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Başak Kalkancı, Feryal Erhun,

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Pricing Games and Impact of Private Demand Information in Decentralized Assembly Systems

Başak Kalkancı
Engineering Systems Division, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, kalkanci@mit.edu

Feryal Erhun
Management Science and Engineering Department, Stanford University, Stanford, California 94305, ferhun@stanford.edu

This paper analyzes decentralized assembly systems under asymmetric demand information and sequential contracting. We reveal new insights on the value of contract type (price-only versus complex), demand information (complete versus asymmetric), and contract sequence (first mover versus second mover) to different players. Our results for the basic model show the following: (1) Complex contracts increase the suppliers' aggregate profit; however, individual suppliers do not necessarily benefit from a complex contracting equilibrium. We identify the conditions under which each supplier benefits from such an equilibrium. (2) Eliminating information asymmetry is not always beneficial for the suppliers because obtaining information might bring only marginal value and hence might not be realistically justified. Furthermore, a downstream supplier might prefer information asymmetry to complete information, especially when demand variability is moderate. (3) Unless there is a high demand risk, the first-mover advantage is prevalent when the assembler is a price-taker.

We extend our basic model to analyze two additional scenarios. First, we study cases where the suppliers may offer contracts of different complexity. Beyond enriching our understanding of contract choice in decentralized assembly systems, such variations enhance the analysis beyond the standard methodology of principal-agent models and utilize solution techniques from optimal control. Second, we analyze the situation where the suppliers may possess different levels of information on demand under complex contracts. We show that an upstream supplier always benefits from a downstream supplier's superior information. However, the additional information might decrease the downstream supplier's profit, especially when the forecast variability is low compared to the total demand variability in the system. Our results for the basic model and its extensions confirm that studying interactions between suppliers, specifically under different contract types and information structures, in assembly systems presents rich opportunities for future research.

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1. Introduction

Today's global supply chains are mostly characterized by *decentralized assembly systems*, in which several suppliers produce components and deliver them to a single manufacturer, who assembles these components to produce the final product. This decentralization has many advantages, including lower production costs and faster time-to-market. However, it also has several disadvantages, including loss of control of supply chain functionalities and inefficiencies due to incentive issues among different players.

A common cause of these incentive issues is the information asymmetry among supply chain partners regarding demand forecasts. Compared to their suppliers, manufacturers often possess better end-product demand information as they are closer to the end-consumer market. They might use this additional information strategically, sometimes to the extent of misrepresenting it to their suppliers. For example, personal computer and electronics manufacturers often submit "phantom orders" to guarantee a higher component capacity from their suppliers (Lee et al. 1997). Such incentive issues have been analyzed in the operations management literature; e.g., Corbett et al. (2004) study asymmetric buyer-cost information, Cachon and Zhang (2006) asymmetric supplier-cost information, and Özer and Wei (2006) asymmetric forecast information. However, the existing literature limits itself to contractual agreements between a *single* supplier and a manufacturer, in isolation of the manufacturer's contracts with her other suppliers.

Single-supplier, single-manufacturer results under asymmetric demand information are not immediately applicable to assembly systems due to *interactions among suppliers*. Even if a supplier can create a contractual agreement that accounts for information asymmetry, the performance of such an agreement depends heavily on the manufacturer's contracts with her other suppliers, because the suppliers produce perfectly complementary components in the assembly system. Furthermore, the suppliers' objectives are different and often create conflict. This conflict generates indirect competition between the suppliers, because each supplier would like to maintain or increase his margin from the shared manufacturer. Hence, the existence of other suppliers should be an essential part of a supplier's own decision-making process. Our goal is to understand the dynamics of this decision-making process under sequential contracting and to analyze the interactions of the suppliers facing a downstream manufacturer with private demand information. To the best of our knowledge, despite their relevance, such interactions have not yet been examined in the operations management literature.

We study a simple decentralized assembly system with two suppliers and a single manufacturer who is better informed about demand relative to the suppliers. Each supplier offers a contract to the manufacturer to determine the quantity of and payment for components to be delivered. A traditional contracting approach in this setting applies *complex contracts* under which each supplier specifies a detailed total payment scheme for each quantity that the manufacturer may choose to procure (Bolton and Dewatripont 2005). This contract structure performs effectively due to its ability to differentiate manufacturers with different demand forecasts. However, such contracts suffer in terms of implementability due to their complex nature (Holmström and Milgrom 1987). Thus, we also study *price-only contracts*, which are not only the simplest contracts conceivable because they require only a single parameter (the wholesale price) (Lariviere and Porteus 2001) but also are widely used for a range of products and services, even for complex and expensive products such as components for airplanes (Boeing 2008). By comparing these two contract extremes, we explore the *value of contract complexity* to different players.[1] We also study cases where the suppliers may offer contracts of different complexity. We are not aware of any other studies in the literature that examine such variations. Beyond enriching our understanding of contract choice in decentralized assembly systems, such variations extend the analysis beyond the standard methodology of principal-agent models and necessitate solution techniques from optimal control.

There is a growing literature on decentralized assembly systems (Wang and Gerchak 2003; Gerchak and Wang 2004; Wang et al. 2004; Carr and Karmarkar 2005; Feng and Zhang 2005; Bernstein and DeCroix 2006; Wang 2006; Zhang 2006; Jiang and Wang 2007, 2010; Fang et al. 2008; Granot and Yin 2008; Zhang et al. 2008; Nagarajan and Sošić 2009). As comprehensive as it is, this literature does not address incentive issues due to asymmetric information, which has been identified as a limitation (Wang and Gerchak 2003, Gerchak and Wang 2004, Wang et al. 2004). We show how and why the current results extend or fail when the suppliers have the same prior asymmetric information, and then we use these results to characterize the *value of information*. In addition, we study the situation where the suppliers might possess different levels of information.

The suppliers' contracting sequence is another important criterion in assembly systems under sequential contracting. The suppliers' decisions, hence their profits, depend whether they move first or second. By comparing their profits, we explore the *value of contract sequence* for the suppliers and the potential first- and second-mover advantages in decentralized assembly systems under information asymmetry. In addition, by comparing sequential contracting with simultaneous contracting (which is commonly studied in the literature on decentralized assembly systems), we provide additional insights on the effect of the suppliers' information on each other's contracts.[2]

Our setting under complex contracts lends itself naturally to the use of the *common agency framework*, where several principals (suppliers) contract with the same agent (manufacturer) to influence her decision-making. The common agency framework was developed in the economics literature; see Martimort (2007) for an extensive review. Previous results in this literature do not consider any bounds on the equilibrium quantities. However, studying these bounds corresponds to many realistic business scenarios and provides valuable information in understanding the impact of demand uncertainties on the suppliers' and the manufacturer's decisions. Therefore, we extend the current common agency literature by considering these cases. We observe that selling at the lower bound of the demand distribution provides the first-mover supplier an "outside" option to compare his profit with when he is designing his contract. This is true particularly when the demand variability is high. We also investigate the value of contract complexity, which to our knowledge has not been assessed before under common agency literature despite being recognized as important in economics (Wilson 1993, Laffont and Martimort 2002).

The remainder of this paper is organized as follows. We explain our assembly system in detail and list our assumptions in §2. We characterize the equilibrium under complex and simple contracts in §3. We discuss these decisions and compare our results with the complete-information setting. In §4, we theoretically and numerically analyze the value of eliminating system inefficiencies by characterizing the value of contract complexity, the value of information and the value of contract sequence with respect to the parameters of the business environment. In §5, we extend our analysis to cases where the suppliers might use contracts of different complexity and where they might possess different levels of information. Finally, we conclude in §6 with a discussion of insights from our results. An electronic companion to this paper is available as part of the online version at http://dx.doi.org/10.1287/opre.1120.1084. For completeness, we provide several results on simultaneous contracting in an online appendix. These results extend the current literature to our problem setting.

Proofs of all results are presented in an online appendix. We use $E_x[\cdot]$ to denote the expectation over the random variable x and the subscript $-i$ to denote the supplier opposing supplier i. The first derivative of a function $f(\cdot)$ is denoted $f'(\cdot)$. We use the terms "increasing" and "decreasing" in the weak sense; i.e., they are equivalent to "nondecreasing" and "nonincreasing," respectively.

2. Model Details

We study an assembly system consisting of a single manufacturer (M) and two suppliers (S1 and S2). The suppliers produce perfectly complementary components and incur unit production costs of $k_1 > 0$ and $k_2 > 0$, respectively. The manufacturer assembles one unit of each of these components in her final product and sells the final product to end-consumers at an exogenously specified market price of p. We define the suppliers' total cost normalized by the market price as $k := (k_1 + k_2)/p$. We normalize the manufacturer's assembly cost to zero and we restrict our attention to the situation where production is profitable; i.e., $0 < k < 1$. Any unmet demand is lost without a stock-out penalty. There is no salvage value for leftover products.

We focus on a one-time interaction between the manufacturer and the suppliers. The manufacturer and each supplier contract on the production quantity and the manufacturer's corresponding payment to that supplier. Then, the suppliers produce their respective contracted quantities, deliver them to the manufacturer and receive their payment *before* the end-consumer demand is realized. This process is complicated by the fact that by being closer to the end-consumer market, the manufacturer is better informed about the demand, which we model as

$$Demand = \mu + \alpha,$$

where μ is the demand forecast and α is a random fluctuation. The demand forecast (which we also refer to as the manufacturer's *type*) is the manufacturer's private information at the time of contracting. The suppliers do not know μ with certainty but do know its distribution. We represent the probability density function (pdf) of this common prior distribution as $g(\mu)$ and the cumulative distribution function (cdf) as $G(\mu)$, which has finite and positive support $\Lambda := [\underline{\mu}, \bar{\mu}]$. The mean and standard deviation of μ are μ_0 and σ_0, respectively. Neither the manufacturer nor the suppliers observe the value of α during contracting. This makes ours a newsvendor setting similar to that in Gerchak and Wang (2004) and Granot and Yin (2008). We assume that α follows a continuous distribution with cdf $\Phi(\cdot)$ and pdf $\phi(\cdot)$. The mean and standard deviation of α are 0 and σ_1, respectively. We bound α below by $\underline{\alpha}$, which enables us to study markets with a minimum guaranteed size. For clarity of exposition, we define a as the ratio of the forecast variability to the overall demand variability in the supply chain (i.e., $a := \sigma_0/\sqrt{\sigma_0^2 + \sigma_1^2}$) and c_v as the coefficient of variation of the consumer demand distribution (i.e., $c_v := \sqrt{\sigma_0^2 + \sigma_1^2}/\mu_0$).

We define the hazard rates of α and μ as $h_\phi(\cdot) := \phi(\cdot)/(1 - \Phi(\cdot))$ and $h_g(\cdot) := g(\cdot)/(1 - G(\cdot))$, respectively. For clarity of exposition, we also define $\bar{h}_g(\cdot) := h_g^{-1}(\cdot) = (1 - G(\cdot))/g(\cdot)$. In the analysis of complex contracts and principal-agent models, it is common to assume that $h_\phi(\cdot)$ and $h_g(\cdot)$ are increasing. The assumption that $h_g(\cdot)$ is increasing (e.g., Laffont and Tirole 1991, Martimort 2007) ensures that the manufacturer's order quantity is increasing with respect to her demand forecast. The assumption that $h_\phi(\cdot)$ is increasing (e.g., Özer and Wei 2006, Taylor and Xiao 2009) ensures that the supplier's objective is unimodal for each demand forecast. Many frequently used distributions have increasing hazard rates (IHRs), such as the uniform, normal, and exponential distributions (Bolton and Dewatripont 2005). To facilitate our analysis of sequential contracting, we assume that $h'_\phi(\cdot)$ and $\bar{h}'_g(\cdot)$ are increasing as well. This additional assumption guarantees that the relationships above are propagated one level up the supply chain, and it is satisfied by many frequently used distributions, such as the uniform, normal, and exponential distributions. Moreover, we assume that $\underline{\alpha} + \underline{\mu} \geqslant 0$, which ensures that the demand will be nonnegative even for the lowest demand forecast. Finally, $h_\phi(\cdot)$, $\bar{h}_g(\cdot)$, $\Phi(\cdot)$ and $G(\cdot)$ are assumed to be twice differentiable.

Our goal in this paper is to provide a comprehensive analysis of the assembly systems under information asymmetry and sequential contracting. Next, we study complex and simple contracts to characterize the inherent inefficiencies in an assembly system and the value of eliminating them.

3. Analysis of Sequential Contracting

In our model setting, S2 offers his contract after observing S1's contract, and then the manufacturer chooses her procurement quantities from both suppliers. We call S1 (who moves first) the upstream supplier and S2 (who moves second) the downstream supplier.[3] First, we analyze the equilibrium under complex and simple contracts. Then we state our observations.

3.1. Complex Contracts

Recall that under complex contracts each supplier specifies a detailed total payment scheme for each quantity that the manufacturer may choose to procure (Bolton and Dewatripont 2005). Using Martimort and Stole's (2002) "delegation principle"[4] in common agency games and without loss of generality, we restrict our attention to the nonlinear pricing game between the suppliers. In this game, the suppliers offer nonlinear pricing schemes $t_i(y)$, $i = 1, 2$, which specify the total payments to each supplier when the manufacturer orders y units. After observing the contracts, the manufacturer chooses quantities and makes the corresponding payments. Assuming that each supplier's total payment is strictly increasing in procurement quantity (which is indeed the case, as we later verify), the manufacturer does not have an incentive to choose different quantities from different suppliers. Thus, the manufacturer's profit maximization program given the contracts can be formulated as

$$\max_{y}\{pE_\alpha[\min(\mu+\alpha, y)]-t_1(y)-t_2(y)\}. \quad (1)$$

To avoid inefficient equilibria where the suppliers fail to coordinate on the prices, we restrict our attention to contracts such that $k_i \leqslant t_i'(y) \leqslant p-k_{-i}$, where $i=1,2$. These conditions guarantee that the suppliers have sufficient margin to cover their costs.

Next, using the sequential nature of our problem, we identify S2's best response to a payment scheme proposed by S1. Using the revelation principle (Laffont and Martimort 2002), we can restrict our attention to the class of truthtelling menu of contracts in the form of $\{T_2(\mu), y_2(\mu)\}$ where $T_2(\mu)$ is the total payment to S2 from the manufacturer with type μ and $y_2(\mu)$ is a type μ manufacturer's procurement quantity for all $\mu\in[\underline{\mu},\bar{\mu}]$. S2's problem can then be defined as

$$\max_{t_2(\cdot),\, y_2(\cdot)} \int_{\underline{\mu}}^{\bar{\mu}} (T_2(\mu)-k_2y_2(\mu))g(\mu)\,d\mu, \quad (2)$$

subject to
$$pE_\alpha[\min(\mu+\alpha, y_2(\mu))] - T_2(\mu)-t_1(y_2(\mu))\geqslant 0 \quad \forall \mu\in[\underline{\mu},\bar{\mu}],$$
$$pE_\alpha[\min(\mu+\alpha, y_2(\mu))]-T_2(\mu)-t_1(y_2(\mu)) \geqslant pE_\alpha[\min(\mu+\alpha, y_2(\hat{\mu}))]-T_2(\hat{\mu})-t_1(y_2(\hat{\mu})) \quad \forall\mu\in[\underline{\mu},\bar{\mu}].$$

S2's objective is to maximize his expected profit, which is equal to the total payment to him from the manufacturer with type μ, less the production cost. The constraints are the individual rationality (IR) and incentive compatibility (IC) constraints, respectively. The IR constraints ensure that for any type, the manufacturer will make as much expected profit as she could without participating in any contract. The IC constraints reflect the fact that a manufacturer with type μ prefers to choose $\{T_2(\mu), y_2(\mu)\}$ over any other $\{T_2(\hat{\mu}), y_2(\hat{\mu})\}$, which ensures truthtelling. Once S2's best response is characterized, S1's problem can be formulated using backward induction. In particular, S1's objective is given by

$$\max_{y_2^*(\cdot)}\int_{\underline{\mu}}^{\bar{\mu}}(t_1(y_2^*(\mu))-k_1y_2^*(\mu))g(\mu)\,d\mu$$
$$=\int_{\underline{\mu}}^{\bar{\mu}}(pE_\alpha[\min(\mu+\alpha, y_2^*(\mu))]-\bar{h}_g(\mu)p\Phi(y_2^*(\mu)-\mu) - (k_1+k_2)y_2^*(\mu)-\Pi_2(\mu))g(\mu)\,d\mu,$$

where $\Pi_2(\mu)$ is S2's valuation of a type μ manufacturer, i.e., S2's profit less the monetary incentive that he needs to give the manufacturer to guarantee her acceptance of the contract that he offers (i.e., the "information rent" that he must pay), as identified by solving the S2's best-response problem above. The closed-form expression for this term is in the online appendix.

We first analyze complex contracts under the complete information benchmark. Under this setting, $\mu=\underline{\mu}=\bar{\mu}$, and each supplier's problem has only one constraint, which is a binding IR constraint (i.e., the manufacturer's expected profit is zero). Our first proposition characterizes the equilibrium under this benchmark.

Proposition 1. *Under complex contracts and complete information, the manufacturer procures the first-best quantity*

$$q_{FB}^*+\mu=\Phi^{-1}\left(\frac{p-k_1-k_2}{p}\right)+\mu.$$

*S*1 *captures the total expected system profit, while S*2 *and M make zero expected profits.*

When the suppliers know the manufacturer's demand forecast and use complex contracts, they capture the expected revenue of the manufacturer through the payments. Thus, inefficiencies due to double marginalization are eliminated. In addition, because the manufacturer chooses the quantities (instead of the suppliers dictating them), the quantities from both suppliers will be identical and hence the suppliers' decisions will be coordinated. Thus, inefficiencies due to horizontal decentralization are also eliminated. As a result, the suppliers sell the first-best quantity (which is the systemwide optimal procurement quantity). This scenario heavily favors the suppliers because the manufacturer makes zero expected profit. Furthermore, there is a strong first-mover advantage: S1 captures all of S2's profit as well when he moves first.

To analyze the equilibrium under asymmetric information, let $\Upsilon_{\text{seq}}(y)$ be the derivative of S1's objective function with respect to the quantity at type μ in the region where $y>\mu+\underline{\alpha}$:

$$\Upsilon_{\text{seq}}(y)=-(k_1+k_2)+p(1-\Phi(y))\big[(1-\bar{h}_g(\mu)h_\phi(y))^2 +\bar{h}_g(\mu)\bar{h}_g'(\mu)h_\phi(y)-\bar{h}_g(\mu)^2h_\phi'(y)\big]. \quad (3)$$

In addition, we define $\kappa_1(\mu)$ as the value of S1's objective function if his sales quantity is strictly above $\mu+\underline{\alpha}$ and $\kappa_2(\mu)$ as the value of S1's objective function if his sales quantity is $\mu+\underline{\alpha}$. The closed-form expressions for all these terms are in the online appendix. The next theorem presents an equilibrium under complex contracts.

Theorem 1 (Complex Contracts). *A manufacturer of type μ buys the quantity $y_{\text{seq}}(\mu)$ where*

$$y_{\text{seq}}(\mu)=\begin{cases}\mu+\underline{\alpha} & \text{if } \Upsilon_{\text{seq}}(\mu+\underline{\alpha})\leqslant 0 \\ & \quad \text{or } \kappa_2(\mu)>\kappa_1(\mu),\\ \{y\colon \Upsilon_{\text{seq}}(y)=0\} & \text{otherwise}.\end{cases}$$

The suppliers' payment schemes satisfy the following conditions:

$$\begin{aligned} t(y_{\text{seq}}(\mu)) &= t_1(y_{\text{seq}}(\mu)) + t_2(y_{\text{seq}}(\mu)) \\ &= pE_\alpha[\min(\mu+\alpha, y_{\text{seq}}(\mu))] \\ &\quad - \int_{\underline{\mu}}^{\mu} p\Phi(y_{\text{seq}}(\tau)-\tau)\,d\tau, \end{aligned}$$

$$\begin{aligned} t_1(y_{\text{seq}}(\mu)) &= pE_\alpha[\min(\mu+\alpha, y_{\text{seq}}(\mu))] \\ &\quad - \bar{h}_g(\mu)p\Phi(y_{\text{seq}}(\mu)-\mu) - k_2 y_{\text{seq}}(\mu) - \Pi_2(\mu). \end{aligned}$$

When the suppliers have limited information on the manufacturer's demand forecast, asking the manufacturer for her forecast would lead to a bias because the suppliers extract the manufacturer's total profit when they know her demand forecast, as we observe in Proposition 1. That is, the manufacturer would be better off declaring that her forecast is low and buying a quantity that is intended for a manufacturer with a low demand forecast (see Proposition EC.1 in the online appendix). Because the suppliers are aware of this incentive problem, they cannot base their decisions on any information shared by the manufacturer. Instead, they differentiate among manufacturers with different forecasts and make sure that manufacturers with higher demand forecasts do not buy lower quantities. To enable the differentiation, the suppliers provide discounts to a manufacturer with higher forecast and increase her safety stock.[5] This procurement structure is fundamentally different than one would expect. Intuitively, the manufacturer's safety stock should increase with the coefficient of variation, favoring manufacturers with low forecasts.[6] We conclude that, under asymmetric information, the suppliers' pricing decisions are affected more by incentive concerns than by concerns due to the uncertainty in demand.

Note that S1's equilibrium payment is a function of S2's valuation; that is, the supplier interactions are important in determining the equilibrium (justifying our arguments in §1). Not only should the suppliers incentivize manufacturers with high demand forecasts to increase their quantities, but S1 must also incentivize S2, as shown by our next proposition.

Proposition 2. *In an equilibrium,* $\Pi_2(\mu) = 0$ *for* $\underline{\mu} \leqslant \mu < \mu'$ *and is strictly increasing in* μ *when* $\mu \geqslant \mu'$, *where* $\mu' = \sup\{\mu\colon y_{\text{seq}}(\mu) = \mu + \underline{\alpha}\}$.

When S1 wants to sell more to a manufacturer with a high forecast, he must ensure that the manufacturer is able to pay S2 so that S2 will also sell a higher quantity. If S1 fails to do so, S2 will prefer to sell a lower quantity. Thus, an aggressive S1 might actually decrease his own profit by alienating S2 and consequently decreasing the quantity he is able to sell. In other words, S2 poses a "threat" to S1, and as a result actually *benefits* from the manufacturer's private information under complex contracts.

3.2. Simple Contracts

Under simple contracts, the manufacturer's and the suppliers' problems can be formulated similar to the ones under complex contracts; however, supplier i simply charges a single wholesale price w_i for each unit the manufacturer procures. Let $\Gamma_{\text{seq}}(q)$ be the derivative of S1's objective function with respect to the quantity at type $E[\mu]$ in the region where $y > E[\mu] + \underline{\alpha}$:

$$\begin{aligned} \Gamma_{\text{seq}}(q) = -(k_1+k_2) + p(1-\Phi(q))\big[(1-h_\phi(q)(q+E[\mu]))^2 \\ - h_\phi(q)(q+E[\mu]) - h'_\phi(q)(q+E[\mu])^2\big]. \qquad (4) \end{aligned}$$

In addition, we define $\mathfrak{L}_1$ as S1's profit if his average sales quantity is strictly above $E[\mu]+\underline{\alpha}$, and $\mathfrak{L}_2$ as S1's profit if his average sales quantity is $E[\mu]+\underline{\alpha}$. The closed forms of these expressions are provided in the online appendix. The following theorem characterizes the quantities for each type of manufacturer and wholesale prices of the suppliers.

Theorem 2 (Simple Contracts). *A manufacturer of type* μ *procures* $q(\mu) = \mu + q^*_{\text{seq}}$ *units, where*

$$q^*_{\text{seq}} = \begin{cases} \underline{\alpha} & \text{if } \Gamma_{\text{seq}}(\underline{\alpha}) \leqslant 0 \text{ or } \mathfrak{L}_2 > \mathfrak{L}_1, \\ \{q\colon \Gamma_{\text{seq}}[q] = 0\} & \text{otherwise}. \end{cases}$$

The suppliers' wholesale prices satisfy the following conditions:

1. *The total wholesale price satisfies* $w = w_1 + w_2 = p(1-\Phi(q^*_{\text{seq}}))$.
2. (a) *If* $q^*_{\text{seq}} = \underline{\alpha}$, $w_2 - k_2 = 0$, *and* $w_1 = p - w_2$. (b) *If* $q^*_{\text{seq}} > \underline{\alpha}$, $w_2 - k_2 = (q^*_{\text{seq}} + E[\mu])p\phi(q^*_{\text{seq}})$, *and* $w_1 = w - w_2$.

If the suppliers knew the manufacturer's forecast and used simple contracts, they would charge a higher wholesale price to a manufacturer with a higher forecast.[7] Therefore, the manufacturer would be better off declaring that her forecast is low. Similar to the equilibrium with complex contracts, the suppliers cannot rely on any information shared by the manufacturer in their decision making, and they use only their estimate of the demand forecast (which is its expectation μ_0). Thus, the complete-information case is a degenerate case of asymmetric information, and our conclusions under simple contracts in the following sections apply to the complete-information setting as well.

Corollary 1. *Under simple contracts and complete information, the manufacturer's procurement quantity and the suppliers' wholesale prices can be found by replacing* $E[\mu]$ *in Theorem 2 with* μ.

3.3. Complex Contracts vs. Simple Contracts

As is the case with settings under asymmetric information, under both contracts the quantity sold to each type of manufacturer is less than the systemwide optimal quantity in our assembly system. This can be explained with three types of inefficiencies: information asymmetry, horizontal decentralization, and double marginalization. When there is *information asymmetry*, the suppliers must pay an information rent to the manufacturer. Under complex contracts, to decrease the information rent received by a manufacturer with a higher forecast (manufacturers with higher forecasts are the more valuable types of the manufacturer for the suppliers), the suppliers reduce the quantities of all but the manufacturer with the highest demand forecast ($\bar{\mu}$) below the first-best, introducing inefficiencies to the system. Under simple contracts, the types below μ_0 end up paying a higher wholesale price (and procuring a lower quantity) than they would under complete information due to information rent considerations. Furthermore, perfect complementarity imposes a negative externality between decentralized suppliers. A supplier who intends to increase his expected profit by selling more can only *partially* capture the increase in the manufacturer's expected profit because the manufacturer must buy more from the other supplier as well, and hence channels some of the increase in her expected profit to that supplier. Thus, quantities under both contracts are further reduced due to *horizontal decentralization*. Finally, the suppliers cannot extract the total system profit with simple contracts, even under the complete-information case; thus the assembly system with simple contracts suffers from *double marginalization* as well.

Due to the newsvendor setting, the procurement quantity of the manufacturer consists of her demand forecast and a safety stock to cover demand fluctuation regardless of the contract used.[8] Furthermore, the safety stock term depends *only* on the aggregate production cost of the suppliers, as evidenced by $\Upsilon_{\text{seq}}(y)$ and $\Gamma_{\text{seq}}(q)$ (Equations (3) and (4)). Therefore, the split of the suppliers' individual costs does not play a role in the quantity procured by the manufacturer. A supplier's profit is determined solely by his position during contracting (i.e., whether he is the first or second to offer his contract) and is independent of how the individual costs are allocated between the suppliers. These observations extend previous results in the assembly literature (Gerchak and Wang 2004, Wang 2006, Jiang and Wang 2007, Granot and Yin 2008) to the asymmetric demand information setting and validate that these results are robust with respect to the contract and information structures.

4. Contract Complexity, Information, and Contracting Sequence

In this section, we compare the suppliers' profits under the models studied §3 to better understand relative preferences of contract types, information, and contracting sequences. Our results are mostly analytical; however, we also rely on numerical analysis. For the parameter values that we use in the numerical analysis, we refer the reader to §A in the appendix.

4.1. The Value of Contract Complexity

In a single-supplier, single-manufacturer supply chain, it is well known that the supplier can get at least as much expected profit from writing a complex contract as from a simple one. However, the comparison of simple and complex contracting equilibrium is not trivial in an assembly system due to suppliers' interaction. The comparison is affected by the properties of both forecast distribution and fluctuation distribution and is quite involved (as seen in Theorems 1 and 2). In many real-life situations, companies might know only a range for the demand forecast but nothing more, which can be represented with a uniform distribution. Once the forecast is determined, the variation in the actual customer demand around the forecast can be realistically modeled by a normal distribution. We limit ourselves to these distributions in Proposition 3, in which we provide a comparison of S1's, S2's, and the suppliers' total profits under simple and complex contracting equilibria.

Proposition 3. *If μ and α belong to location-scale families, the comparison of profits under interior simple and complex contracting equilibria depend only on the parameters a, k, and c_v.*

Numerical Observation 1. *If $\mu \sim U[\underline{\mu}, \bar{\mu}]$ and $\alpha \sim Normal(0, \sigma_1)$, the following hold:*

(i) *S1 is always better off under the complex contracting equilibrium.*

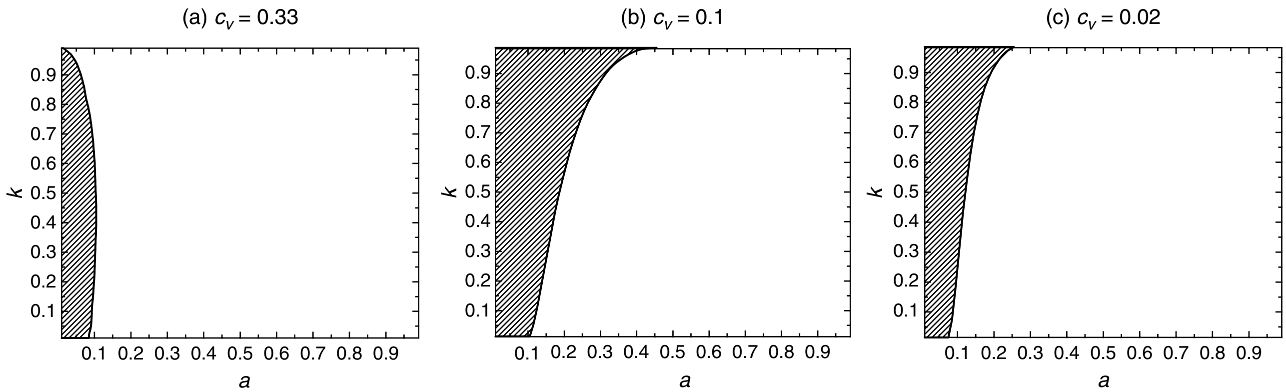
(ii) *For a given k and c_v, S2 is worse off under the complex contracting equilibrium when $a \leqslant \bar{a}_c$ and better off under the complex contracting equilibrium otherwise.*

(iii) *Suppliers, as a whole, are better off under the complex contracting equilibrium.*

The advantage of using a complex contract is its ability to distinguish between manufacturers with different demand forecasts and to eliminate double marginalization. Therefore, each supplier's best response to a given contract by the other supplier would be a complex contract (see the discussions in §5). However, a complex contracting equilibrium can substantially increase one supplier's *contracting power* at the expense of the other. As a result, it is possible to find settings where one supplier is worse off in an equilibrium where the suppliers write complex contracts.

For S2, we observe a threshold structure (Numerical Observation 1(ii) and Figure 1): when the ratio of the forecast variability to the total demand variability is below (above) a certain level, S2 is worse (better) off under a complex contracting equilibrium. This ratio is low either when demand fluctuation variability is relatively high or when forecast variability is relatively low. When demand fluctuation variability is high, S1 must leave higher profits to the lower levels of the supply chain. Simple contracts, which do not provide much flexibility to S1, require S1 to leave high profits to S2 and the manufacturer, which benefits S2. Thus, *despite leading to inefficiencies, simple contracts might be preferred by the downstream supplier,*

Figure 1. Comparison of S2's expected profits under complex and simple contracting equilibria.



Note. S2 is strictly better off with simple contracting equilibrium in the shaded regions of each figure and better off with complex contracting equilibrium otherwise.

especially when the demand variability is high. When the forecast variability is low, the environment is similar to a complete-information setting in which S1 can fully capture S2's profit under complex contracts (Proposition 1). Thus, *the downstream supplier is also better off with simple contracting equilibrium when there is low variability in forecasts.*

The change in the threshold value $\bar{a}_c$ with respect to c_v provides interesting observations as well. First, consider the case where $c_v = 0$; i.e., there is no variability in the system. In this case, the upstream supplier S1 can extract the total expected profit even with a simple contract; i.e., S2's profits are the same under these two contracts. As c_v increases, S1 has to pay rent to S2 and the manufacturer. As discussed above, S1's flexibility is lower under simple contracts; therefore, the region where S2 strictly prefers simple contracts starts to expand. Next, consider the case where c_v is very high. As demand variability is quite high in this situation, the suppliers must compensate the manufacturer accordingly. It is important for the suppliers to employ complex contracts and extract as much profit as possible. Unless a is low, S2 thus prefers complex contracts as well; that is, the region where S2 prefers simple contracts starts to shrink for larger values of c_v. For intermediate values of c_v, simple contracts provide a perfect balance for S2; the suppliers can extract profits overall, and S2 can retain a better share for himself with simple contracts, even for relatively higher values of a, thus the region where S2 prefers simple contracts reaches its maximum size.[9]

For low to medium values of k, the threshold value $\bar{a}_c$ is not very sensitive to k. However, for larger values of k, we observe interesting dynamics. Because the suppliers' aggregate profit margin is low, S1 will squeeze S2 and the manufacturer more with complex contracts. That is why for low to medium c_v values, the threshold increases with k. When c_v is high, on the other hand, it is once again important for the suppliers to employ complex contracts and extract as much profit as possible from the manufacturer; thus the threshold decreases with k.

Complex contracts are known to be difficult to write and administer. Making the (often costly) effort to use such contracts is justified only when their value is sufficiently high. Therefore, identifying the conditions under which implementing complex contracts pays off is crucial. Proposition 4 shows that the value of using complex contracts for the suppliers, as a whole, decreases with demand forecast variability.

Proposition 4. *When μ and α come from location-scale families,*

(i) *suppliers' profits are independent of demand forecast variability under simple contracts*; *and*

(ii) *suppliers' total profit decreases with the demand forecast variability under complex contracts.*

When the variability of the demand forecast is very low, the situation is similar to a complete-information setting. Because a complex contract eliminates double marginalization, in this setting the suppliers can extract all profit from the manufacturer. However, when the forecast is highly variable, the suppliers are forced to pay higher information rents to the manufacturer, and they have to significantly reduce the quantities for a manufacturer with a lower demand forecast. On average, the quantities that the suppliers sell and the suppliers' aggregate profit are reduced (Proposition 4(ii)). The suppliers' decisions and expected profits do not depend on the demand forecast variability under simple contracts (Proposition 4(i)). Therefore, the gap between simple and complex contracts closes as the variability of the demand forecast increases.

We rely on numerical methods to examine the effect of other business parameters on the value of complex contracts. Table 1 quantifies the value of using complex contracts with respect to the variability of demand fluctuation and the suppliers' margin. We observe that the value of a complex contract is high when the variability of the demand fluctuation and the margin of the suppliers are high. When the variability of the demand fluctuation is high, the manufacturer faces a higher demand risk. Providing flexibility

Table 1. Percentage gain in the suppliers' aggregate profit from using complex contracts.

Parameters	Average	Maximum
Demand fluctuation		
$\sigma_1 = 2$	0.8	1.5
$\sigma_1 = 30$	15	36
$\sigma_1 = 70$	34	79
Forecast variability		
$\underline{\mu} = 100$ (high)	6.4	18
$\underline{\mu} = 180$ (low)	33	79
Margin		
$p - (k_1 + k_2) = 15$	18	79
$p - (k_1 + k_2) = 5$	12	61

in terms of quantities and payments helps the manufacturer alleviate this risk partially, and hence increases the total quantity and the suppliers' aggregate profit. As the suppliers' margin decreases (i.e., the suppliers' aggregate cost increases), there is little room for complex contracts to achieve improvement over simple contracts. Hence, the value of a complex contract is higher when the margin of the suppliers is high.

The value of using complex contracts can be substantial; we observe instances with improvement as high as 79%. In the operations management literature, a number of papers (e.g., Cachon and Zhang 2006) show that simple contracts perform near optimally under suppliers' cost information asymmetry. We observe a larger gap between simple and complex contracts than reported in these studies because in our setting the party to which the contract is offered (the manufacturer) bears the demand risk. In this case, simple contracts are prone to double marginalization even when there is no information asymmetry (which is not the case for models with cost information asymmetry), and complex contracts can improve the efficiency considerably.

To summarize, all suppliers in an assembly system do not necessarily benefit from complex contracts. In fact, depending on the business conditions, the downstream supplier S2 might actually be worse off under a complex contracting equilibrium when demand fluctuation variability is high or when forecast variability is low. In addition, the overall value of complex contracts decreases as the variability of the demand forecast increases, the variability of the demand fluctuation decreases and the margin of the suppliers decreases. Given that complex contracts are known to be difficult to write and administer, the suppliers might prefer simple contracts in these situations. However, as the variability of the demand forecast decreases, the variability of the demand fluctuation increases or the margin of the suppliers increases, complex contracts become a viable option for the suppliers.

4.2. The Value of Information

In a single-supplier, single-manufacturer supply chain, it is well known that the supplier benefits from having more information on the manufacturer's demand. In an assembly system, the value of information is less clear due to the interaction of the suppliers. We now compare the suppliers' profits under complete and asymmetric information to assess the value of demand information.

Using Theorem 1 and Propositions 1 and 2, it is straightforward to conclude that under complex contracts S1 is always better off and S2 is worse off with complete information because S1 extracts the entire expected profits under complete information but has to pay rent to the manufacturer and S2 under asymmetric information. Next, we investigate the value of information under a simple contracting equilibrium.

Numerical Observation 2. *Under simple contracts, if* $\alpha \sim Normal(0, \sigma_1)$ *where* $\sigma_1 \leqslant \mu/3$, *the following hold*:

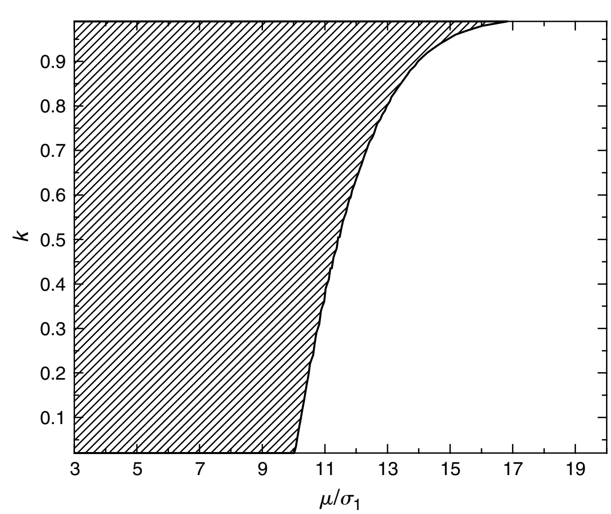
(i) *S1 is always better off with complete information.*

(ii) *For a given* k, *S2 is worse off with complete information when* $\mu/\sigma_1 \leqslant \bar{a}_i$ *and better off with complete information otherwise.*

(iii) *Suppliers, as a whole, are better off with complete information.*

S1 is always better off with complete information (Numerical Observation 2(i)); however, the downstream supplier S2 might prefer information asymmetry to complete information. Unlike the case with complex contracts, there are settings under which S2 is also better off with complete information (Numerical Observation 2(ii) and Figure 2). We observe that S2 can leverage information asymmetry only under considerable demand fluctuation variability σ_1. This is quite intuitive because under low values of σ_1, S1 does not have to leave much rent to downstream players and S2 would prefer not to share this small

Figure 2. Comparison of S2's expected profits under simple contracts with asymmetric and complete information.



Note. S2 is better off under asymmetric information in the shaded region and better off under complete information otherwise.

amount with the manufacturer. However, for moderate values of σ_1, S1 needs to leave a sizable rent to S2 as well as the manufacturer under information asymmetry, and S2 can retain a good portion of this rent for himself. Thus, S2 can manage his profits more effectively under asymmetric information. This result also indicates that information asymmetry is a problem for S1 only when there is demand fluctuation variability because otherwise, he can charge the market price and extract total profit of the system, even under simple contracts.

The suppliers can make efforts to better understand the demand. For example, many suppliers in the semiconductor industry subscribe to the services of market research companies, such as VLSI Research, to obtain market information, including their customers' demand and historic market share performance as well as demand forecasts. Hence, we also examine whether the value justifies the effort to obtain information on the manufacturer's demand forecast by considering the percentage gain in the suppliers' aggregate profit from information. The value of additional information to the suppliers' aggregate profit is low under simple contracts (on average 1% with a maximum of 7.5%) as opposed to under complex contracts (on average 33% with a maximum of 92%). Combining this observation with the earlier result, we conclude that especially the upstream supplier has a significant incentive to acquire additional demand information under complex contracts. The low value of information under simple contracts parallels the observation of Corbett et al. (2004). That is, contract complexity increases the additional value of better information. In other words, if the suppliers are committed to using simple contracts, then combining efforts to learn more about demand is only marginally beneficial to the suppliers.

To summarize, all suppliers in an assembly system do not necessarily benefit from additional information. In fact, depending on the types of contractual arrangements and the business conditions, the downstream supplier S2 might actually *lose* money when the manufacturer's demand forecast is shared by all parties in the supply chain.

4.3. The Value of Contracting Sequence

In this subsection, we elaborate on the comparison of supplier's profits. The suppliers' individual profits depend on whether they move first or second under both contract types. For simple contracts, we can further characterize the conditions leading to first- or second-mover advantages.

PROPOSITION 5. *Under simple contracts, the following relationships hold for S*1 *and S*2:

(i) *S*1 *has higher expected profit than S*2 *if* $\Phi(\cdot)$ *has IHR.*

(ii) *S*2 *can make higher expected profit than S*1 *if* $\Phi(\cdot)$ *has decreasing hazard rate (DHR).*

Under simple contracts, when it is highly probable that the demand will be low and the manufacturer will face high demand "risk," i.e., when $\Phi(\cdot)$ has DHR,[10] the suppliers must encourage the manufacturer to increase her quantity by leaving her enough margin. That is possible only if S1 first leaves sufficient margin for S2. Therefore, S1 might have to choose a smaller margin than S2 due to a threat by S2 of raising his own margin and reducing the manufacturer's order quantity. This, in turn, might decrease S1's profit margin. When $\Phi(\cdot)$ has IHR, on the other hand, S1 can claim a high margin, knowing that S2 will observe S1's unit price and will be forced to react by reducing his own price (Proposition EC.2 in the online appendix). Because our results do not depend on the distribution of the demand forecast under simple contracts, the comparisons in the above proposition continue to hold in a complete-information setting.

Yet another contract sequence comparison involves the suppliers' total profits under sequential contracting and simultaneous contracting. Recall that we provide several results on simultaneous contracting, including its equilibrium characterization, in the online appendix. The relative preference for sequential versus simultaneous contracting is not immediate. However, under distributional assumptions, we can find the following results.

PROPOSITION 6. (i) *Under complex contracts, if* $\mu \sim U[\underline{\mu}, \bar{\mu}]$, *then the suppliers' total profits and the manufacturer's profit are higher under simultaneous contracting.*[11]

(ii) *Under simple contracts, the suppliers' total profits and the manufacturer's profit are higher under simultaneous contracting if the distribution of demand fluctuation* $\Phi(\cdot)$ *has IHR. If* $\Phi(\cdot)$ *has DHR, then the suppliers' total profits and the manufacturer's profit might strictly be higher under sequential contracting.*

The intuition behind the result in Proposition 6(ii) directly follows from the discussion of Proposition 5. Interestingly, these two results contrast with previous results in the literature. Particularly, in the operations management literature regarding complete information, Wang (2006) and Jiang and Wang (2007) report that sequential contracting leads to higher total profits than simultaneous contracting. Furthermore, the authors observe second-mover advantages. However, in our newsvendor setting, either contracting sequence prevails and assembly systems may experience first- or second-mover advantages. The primary difference among all these models is the "utility" function of the suppliers, which is determined in part by the demand structure. Thus, we conclude that results on the contracting sequence are not robust to demand assumptions.

To summarize, assembly systems under simple contracts could experience first- or second-mover advantages depending on the demand structure and on the possibility of observing low demand. One should understand these impacts fully before reaching definitive conclusions. One important point to note is that S1 is always better off under sequential contracting than under simultaneous contracting even though he cannot always realize a first-mover advantage. This is because S1's optimal unit price under simultaneous contracting is feasible under sequential contracting, and therefore S1's profit under simultaneous contracting is a lower bound for his profit under sequential contracting. In other words, S1 is always better off revealing his unit price to S2.

5. Individual Contract and Information Preferences

In the previous sections, we have treated the contract types of the suppliers as exogenous. We have covered two extremes in terms of contract types (simple contracts vs. complex contracts) and demand information asymmetry (complete information versus asymmetric information with common beliefs) in terms of information structures. In this section, we relax our assumptions and analyze situations where the suppliers can rely on different levels of contract complexity or possess different levels of information. The results of this analysis allow us to capture individual contract and information preferences of the suppliers in situations where such decisions are endogenous.

5.1. When Suppliers Rely on Different Levels of Contract Complexity

In this section, we characterize contracts under settings where the suppliers use different levels of contract complexity. We first analyze sequential contracting where S1 uses a simple contract and S2 uses a complex contract. In this case, the manufacturer's and S2's problem can be formulated as the ones given in (1) and (2), respectively, with the following modification: $t_1(y_2(\mu)) = w_1 y_2(\mu)$ where w_1 is S1's wholesale price. Once S2's best-response quantity choice to S1's contract $(y_{sc}(\mu, w_1))$ is characterized, by backward induction, S1's problem can then be formulated as

$$\max_{k_1 \leqslant w_1 \leqslant p-k_2} \int_{\underline{\mu}}^{\bar{\mu}} (w_1 - k_1) y_{sc}(\mu, w_1) g(\mu)\, d\mu.$$

Theorem 3 characterizes the equilibrium contracts when S1 uses simple contracts and S2 uses complex contracts.

Theorem 3 (S1 Uses Simple Contracts and S2 Uses Complex Contracts). (i) *Under S2's best-response contract to w_1, a manufacturer of type μ buys*

$$y_{sc}(\mu, w_1) = \begin{cases} \mu + \underline{\alpha} & \text{if } \Upsilon_2(\mu + \underline{\alpha}, w_1) \leqslant 0, \\ \{y\colon \Upsilon_2(y, w_1) = 0\} & \text{otherwise,} \end{cases}$$

where

$$\Upsilon_2(\mu, w_1) = -(w_1 + k_2) + p(1 - \Phi(y_2 - \mu)) \cdot (1 - \bar{h}_g(\mu) h_\phi(y_2 - \mu)).$$

(ii) *S1's optimal wholesale price w_1 is either $p - k_2$ or satisfies*

$$\int_{\underline{\mu}}^{\bar{\mu}} \left((w_1^* - k_1) \frac{dy_{sc}(\mu, w_1^*)}{dw_1} + y_{sc}(\mu, w_1^*) \right) g(\mu)\, d\mu = 0,$$

where

$$\frac{dy_{sc}(\mu, w_1)}{dw_1} = \begin{cases} 0 & \text{if } y_{sc}(\mu, w_1) = \mu + \underline{\alpha}, \\ D(y_{sc}(\mu, w_1)) & \text{otherwise,} \end{cases}$$

and $D(y_{sc}(\mu, w_1))$ equals the inverse of

$$-p(1 - \Phi(y_{sc}(\mu, w_1) - \mu)) \cdot \big[h_\phi(y_{sc}(\mu, w_1) - \mu)(1 - \bar{h}_g(\mu) h_\phi(y_{sc}(\mu, w_1) - \mu)) + \bar{h}_g(\mu) h'_\phi(y_{sc}(\mu, w_1) - \mu) \big].$$

In this setting, the downstream supplier S2 essentially considers his own cost to be $k_2 + w_1$ and writes a contract similar to that of a single-principal, single-agent model with this adjusted cost. Similar to our discussions in §3.3, S2 provides discounts to a manufacturer with higher forecast and increases her safety stock in order to enable differentiation. The procurement quantity of the manufacturer consists of her demand forecast and a safety stock term to cover demand fluctuation. Once again, the split of the suppliers' individual costs does not play a role in the quantity procured by the manufacturer.

Next, we analyze a setting where S1 uses complex contracts and S2 uses simple contracts. Given the manufacturer's best-response quantity $y(\mu)$, S2's objective can be written as

$$\max_{w_2} \int_{\underline{\mu}}^{\bar{\mu}} (w_2 - k_2) y(\mu) g(\mu)\, d\mu.$$

As can be shown in the proof of Theorem 4 in the online appendix, the first-order condition of S2's problem is

$$(w_2^* - k_2) \int_{\underline{\mu}}^{\bar{\mu}} -\frac{y'(\mu)}{p\phi(y(\mu) - \mu)} g(\mu)\, d\mu + \int_{\underline{\mu}}^{\bar{\mu}} y(\mu) g(\mu)\, d\mu = 0. \tag{5}$$

By backward induction, S1's objective function can be written as[12]

$$\max_{y(\cdot)} \int_{\underline{\mu}}^{\bar{\mu}} (t_1(y(\mu)) - k_1 y(\mu)) g(\mu)\, d\mu = \max_{y(\cdot)} \left\{ \int_{\underline{\mu}}^{\bar{\mu}} p\big(E_\alpha[\min(\mu + \alpha, y(\mu))] - \bar{h}_g(\mu)\Phi(y(\mu) - \mu) - k y(\mu)\big)\, d\mu - (w_2^* - k_2) \int_{\underline{\mu}}^{\bar{\mu}} y(\mu) g(\mu)\, d\mu \right\},$$

subject to (5). In settings where both suppliers use the same type of contracts, the principal-agent models can be transformed so that optimal contracts are characterized using pointwise optimization. However, when S1 uses complex contracts and S2 uses simple contracts, such a transformation is not possible as can be seen from (5), and standard techniques fail. Thus, we rely on techniques from optimal control to solve this particular combination of contracts.[13]

Theorem 4 (S1 Uses Complex Contracts and S2 Uses Simple Contracts). *Assuming S1's payment scheme is strictly increasing and differentiable, and M's, S1's, and S2's best responses are interior solutions, the quantities for each type of the manufacturer are found from*

$$y_{cs}(\cdot) = \arg\max_{y(\cdot)} \left\{ \int_{\underline{\mu}}^{\bar{\mu}} p\big(E_\alpha[\min(\mu+\alpha, y(\mu))] - \bar{h}_g(\mu)\Phi(y(\mu)-\mu) - ky(\mu)\big) g(\mu)\, d\mu - (w_2^* - k_2)\int_{\underline{\mu}}^{\bar{\mu}} y(\mu) g(\mu)\, d\mu \right\}.$$

The suppliers' payment schemes satisfy the following conditions:

$$t_1(y_{cs}(\mu)) = pE_\alpha[\min(\mu+\alpha, y_{cs}(\mu))] - \int_{\underline{\mu}}^{\mu} p\Phi(y_{cs}(\tau)-\tau)\, d\tau - w_2^* y_{cs}(\mu),$$

$$(w_2^* - k_2)\int_{\underline{\mu}}^{\bar{\mu}} -\frac{y'(\mu)}{p\phi(y(\mu)-\mu)} g(\mu)\, d\mu + \int_{\underline{\mu}}^{\bar{\mu}} y(\mu) g(\mu)\, d\mu = 0.$$

Under this contract, the manufacturer's total transfer payments to the suppliers are similar to those we observe under a setting where both suppliers use complex contracts (Theorem 1). That is, the procurement quantity of the manufacturer and the supplier's profits are still a function of the total cost only and are independent of the split of costs, and the supplier's profits depend only on their position. However, S2 leaves a higher rent in expectation to the manufacturer due to limiting himself to a simple contract.

Our numerical studies with $\mu \sim U[\underline{\mu}, \bar{\mu}]$ and $\alpha \sim Normal(0, \sigma_1)$ show that S1 benefits from a *unilateral* deviation to complex contracts under the scenario that we analyze in Theorem 3. The same is true for S2 under the scenario that we analyze in Theorem 4. At first, this observation may appear to contradict with the result in Numerical Observation 1(ii). However, recall that for Numerical Observation 1, we compare two cases where both suppliers use a simple contract and both suppliers use a complex contract. When we combine our observations for unilateral contract deviations with the results in Numerical Observation 1, we conclude that even if a supplier can benefit from using a complex contract, the change of the other supplier's contract can have a much higher negative impact on his profits.[14]

When we compare the total supply chain profits under different contracting scenarios, we observe interesting dynamics: the case where S1 uses a complex contract and S2 uses a simple contract leads to the highest total supply chain profits in the majority of the instances in our numerical study. Note that this case leads to S1 wielding the most power in the supply chain because S2's power is reduced by using a simple contract. This reduction in power (hence the horizontal decentralization) achieves a higher supply chain efficiency. Note that this is certainly not the case when S1 uses a simple contract and S2 uses a complex contract: in this case S1's power by his position is compensated by the simple contract, and therefore inefficiency cannot be eliminated. As a result, this case leads to lower supply chain profits than an equilibrium with complex contracts.

The manufacturer's profit shows similarities with the total supply chain profits (because of its close relationship with the channel quantity). Hence, in many instances the equilibrium under complex-simple contracting scenario leads to a better outcome compared to the equilibrium under complex-complex and simple-complex scenarios. However, it is possible to find instances where the simple-simple equilibrium performs very well for the manufacturer, particularly when a is small (which might be associated with high demand variability).

5.2. When Suppliers Possess Different Levels of Demand Information

In our basic model, we have assumed that the suppliers have identical information on the customer demand. However, there might be situations where the suppliers possess different levels of information as well. For example, because S2 is closer to the manufacturer and hence to the end-consumer market, S2 might possess more information than S1. We next analyze such a setting under complex contracts. Because complete information can totally eliminate inefficiencies under complex contracts, studying the situation with additional information under these contracts is the natural choice. In the next proposition, we use "cooperative benchmark" to denote the case where the suppliers cooperate and offer a single contract to the manufacturer to maximize their total expected profits (i.e., single-supplier, single-manufacturer contracting where the supplier's cost equals $k_1 + k_2$).

Proposition 7. *Under complex contracts, if S1 knows that $\mu \in [\underline{\mu}, \bar{\mu}]$ and S2 knows the exact value of μ, the following hold*:

(i) *S1's profit equals the total supplier profit under the cooperative benchmark.*

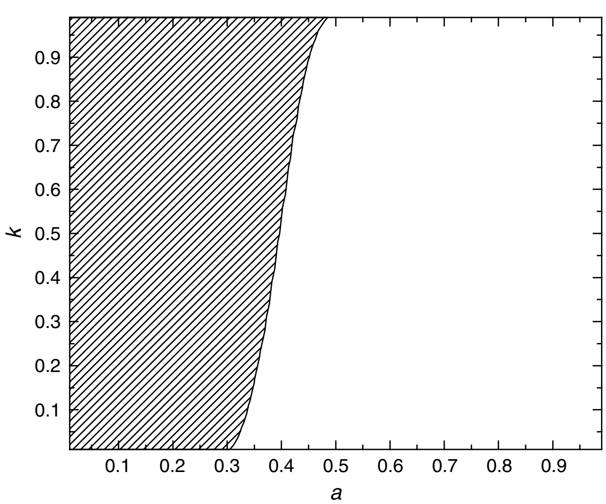
(ii) *S1 always benefits from S2's additional demand information.*

When S2 knows the exact value of μ, he can extract the entire profit of the manufacturer with a complex contract. Thus, the upstream supplier S1 does not have to compensate S2 additionally for the manufacturer. For S1, the downstream supplier S2 and the manufacturer are essentially just one player in this case (i.e., the system is reduced to a single-supplier, single-manufacturer supply chain), and the additional layer of information rent is eliminated. This explains why S1 always benefits from S2's additional information (Proposition 7(ii)). As discussed earlier, the suppliers' profits are not a function of their individual costs but rather of the total cost. Thus, S1's profit is equal to the total supplier profit under the cooperative benchmark (Proposition 7(i)). Numerical Observation 3 characterizes the value of this additional information for S2.

Numerical Observation 3. *If* $\mu \sim U[\underline{\mu}, \bar{\mu}]$ *and* $\alpha \sim Normal(0, \sigma_1)$, *for a given* k, *S2 is worse off with the demand information when* $a \leqslant \bar{a}_{ci}$ *and S2 is better off with the demand information otherwise.*

S2 is worse (better) off with the additional demand information when the ratio of the forecast variability to the total demand variability is below (above) a certain threshold (Numerical Observation 3 and Figure 3). This ratio is low either when the demand fluctuation variability is high or when the forecast variability is low. When the demand fluctuation variability is high, S2 must leave higher profits to the manufacturer and does not receive an additional compensation from S1 to do so, and hence he is worse off. When the forecast variability is low, the environment is similar to a complete-information setting in which, as can be seen from Proposition 1, S1 can fully capture S2's profit under complex contracts, and hence S2 is once again worse off. Furthermore, this negative impact of the additional demand information on S2's expected profit can be substantial; for example, for low values of a, S2's expected profit could be 40+% lower with the additional demand information. However, there is also a significant opportunity for S2 to obtain additional demand information especially for medium to high values of a and low to medium values to k. For such parameter values, S2 can increase his expected profit by at least 10% with the additional demand information.[15]

Figure 3. Comparison of S2's expected profits with and without the additional demand information.



Note. S2 is worse off with the additional demand information in the shaded region, and S2 is better off with the additional demand information otherwise.

6. Conclusion

We analyze an assembly system with two suppliers and a manufacturer who procures complementary components from each supplier to produce her final product. The suppliers, who have less information about the end-consumer demand than the manufacturer, offer contracts that determine the payments for the components they will sell to the manufacturer. Given these contracts, the manufacturer decides how much to buy from each supplier. Although the manufacturer has better end-consumer demand information at the time of contracting, she still faces some uncertainty because actual end-consumer demand is realized after the contracts are developed. Therefore, the manufacturer bears the demand risk. Our study is a first attempt in the operations management literature to integrate a decentralized assembly system with information asymmetry. Our goal is to analyze the role that contract complexity, information and contracting sequence play in contract design in this setting.

We observe inefficiencies due to asymmetric information, double marginalization and horizontal decentralization in our assembly system. Complex contracts help the suppliers to increase their aggregate profit by reducing or eliminating these three inefficiencies. For the suppliers, the value of complex contracts is especially high when the demand risk to the manufacturer is high (i.e., the demand fluctuation is highly variable) and the suppliers' risk due to the uncertainty of the manufacturer's demand forecasts is low (i.e., the demand forecast is relatively stable). However, individual suppliers do not necessarily benefit from an environment where both suppliers use complex contracts. In such an environment, the contracting power of the upstream supplier might substantially increase, leading the downstream supplier to be worse off compared to an equilibrium with simple contracts. Hence, downstream suppliers might prefer a simple contracting equilibrium rather than a complex contracting equilibrium, especially when demand fluctuation variability is high or when forecast variability is low.

Intuition suggests that eliminating information asymmetry would be beneficial for the suppliers; this holds only to a certain extent in our model. When the suppliers learn the manufacturer's private demand information, they benefit collectively because the information rent can be eliminated. However, this benefit might only be marginal, especially under simple contracts, and hence might not be realistically justified. In addition, this additional information is another factor that potentially increases the contracting power of one of the suppliers at the expense of the other. We observe many instances where the downstream supplier is better off when the manufacturer has a private demand forecast. This supplier always prefers information asymmetry when the upstream supplier uses a complex contract and prefers information asymmetry when the demand fluctuation variability is moderate under a simple contracting equilibrium.

From the discussions above for the value of contract complexity and the value of information, we conclude that only when the complex contracts and more or perfect demand information are coupled together, there is a significant profit improvement potential for the total supplier profit. This is mainly because contract complexity and information are strategic complements in our model. Therefore, increasing information increases the value of using complex contracts and increasing complexity increases the value of additional demand information. As a result, the existence of one inefficiency reduces the additional value from eliminating another efficiency and prevents suppliers (as the leaders of the game) from significant profit improvement.

Several results on contracting sequence in the decentralized assembly system literature extend to information asymmetry and complex contracts under a newsvendor setting: for example, the suppliers' profits continue to depend only on their position in the contracting sequence. However, there are also notable differences from the literature. For instance, demand structure is a critical factor that determines the results of contracting sequence. The suppliers experience a second-mover advantage when the demand is price-sensitive as shown in the literature. Conversely, when there is a fixed market price for the final product, we observe a significant first-mover advantage for many demand distributions. The only situation that may provide a second-mover advantage to the downstream supplier is when demand risk is high.

We extend our basic model to analyze two additional scenarios. First, we study cases where the suppliers may offer contracts of different complexity. We are not aware of any other studies in the literature that examine such variations. Beyond enriching our understanding of contract choice in decentralized assembly systems, such variations extend the analysis beyond the standard methodology of principal-agent models and utilize solution techniques from optimal control. Second, we analyze the situation where the downstream supplier may have full information on demand forecast under complex contracts. We show that an upstream supplier always benefits from a downstream supplier's superior information. However, the additional information may decrease the downstream supplier's profits, especially when the forecast variability is low compared to the total demand variability in the system.

Our results confirm that studying interactions between suppliers, specifically under different contract types and information structures, in assembly systems present opportunities for future research. In this work, we have covered two extremes in terms of contract types, namely, simple price-only contracts versus complex contracts. Analyzing situations where suppliers rely on other contracts at different levels of complexity would be especially beneficial.

Electronic Companion

An electronic companion to this paper is available as part of the online version at http://dx.doi.org/10.1287/opre.1120.1084.

Appendix A. Details of the Numerical Study

We assume that the demand forecast of the manufacturer μ is distributed uniformly between $\underline{\mu}$ and $\bar{\mu}$ and that the demand fluctuation α follows a normal distribution with mean 0 and standard variation σ_1. Our numerical study consists of 99 scenarios from the combinations of the following parameters: market price $p = 20$; suppliers' aggregate cost $(k_1 + k_2) \in \{5, 10, 15\}$; $E[\mu] = 200$; $\{\underline{\mu}, \bar{\mu}\} \in \{\{60, 340\}, \{100, 300\}, \{120, 280\}, \{160, 240\}, \{180, 220\}\}$, and $\sigma_1 = \varrho E[\mu]$ where $\varrho \in \{0.01, 0.05, 0.10, 0.15, 0.20, 0.25, 0.35\}$. When the demand forecast is distributed between 60 and 340, we consider only the cases where the demand fluctuation's standard deviation is less than or equal to 40 to eliminate situations where the distribution of the demand fluctuation is truncated by more than 10%. Otherwise, all combinations of the parameters are included in our numerical study. We consider suppliers' aggregate cost instead of the individual costs because decisions in equilibrium are determined only by the aggregate cost and the contracting sequence and structure.

For any range of the demand forecast considered, we truncate the demand fluctuation distribution so that the lowest type always observes a nonnegative demand. As an example, if we consider the range of demand forecast $[60, 340]$, where the lowest type is 60, we use the same demand fluctuation distribution truncated at -60 for all types in this demand forecast range. Note that the lower bound of the demand fluctuation might be different among different ranges of the demand forecast and that this can affect comparisons with respect to the demand forecast range.

Endnotes

1. We do not consider contracts with *ex post* terms because such contracts are not necessarily plausible in a decentralized assembly system as they create coordination issues among several suppliers. For a behavioral analysis of complex versus simple contracts, see Kalkancı et al. (2011).

2. The suppliers' information about each others' contracts is an important criterion in assembly systems. For semiconductor manufacturers, the leadtime of the capital equipment tools is critical in determining the time of purchase. The manufacturers order capital equipment tools that have long production leadtimes (such as lithography tools) far in advance, while purchasing complementary tools with shorter leadtimes just before production. Because there are few players in this industry, the prices set between a manufacturer and a supplier early on can be estimated by the suppliers who write their contracts later (Hertzler 2008). Accordingly, the latter suppliers' decisions are affected by the earlier contracts (*sequential* contracting). Conversely, if the components are readily available, the manufacturer prefers to purchase them right before production. In that case, all of the suppliers contract with the manufacturer without learning about each others' agreements (*simultaneous* contracting). To capture these differences, we consider both contracting scenarios in our analysis.

3. Note that our setting is the same as one with three vertical tiers of decentralized channel members where two suppliers with complementary products supply to a manufacturer. In the latter setting, one research stream studies how to determine the supply chain hierarchy; i.e., whether the manufacturer should control the supply chain contracting or delegate it to one of the suppliers. The sequential setting that we analyze is analogous to delegation, where the lower-tier supplier contracts with the upper-tier supplier, and the manufacturer contracts only with the lower-tier supplier. Simultaneous contracting is analogous to control, where the manufacturer contracts with both suppliers herself. Please refer to Kayış et al. (2012) and the references therein for a review of the literature on supply chain hierarchies.

4. Delegation principle states that "the set of equilibrium outcomes obtainable in an indirect communication game with arbitrary message spaces can be replicated as equilibrium outcomes in a game in which the principals offer payoff relevant menus from which the agent chooses" (Martimort and Stole 2002). As such, delegation principle is an extension of the taxation principle (which establishes the equivalence of forecast-contingent and quantity-contingent payments) for common agency games.

5. The order quantity of a manufacturer with demand forecast μ satisfies $t_1'(y_{\text{seq}}(\mu)) + t_2'(y_{\text{seq}}(\mu)) = p(1 - \Phi(y_{\text{seq}}(\mu) - \mu))$. Because the safety stock term is $y_{\text{seq}}(\mu) - \mu$, a lower marginal payment from the suppliers, i.e., a lower $t_1'(y_{\text{seq}}(\mu)) + t_2'(y_{\text{seq}}(\mu))$, indicates higher safety stock.

6. Under complete information and price-only contracts, Lariviere and Porteus (2001) show that this is in fact the case; i.e., the manufacturer is compensated for demand uncertainty.

7. This is because a lower coefficient of variation of the manufacturer induces a higher wholesale price, as shown by Lariviere and Porteus (2001). Because the distribution of the demand fluctuation is the same for all types in our model, their result implies a higher wholesale price charged to a manufacturer with a higher demand forecast.

8. For complex contracts, this fact is not obvious at first sight. However, the result follows from rewriting $\Upsilon_{\text{seq}}(y)$ in terms of q (similar to what we have done for $\Gamma_{\text{seq}}(q)$).

9. This observation can also be explained as follows. S2's profit is constant with respect to c_v under complex contracts. Under simple contracts, as c_v decreases, the manufacturer's procurement quantity increases but S2's profit margin decreases. Therefore, under simple contracts, S2 observes a trade-off between quantity and profit margin as c_v decreases or increases. When c_v is either too low or too high, S2 suffers from either low margin or low quantity under simple contracts; thus the region where S2 prefers simple contracts is smaller. For intermediate values of c_v, simple contracts provide a perfect balance for S2, and the region where S2 prefers simple contracts reaches its maximum size.

10. Depending on the parameters, gamma, Weibull, and lognormal distributions can have DHR. Demand with DHR is studied by other researchers; e.g., Akşin et al. (2008).

11. It is possible to find examples where sequential contracting leads to higher profits under complex contracts (for at least some types), e.g., when both the demand forecast and demand fluctuation have exponential distributions.

12. The interested reader may refer to the proof of Theorem 4 in the online appendix for the details of the transformations.

13. To solve this particular combination of contracts, we use The TOMLAB Optimization Environment within Matlab.

14. Because analyzing the general model is analytically intractable, we rely on numerical analysis for the comparisons. However, when we make additional simplifying assumptions on demand (linear-inverse demand function) and distribution of α (uniform type distribution), we can make additional theoretical observations. Unfortunately, even under these simplifying assumptions, we cannot characterize the closed-form solution for the setting where S1 uses a complex contract and S2 uses a simple contract (i.e., complex-single setting). However, we can solve the remaining three cases (complex-complex, simple-complex, and simple-simple) and make comparisons. Under the simplifying assumptions, we can show that S1 unilaterally benefits by switching from a simple-complex setting to a complex-complex setting. Thus, a simple-complex setting cannot be an equilibrium. Similarly, S2 unilaterally benefits by switching from a simple-simple setting to a simple-complex setting. Thus, a simple-simple setting cannot be an equilibrium, either. Although we cannot perform the same analysis for the complex-single setting, we conjecture that S2 would unilaterally benefit by switching from a complex-simple setting to a complex-complex setting. Thus, if contract choice is an option, we conjecture that the only equilibrium is the one where both suppliers use a complex contract.

15. Details of the analysis are available from the authors upon request.

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Başak Kalkancı is a postdoctoral associate in the Engineering Systems Division at Massachusetts Institute of Technology. Her research interests are in supply chain management, including behavioral operations management, environmental reporting and sustainability, supply contracts, and the role of information in supply chains. She earned her Ph.D. in management science and engineering from Stanford University in 2010.

Feryal Erhun is an assistant professor in the Management Science and Engineering Department of Stanford University. She is also an affiliated faculty member of the Stanford Global Supply Chain Management Forum. Her research interests are in the area of supply chain management, including risk management in supply chains, new product transitions, and supply contracts. Her current research also studies corporate and nongovernmental organization decisions when a potentially hazardous substance is discovered in a product. Recently, in collaboration with Intel Corporation, her research group designed a decision support system for optimizing capital investment decisions for firms in capital-intensive industries. This work was selected as a finalist in the 2012 Edelman competition, and she has been inducted as an Edelman Laureate. She is a recipient of a 2006 NSF CAREER Award.