g_i \), \( i = 1, 2 \). Then, (1) the reversed hazard rate \( g_i(x)/G_i(x) \) is decreasing in \( x \); (2) if \( f(x) \) is twice differentiable, strictly increasing, and concave, then \( G_i(f(x)) \) is a log-concave function of \( x \); and (3) the convolution \( G(x) = \int_0^x G_1(x - x_2) dG_2(x_2) \) is log-concave.

These properties, along with the following reversed hazard rate order and its properties, are useful in later sections for comparative static analysis of the optimal wholesale prices.

**Lemma 4** [Shaked and Shanthikumar, 1994]. If random variables \( Y_1 \) and \( Y_2 \) are such that \( Y_1 \leq \text{stoch} Y_2 \), and if \( Z \) is a random variable independent of \( Y_1 \) and \( Y_2 \) with a decreasing reversed hazard rate, then \( Y_1 + Z \leq \text{stoch} Y_2 + Z \).

**Proof for Proposition 1.** Condition \( \hat{X}_t \geq \text{stoch} X_t \) implies that \( \hat{F}_t(x)/\hat{F}_t(x) \leq \Phi_t(x)/\Phi_t(x) \). From (5), we can argue by contradiction that \( \hat{W}_t \geq W_t \), and from (4), we can further derive that \( \hat{W}_m \leq W_m \). The proof for the second part is similar. □

**Proof for Proposition 2.** As \( X_0 \) has a log-concave density, it has a decreasing reversed hazard rate. Then, according to Lemma 4, \( X_m + \hat{X}_t \geq \text{stoch} X_t + X_m \), which implies that

\[
\int_0^{\hat{w}_m} \frac{\partial w}{\partial x} \Phi_m(w - x) d\Phi_m(x_t) \leq \int_0^{w_m} \frac{\partial w}{\partial x} \Phi_m(w - x) d\Phi_m(x_t).
\]

According to (8), \( \hat{W}_m \geq W_m \). □

**Proof for Lemma 1.** If \( \hat{F}_t(x)/\hat{F}_t(x) \) is convex in \( x \), Lemma 3 and (11) imply that \( \hat{w}_m/(W_m(X_m)) \) is an increasing and concave function of \( W_m - X_m \). Also, according to Lemma 3, \( \hat{F}_t(W_t(W_m(X_m))) \) is a log-concave function of \( W_m - X_m \). Thus the convolution \( \int_0^{\hat{w}_m} \frac{\partial w}{\partial x} \hat{F}_t(w) d\Phi_m(x_m) \) is log-concave in \( w_m \). Consequently, (15) is log-concave and has a unique optimum. □

**Proof for Proposition 3.** \( \hat{X}_t \geq \text{stoch} X_t \) implies that \( \hat{F}_t(x)/\hat{F}_t(x) \leq \Phi_t(x)/\Phi_t(x) \). From (11), we can derive that \( \hat{w}_m/(W_m(X_m)) \geq W_m(X_m) \) and \( \hat{F}_t(W_t(W_m(X_m))) \leq \Phi_t(W_t(W_m(X_m))) \)

\( \hat{t}_t(W_t(X_m))) \). For all \( W_m(X_m) \).

Also from (11), we can derive that

\[
\frac{dW_m}{\hat{w}_m} = 1 + \frac{\hat{F}_t(W_t)}{\hat{F}_t(W_t)}.
\]

Thus, condition \( (\Phi_t(x)/\Phi_t(x))^t \leq (\Phi_t(x)/\Phi_t(x))^t \) implies that \( dW_m/<\hat{w}_m < dW_m < \hat{w}_m < dW_m < W_m \).

Hence, we have, for all \( W_m(X_m) \),

\[
\frac{\hat{F}_t(W_t(W_m(X_m)))}{\Phi_t(W_t(W_m(X_m)))} \leq \frac{\Phi_t(W_t(W_m(X_m)))}{\Phi_t(W_t(W_m(X_m)))}.
\]

Because the reversed hazard rate order is closed under convolution (see Lemma 4), we can further derive that

\[
\int_0^{\hat{w}_m} \frac{\partial w}{\partial x} \Phi_m(w) d\Phi_m(x_m) \leq \int_0^{\hat{w}_m} \frac{\partial w}{\partial x} \Phi_m(w) d\Phi_m(x_m).
\]

Then, according to (16), \( \hat{W}_m \geq W_m \). □

**Proof of Proposition 4.** For consignment, \( (W_m, W_c) \) are decided by first-order conditions (4) and 5. It can be shown that

\[
W_m = \frac{K\beta_m}{2 + \beta_m + \beta_t},
\]

\[
W_c = \frac{K\beta_c}{2 + \beta_m + \beta_c}.
\]

For integration, solving (8) yields,

\[
K = \frac{\int_0^{w_m} (w_m - x_m)^{\beta_m - 1} dx_m}{\int_0^{w_m} \beta_m (w_m - x_m)^{\beta_m - 1} dx_m}.
\]

As the domain of \( X_m \) is \( [0, 1] \), we need to classify \( W_c \) into two cases: \( w_c^1 \leq 1 \). For the first case, the foregoing can be written as

\[
K = \frac{\int_0^{w_m} (w_m - x_m)^{\beta_m - 1} dx_m}{\int_0^{w_m} \beta_m (w_m - x_m)^{\beta_m - 1} dx_m} = \frac{w_m^1 + 1}{\beta_m + \beta_t} = \frac{w_m}{\beta_m + \beta_t}.
\]
where \( B(a,b) = \int_0^1 t^{a-1}(1-t)^{b-1} \, dt \) is the beta function. Solving this equation yields
\[
\omega_a = \frac{k(\beta_m + \beta_s)}{2 + \beta_m + \beta_s}.
\] (28)

This solution is valid if \( k(\beta_m + \beta_s)/(2 + \beta_m + \beta_s) \leq 1 \) or \( \beta_m + \beta_s \leq 2/(k-1) \).

If, instead, \( \beta_m + \beta_s > 2/(k-1) \), then it becomes
\[
\omega_a = \frac{\int_0^1 (w_a^T - x_m) \, x_m^{-1} \, dx_m}{\int_0^1 \beta_m (w_a^T - x_m)^{\beta_m} \, x_m^{-1} \, dx_m}.
\]

Thus,\[
\omega_t = \hat{\omega}_t = \left( \frac{\beta_m (w_m - x_m)}{\beta_m + 1} \right).
\]

Substitute \( \hat{\omega}_t (w_m, x_m) \) and \( \hat{\omega}_t (w_m, x_m) / \hat{\omega}_t \) into (16), and we obtain
\[
K - w_m = \int_0^{w_m} \frac{\beta_m (w_m - x_m) \beta_m}{\beta_m + 1} \beta_m x_m^{-1} \, dx_m.
\]

This is the same equation as (27). Thus, \( w_m = \omega_a \).

**Proof of Proposition 5.** Assume the price for one unit of a product is the same across the three structures, i.e., \( w_a + w_f = w_a + w_f = w_m \). Note that \( P(w_a^T \geq X_m + X_3) \geq P(w_a^T \geq X_m) \) always holds. Thus, integration yields a higher chance of contract success than does consignment.

Denote the optimal solutions to Max\( \omega_a, \Pi_a(w_m) \) by \( w_m^* \). Then,
\[
\max \Pi_a(w_a) = \Pi_a(w_m^*) = \max \Pi_a(w_m),
\] (31)
thus proving (b).

There is no certain order relationship between success probability \( P(w_a^C) \geq X_m) \) and \( P(w_a^C) \geq X_m) \) under consignment and turnkey, given \( w_m + w_f = w^T \). Thus, (c) holds. □

**Proof of Lemma 2.** We take the CM as an example. We fix the supplier's first period decision \( x_{m1} \), and denote it by “dots”. We first assume \( x_{m1} \) to be accepted. The proof for the general case is similar.

Suppose \( x_{m1} = a \); then, the CM obtains the wholesale price \( w_{m1} \) in both periods 1 and 2. Thus, its total profit in the two periods is \( \Pi_m(a, r) = (1 + r)(w_{m1} - c_m)(q(a, r)) \). If \( x_{m1} = r \), then the CM's first period profit is zero, but in period 2 it obtains a higher price, \( w_{m2}(r, r) \), than \( w_{m1} \). Thus, its total profit is \( \Pi_m(r, r) = (1 + r)(w_{m2}(r, r) - c_m)q(r, r) \). Because the optimal ordering quantity satisfies \( q = (k - w_m - w_{f2}(r, r)/2b) \), condition \( w_{m2}(r, r) > w_{m1} \) implies \( q(r, r) < q(a, r) \).

Assume \( \Pi_m(a, r) = \Pi_m(r, r) \) at \( \tilde{c}_m \). If \( c_m > \tilde{c}_m \), then we have
\[
\Pi_m(a, r) = (1 + r)(w_{m1} - c_m)q(a, r) = (1 + r)(w_{m1} - c_m)q(a, r) + (1 + r)(c_m - \tilde{c}_m)q(a, r) = \gamma(w_{m1} - c_m)q(a, r) + (1 + r)(c_m - \tilde{c}_m)q(a, r) < \gamma(w_{m2}(r, r) - c_m)q(r, r) + (1 + r)(c_m - \tilde{c}_m)q(r, r) = \gamma(w_{m2}(r, r) - c_m)q(r, r) + \tilde{c}_m - c_m)q(r, r) = \Pi_m(r, r).
\]

Thus, the optimal decision is to reject. Similarly, we can show that when \( c_m < \tilde{c}_m \), \( \Pi_m(a, r) > \Pi_m(r, r) \), the optimal decision is to accept. □

**Proof of Proposition 6.** We focus on the CM's profit functions. The results for the supplier can be derived similarly.

Assume \( c_m = \tilde{c}_m \); then, the CM can take one of the following two actions.

Case 1: The CM rejects the contract in period 1.
In this case, the CM's profit in the first period is zero, i.e., \( \Pi_m(r, r) = 0 \), and the OEM updates its belief about the CM's cost according to (5).

If the supplier's action \( x_{m1} = a \), then the OEM offers the same price to the supplier in period 2, i.e., \( w_s(z(r)) = w_s \), and offers a higher price, \( w_m z(r, a) \), to the CM, which solves the following first-order condition (similar to (4)):
\[
\frac{K - w_m - w_{s1}}{2} = \frac{\phi_m(w_m(r))}{\phi_m(w_m(r))} - \frac{\phi_m(w_m(r)) - \phi_m(c_m)}{\phi_m(w_m(r))}
\]

(According to (18), this indeed guarantees \( w_m z(r, a) > w_m \).) The corresponding optimal order quantity is
\[
qu(r, a) = \frac{K - w_m - w_{s1} - w_{s1}}{2b}
\]

The behavior of each player in period 2 resembles that under one-period consignment. In particular, according to the commitment assumption, because the supplier obtains the same price as in the
From (17), we have

\[ \frac{K-W_{m2}(r,a)}{2\theta} = \Phi_m(W_m) - \Phi_m(W_m) - \Phi_m(W_m) - \Phi_m(W_m) = \frac{K-W_{m1}-W_{m1}}{2\theta} \] (32)

If the supplier chooses \( x_s = r \), then the OEM updates its belief about the supplier’s cost according to (17), and the optimal wholesale prices offered by the OEM in period 2, \( (W_m(z(r,r), W_s(z(r,r)) = \) solve

\[ \frac{K-W_{m1}-W_{m1}}{2} = \frac{\Phi_m(W_m) - \Phi_m(W_m) - \Phi_m(W_m) - \Phi_m(W_m)}{\Phi_m(W_m)} = \frac{K-W_{m2}(r,a)-W_{m2}(r,a)-\hat{c}_m}{\Phi_m(W_m)} \] (33)

which are similar to (4) and (5). The expected second-period profit for the CM under this condition is then

\[ I_{II}(r,m,a)(a,0) = \frac{K-W_{m1}-W_{m1}}{2\theta} \] (34)

In period 1, anticipating the threshold-type policy of the supplier, the CM holds the belief that the supplier will choose to accept with probability \( \Phi_m(\hat{c}) \) and to reject with probability \( 1-\Phi_m(\hat{c}) \). Thus, if the CM chooses to reject in period 1, then its expected total discounted profit in the two periods can be expressed as

\[ I_{II}(r,m,a)(a,0) = [1-\Phi_m(\hat{c})] \eta \] (35)

Case 2: The CM accepts the contract in period 1.

In this case, if the supplier chooses \( x_s = a \), then the OEM ends the negotiation processes with both the CM and the supplier and offers them the same prices in period 2. Thus,

\[ I_{II}(a,m,a)(a,0) = I_{II}(a,m,a)(a,0) = \frac{K-W_{m1}-W_{m1}}{2\theta} \] (36)

If the supplier chooses \( x_s = r \), then \( I_{II}(a,m,a)(a,0) = 0 \). The CM gets the same price in the second period, i.e., \( W_m(z(r,a) = W_m \). The supplier gets a higher price, \( w_s(z(r,a) = \). Therefore, the expected second-period profit in the two periods can be expressed as

\[ I_{II}(r,m,a)(a,0) \]

(37)

Here again, the CM holds the belief that the supplier will choose to accept with probability \( \Phi_m(\hat{c}) \) and to reject with probability \( 1-\Phi_m(\hat{c}) \). Thus, if the CM chooses to accept in period 1, then its expected total discounted profit in the two periods is

\[ I_{II}(a,m,a)(a,0) \]
The above inequality follows from the fact that $\omega_{m2}(r,a) - \hat{c}_m > \omega_{m1} - \hat{c}_m$ and $\omega_{m2}(r,r) - \hat{c}_m > \omega_{m2} - \hat{c}_m$, along with (19). Hence, $\Pi_m(r|\hat{c}_m,\hat{c}_s) > \Pi_m(a|\hat{c}_m,\hat{c}_s)$.

Thus, as $\hat{c}_s$ increases to $\hat{c}_{su}$, $\hat{c}_m$ should increase to a larger value $\hat{c}_{su}$, such that $\Pi_m(r|\hat{c}_{su},\hat{c}_s) = \Pi_m(a|\hat{c}_{su},\hat{c}_s)$. Thus, part 2 is proved. □

Part 3 follows from Tarski's fixed point theorem.

References


