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Heterogeneous Suppliers' Contract Design in Assembly Systems with Asymmetric Information

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Abstract

We investigate a supply contract design problem in an assembly supply chain in which two heterogeneous suppliers produce complementary products and deliver them to the assembler. One supplier is more reliable and exhibits no supply risk, and the other is less reliable and exhibits supply risk. The assembler is better informed about demand and assembles these two types of components into final products. To elicit the assembler's truthful report of private information, the more reliable supplier offers a contract to the assembler to determine the components' quantities and the transfer payment. The less reliable supplier enduring a disruption designs a contract that includes the components' quantities, the transfer payment and the unit penalty for any delivery shortfall. We study the cases where either supplier moves first and where they move simultaneously under symmetric and asymmetric demand information. We explore the values of the assembler's information and find that the first mover is more reliant upon the existence of less asymmetric information and the second mover benefits more from the assembler' information. Further, we find that a low reliability of the less reliable supplier enlarges the first mover's value of information. We also examine the values of the contracting sequence and find that under symmetric information, the first mover benefits more from sequential contracting. However, interestingly, under asymmetric information, the first mover may benefit or be harmed by the first-mover right. We also find that a low reliability of the less reliable supplier discourages the supplier from using the first-mover right.

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Key Words: Mechanism design; Assembly supply chain; Asymmetric information; Heterogeneous suppliers; Supply risk

1 Introduction

Over the last two decades, with the advent of global manufacturing, the sales and profits of one supplier often rely on the quantity delivered and timing of complementary components or products delivered by other suppliers in the assembly system, as well as on the realized demand (Gerchak and Wang 2004). This decentralization contributes to lower production costs and faster time-to-market. As a result, this manufacturing strategy has been popularly used in various industries, including the aerospace, automobile, computer, and electronics. For example, Ford outsources over 65% of the components it assembles, and the corresponding figure is over 55% for General Motors and over 80% for Chrysler (Iyer et al. 2005). Boeing does not manufacture many airplane components but instead outsources them to suppliers (Wang 2006). A number of large original equipment manufacturers, such as Dell and HP, even outsource core components (e.g., CPUs and Operating Systems) to others (Intel and Microsoft, respectively).

However, outsourcing causes interest conflicts into the supply chain. Obviously, outsourcing makes a supply chain decentralized in which the suppliers and assembler are often financially independent, and thus, each firm in the supply chain pays more attention to its own interest first (Fang et al. 2014). In this supply chain, compared to the upstream suppliers, the downstream assembler often possesses better information on end-product demands as it is closer to the end-consumer market. Therefore, the downstream assembler usually behaves opportunistically, given its informational advantage while being reluctant to share proprietary (private) information such as that concerning the demand structure given that such information may be strategically significant and potentially adversely used by the others. For example, personal computer assembler may submit "phantom orders" to ensure a higher delivery from the suppliers (Cohen et al. 2003). Consequently, such asymmetry in demand information leads to an misalignment of the interests of the suppliers and their assembler and inefficiencies due to incentive issues among different players.

In addition, assemblers can typically obtain multiple components from a number of independent suppliers which leads to supply disruptions in a decentralized assembly system. Coordination with only a partial set of the suppliers is insufficient because a shortage at any supplier will bring the assembly line to a halt. For instance, In 2007, Menu Foods Corp., a pet food producer, had to recall more than 60 million cans and pouches of dog and cat food of more than 100 pet food brands because of melamine, which was supplied by a Chinese outsourcing supplier, Xuzhou Anying Biologic Technology Development Co. Ltd. (Yang et al. 2009). The disruption caused Menu Foods stock to fall from 3.09 dollars to 2.30 dollars a unit, and Menu Foods has said this recall will cost at least 45 million dollars [1]. In the automotive industry, even a brief shutdown of the assembly line costs millions of dollars. Consequently, auto assemblers may charge component suppliers thousands of dollars for each minute of lost production due to late delivery (ARC Advisory Group 2002). Thus, the existence of other suppliers and their supply reliabilities is an essential part of a supplier's own decision-making process.

However, most of the existing research on assembly supply chains assumes that the suppliers are homogeneous and the assembler and suppliers are equally aware of demand status. Most papers incorporating asymmetric information do so under the circumstance of homogeneous supplier costs, and only a few consider asymmetric information regarding the assembler's demand and address supply disruptions. There is a critical difference between asymmetric information regarding the assembler's demands and that affecting the suppliers' costs. The demand faced by assemblers affects not only the suppliers' costs, but also the suppliers' contract designs. Furthermore, partial supplier disruptions affect a supplier's risk (risk-return trade off), leading to different decision sequences of the suppliers. As a consequence, to cope with uncertainty over demands and to manage supply risk, suppliers can design information-revelation contracts and also avail themselves of various risk-management tools. Therefore, there is a pressing need for suppliers to ascertain what is practically feasible to eliminate the imperfect alignment in a decentralized assembly supply chain due to information asymmetry in an assembler's demand forecast and to manage the supply risk arising from the component outsourcing.

To address these gaps in the current literature, we investigate the interactions between heterogeneous suppliers, specifically under different contracting sequences and information structures (asymmetric and symmetric information), in assembly systems. In particular, we study the pricing and risk management strategies of two heterogeneous suppliers, one that is more reliable and exhibits no supply risk, and another that is less reliable and exhibits supply risk, facing an assembler who is better informed about demand than the suppliers. To capture the assembler's truthful demand information, the more reliable supplier offers a contract to the assembler in an effort to determine the components quantity and the transfer payment for components to be delivered; the less reliable supplier endures a random production disruption, and has two choices: using a perfectly reliable (but costly) backup production option to fulfill the assembler's order or paying the assembler a penalty for delivery shortfalls. Thus, to cope with the uncertainty over supply disruptions, the less reliable supplier designs a menu of contracts including the components' quantity, the transfer payment for components to be delivered and the unit penalty for delivery shortfall. Due to the heterogeneity of the two suppliers, the decision sequences of the suppliers may affect the supply chain members' decisions. To address this, we study the cases in which the more reliable supplier or the less reliable supplier moves first and those in which they move simultaneously.

In short, to investigate the interactions between heterogeneous suppliers, specifically under different contracting sequences and information structures (asymmetric and symmetric information), in assembly systems, we study the following research questions:

[1] https://www.humanesociety.com/58-pets/pets/800-pet-food-recall

How do suppliers' optimal strategies change under three different decision sequences in the presence of asymmetric information about an assembler's demand forecast?

How valuable is the information about an assembler's demand forecast to the two heterogeneous suppliers, the assembler and the supply chain (Value of Information)? How does the less reliable supplier's reliability affect the value of information?

How do the decision sequences of the two heterogeneous suppliers affect the supply chain members' profits (Value of Contracting Sequence)? How does the less reliable supplier's reliability affect the value of contracting sequence?

Using mechanism design theory, we find the optimal menu of contracts offered to the assembler by the heterogeneous suppliers under three different decision sequences, deriving answers to our research questions. We emphasize several of our results below.

First, in the case of sequential contracting under asymmetric information, the assembler's optimal order quantities and the first-moving supplier's transfer payment are both distorted downward from those under symmetric information. Furthermore, the distortion of the second mover's transfer payment is uncertain and dependent on the demand forecast distribution. In the case of simultaneous contracting, the assembler's optimal order quantity is distorted downward from that under symmetric information, and the two suppliers' total payments from the assembler are equal.

Second, under asymmetric information, the supply chain suffers a loss when the suppliers offer the low-type assembler contracts that differ from what an integrated supply chain would offer. For the two suppliers, the expected values of information are different. Specifically, for the first mover, the expected value of information is positive. Thus, the first mover is more reliant on the existence of less asymmetric information in the trade. For the second mover, however, the expected value of information is negative, i.e., the second mover is always better off when the assembler has an informational advantage. However, asymmetric information has a far greater impact on the first mover. The expected values of information for the two suppliers are equal when they move simultaneously. Further, we find that enlarges the value of information for the first mover.

Third, we learned that sequential contracting has no impact on the total expected supply chain profit, whether with symmetric or asymmetric information. When the assembler's demand information is symmetric, the value of contracting sequence for the first mover is positive, i.e., the first mover benefits more from sequential contracting. For the second mover, it is negative, i.e., the second mover prefers simultaneous contracting to sequential contracting, but they are equal in absolute value. Under asymmetric information, both the first and second mover may benefit from, or be harmed by, the first-mover right. Further, we find that a low reliability of the less reliable supplier discourages the supplier from making use of the first-mover right.

The remainder of this paper is organized as follows. In §2, we briefly review the related literature. The proposed model is described in §3. In §4-6, we present the optimal contracts when the more reliable supplier moves first, when the less reliable supplier moves first and when they move simultaneously, respectively. The value of information and the value of contracting sequence in §7 and §8. In §9, we summarize managerial implications, discuss model limitations, and suggest directions for future research. Proofs with technical results can be found in the Appendix.

2 Related Literature

This study is closely related to a recently growing body of literature investigating the contractual arrangements and strategic interactions among independent suppliers and an assembler, in decentralized assembly supply chains as well as on supply risk management.

The first stream of this literature investigates decentralized assembly systems. Such studies include inventory decision and coordination (Bernstein and DeCroix 2006; Zhang et al. 2008), coalition (e.g., Feng and Zhang 2005; Granot and Yin 2008; Nagarajan and Sošić 2009; Yin 2010), contract schemes and coordination (e.g., Gerchak and Wang 2004; Wang et al. 2004; Zhang 2006), supplier competition (Carr and Karmarkar 2005; Jiang and Wang 2007, 2010), decision sequence (e.g., Wang 2006; Chen et al. 2014; Kyparisis and Koulamas 2016), and supplier financing (e.g., Deng et al. 2018; Hu and Qi 2018). However, most of these works have assumed that information is common knowledge to all the members and seldom investigated the effect of asymmetric information on the members' decisions.

A limited number of studies have considered the issue of the assembler or the suppliers not knowing the information in the assembly supply chain system. For instance, Fang et al. (2014) analyzed the impact of suppliers' private cost information on a general decentralized assembly system with multiple suppliers. Li et al. (2019) investigated the assembler's contract design problem by proposing an incentive compatible in dominating strategies when each supplier's marginal cost information is incomplete. Kalkancı and Erhun (2012) examine the impact of asymmetric demand information on contract design in a assembly system with two suppliers. However, our research differs from Kalkancı and Erhun (2012) in several important aspects: i) We study the impact of an assembler's asymmetric demand information on the contract design of two heterogeneous suppliers in a decentralized assembly system with supply risk, i.e., one supplier is more reliable and exhibits no supply risk and the other is less reliable and suffers supply disruptions; ii) we provide guidelines for the suppliers not only to design information-eliciting contracts (pricing), but also to avail the less reliable supplier of various operational risk management tools (including nondelivery penalty and backup production), when there is a risk of supplier failure; and iii) we address the interactions between heterogeneous suppliers, specifically under different contracting sequences and information structures, in assembly systems.

The second stream of related literature is on supply risk management, which has attracted strong interest from both researchers and practitioners of operations management over the past decade. Various operational tools that address supply disruptions have been studied. These include those techniques for multisourcing (e.g., Tomlin 2005; Babich et al. 2007; Yang et al. 2012, Wu et al. 2019), alternative supply sources and backup production options (e.g., Babich 2006; Yang et al. 2009), flexibility (e.g., Tomlin and Wang 2005), and supplier selection (e.g., Deng and Elmaghraby 2005). For a comprehensive review of the supply risk literature, see Tang (2006).

Most of the supply risk literature, including the above-mentioned studies, focus on a simplified supply chain with an upstream supplier or several suppliers competing for business and a downstream retailer or manufacturer. For instance, Gurnani and Shi (2006) considered a bargaining approach in which a buyer and a supplier have different estimates of supply reliability. Tomlin (2009) proposed a model in which the manufacturer faces two suppliers, one with given reliability and the other with uncertain reliability. Niu et al. (2019) investigated the dual sourcing decision of an original equipment manufacturer facing a competitive supplier and a non-competitive supplier who endures unreliable production yield. Yang et al. (2009) examined a supply chain model consisting of one manufacturer and one supplier with private reliability information, where a backup production option is provided for the supplier to fill the manufacturer's order while refusing to pay a penalty to the manufacturer. Yang et al. (2012) focused on a buyer's strategic use of a dual-sourcing option assuming that the suppliers possess private information about their disruption likelihood, and analyzed the trade-off between competition and diversification. Gümüş et al. (2012) modeled a supply chain in which two suppliers facing private supply risk reliability compete for the buyer's order, presuming equilibrium contracts for the two suppliers and the buyer's optimal procurement strategy. Our study differs from the above by analyzing the impact of an assembler's private demand information on a decentralized assembly system with two heterogeneous suppliers.

This paper contributes to the literature in several ways. First, we examine the effects of asymmetric information and decision sequence in an assembly supply chain with two heterogeneous suppliers and one assembler and characterize the equilibrium solutions in each information scenario and decision sequence. Second, we demonstrate the impact of the assembler's asymmetric demand information, the suppliers' decision sequence and the less reliable supplier's reliability on members' optimal decisions. Third, we analyze the values of information and contracting sequence for heterogeneous suppliers in assembly systems and examine the less reliable supplier's reliability on them.

3 Model

We study a push assembly supply chain system consisting of two heterogeneous suppliers (M and L) and a single assembler, in which supplier M is absolutely reliable and well known to the assembler as a supply source, and supplier L is unreliable because of supply risk. The two suppliers are the leaders and the assembler is a follower. Note that the unreliable supplier acting as a leader is not uncommon in reality. For example, in contrast to Apple's significant market power, the small size cellphone manufacturers (assemblers) in China (sometimes have little bargaining power for prices they pay for the components suppliers, even if the components are unable to supply in time. In addition, this kind of setting is also adopting in literature, such as Babich et al. (2007) and Demirel et al. (2018). In addition, We follow the recent supply-risk literature (e.g., Yang et al. 2009, and Gümüş et al. 2012) and represent this supply risk as a Bernoulli random variable ρ having a no risk probability of θ, that is,

$$\rho = \begin{cases} 1, & \text{with probability } \theta \\ 0, & \text{with probability } 1-\theta, \end{cases} \tag{1}$$

where θ can be interpreted as the degree of supplier L's reliability. The larger θ is, the less difference between the reliabilities of the two suppliers. Suppliers M and L produce perfectly complementary components and incur unit production costs of k_m and k_l, respectively. The assembler faces an uncertain demand. We assume that the assembler's cost to assemble the components into the final product is negligible and that the assembly lead time is so short that the final product can be processed right after demand is realized (Fang et al. 2014). Furthermore, we assume that the assembler sells its final product to the end-consumers at an exogenously given price r, and restrict the attention to the situation where production is profitable, i.e., $r\theta > k_m + \frac{k_l}{\theta}$. Any unmet demand is lost without additional penalty cost and no salvage value exists for leftover products (Özer and Raz 2011; Kalkancı and Erhun 2012).

Since the assembler is closer to the product market, it is better informed about the demand, we model the demand function as

$$D = \xi + \varepsilon.$$

This demand function is composed by two parts. One part is the demand forecast (referred to as the assembler's type) which is the assembler's private information only known by the assembler and unknown to the two suppliers at the time of contracting, so we characterize it as a random variable ξ as the suppliers' estimation of the assembler's demand forecast. The other part is the demand fluctuation ε which is unknown to all the participants and commonly used in the literature (Özer and Wei 2006; Kalkancı and Erhun 2012). The two suppliers do not know the exact value of ξ but know its distribution in the context of both the probability density function (pdf) $g(\cdot)$ and the cumulative distribution function (cdf) $G(\cdot)$, which has finite and positive support $[a, b]$. Neither the two suppliers nor the assembler observes the value of ε during contracting. This implies that our proposed model is of a newsvendor setting similar to that given in Özer and Wei (2006) and Fang et al. (2014). Moreover, we assume that ε follows a continuous distribution with the probability density function (pdf) $f(\cdot)$ and the cumulative distribution function (cdf) $F(\cdot)$, which has a finite and positive support $[\underline{\varepsilon}, \bar{\varepsilon}]$.

We define the hazard rate of ξ and that of ε as $h_g(\cdot) := g(\cdot)/(1 - G(\cdot))$ and $h_f(\cdot) := f(\cdot)/(1 - F(\cdot))$, respectively. We also define $\overline{h}_g(\cdot) := h_g^{-1}(\cdot) = (1 - G(\cdot))/g(\cdot)$. As with the common approach to the analysis of principal-agent models, we assume that $h_g(\cdot)$ and $h_f(\cdot)$ satisfy the increasing hazard rate (IHR) condition, which is satisfied by commomly used distributions such as normal and uniform ones, as well as the gamma and

Weibull families subject to certain parameter restrictions (Barlow and Proschan 1965). For detailed properties and applications of IHR distributions refer to Lariviere (2006). The assumption that $h_g(\cdot)$ is increasing (e.g., Iyer et al. 2005) ensures that the assembler's order quantity is increasing in the demand forecast, while $h_f(\cdot)$ is increasing (e.g., Lariviere and Porteus 2001; Gerchak and Wang 2004) guarantees that the suppliers' objective is unimodal for the demand forecast. In addition, to facilitate the analysis of sequential contracting, we assume that $h'_f(\cdot)$ is increasing and $\overline{h}'_g(\cdot)$ is decreasing, and to ensure that the realized demand is always nonnegative, we assume that $a + \underline{\varepsilon} \geq 0$. Finally, we presume that $\overline{h}_g(\cdot)$, $h_f(\cdot)$, $F(\cdot)$ and $G(\cdot)$ are twice differentiable. Fig. 1 provides a simple illustration of the model and the notations used in the paper are listed in the Appendix.

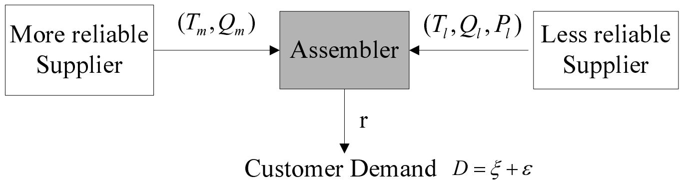

Figure 1: Model Summary

Recall that supplier M uses a nonlinear pricing scheme, specifying a detailed total payment scheme $t_m(Q)$ when the assembler orders Q units (Fang et al. 2014), and that supplier L offers a mechanism consisting of nonlinear pricing $t_l(Q)$ and a penalty $P_l(Q)$ for unit delivery shortfall (Yang et al. 2009) as the assembler orders Q units.

Suppose that each supplier's total payment is strictly increasing in delivery quantity (as we later verify), the assembler has no incentive to choose different quantities from different suppliers. We also assume that $k_i \leq t'_i(Q) \leq r\theta - k_{-i}$, where $i = m, l$. These conditions ensure that the suppliers M and L have a sufficient margin to cover their costs in case of sequential contacting (Kalkancı and Erhun 2012).

Supplier M and supplier L aim to derive an optimal menu of contracts to maximize each expected profit while revealing the asymmetry demand information in the assembly supply chain. A fundamental result called Revelation Principle (Dasgupta et al. 1979, Myerson 1979) states that to obtain the highest expected profit, the suppliers can restrict their attentions to incentive compatible and direct mechanisms, which is a game where the assembler's only action is to report the demand forecast. Therefore, the two suppliers each offer a menu of contracts, in which supplier M's contract consists of two terms: an upfront transfer payment, $T_m \geq 0$ and an order quantity, $Q_m \geq 0$; while supplier L's contract includes three terms: an upfront transfer payment, $T_l \geq 0$, an order quantity, $Q_l \geq 0$, and, because of the possibility of supplier L's supply risk, a unit penalty, $P_l \geq 0$, for delivery shortfall. Such penalty for nondelivery is examined as a supplier's ability to offer contract alternatives to an assembler. Penalty terms in contracts are a common means for the assembler to compensate damages for nondelivery, where the penalty amount is mutually agreed on at the time of contracting as a proactive way to avoid costly litigation for damages. (Yang et al. (2009) and Fang and Shou (2015)).

To analyze how the information structure, the risk-management strategies and the suppliers' decision sequences affect the two suppliers' contracting, while noting that the entire supply chain gains profit as the supply chain members make profits, we consider six separate cases herein, three each for known and unknown ξ value. These cases are listed in Table 1. The first two cases (horizontally), MS and MA represent the market scenarios in which supplier M moves first with the assembler's demand forecast being addressed as symmetric and asymmetric information, respectively. The middle two cases, LS and LA, represent the scenario for which supplier L moves first with the assembler's demand forecast being symmetric and asymmetric, respectively. The remaining two cases, SS and SA, represent the scenario for which the two suppliers move simultaneously with the assembler's demand forecast being considered as symmetric and asymmetric information, respectively.

Table 1: Six distinct cases considered

Decision sequence	ξ known	ξ unknown
Supplier M moves first	Symmetric information (MS)	Asymmetric information (MA)
Supplier L moves first	Symmetric information (LS)	Asymmetric information (LA)
Two suppliers move simultaneously	Symmetric information (SS)	Asymmetric information (SA)

3.1 Less reliable supplier's delivery decisions

In this subsection, we will discuss the less reliable supplier's delivery decision. Note that in case of a supply risk, supplier L has two choices: use a reliable backup production option or pay the assembler a penalty for delivery shortfalls. Backup production option means that supplier L can resort to create an alternate source of supply or purchase from the spot market. We call such alternatives backup production and this backup production is more expensive than the regular one. For example, Menu Foods Corp. facing a disruption by a supplier like ChemNutra might resource its wheat gluten from a different supplier (not Xuzhou Anying, which was the culprit of the disruption), install different quality controls, produce the wheat gluten itself, or perhaps use a combination thereof (Yang et al. 2009). The penalty for nondelivery provides the supplier with an incentive to seek out alternative ways of satisfying the obligations.

For notational convenience, we suppress the arguments from the functions $T_l(\cdot)$, $Q_l(\cdot)$, and $P_l(\cdot)$. In the execution stage, given a contract (T_l, Q_l, P_l) accepted by the assembler, supplier L chooses its regular production size and delivery quantity in order to maximize its expected profit. Supplier L first determines the size of its regular production run z. After finishing the regular production, which has led to ρz due to supply risk. Then, supplier L decides on the delivered quantity to the assembler, y. Subsequently, supplier L engages backup production to cover the difference, $(y - \rho z)^+$, and/or pays a penalty for the shortfall $(Q_l - y)^+$. The following is the optimization problem of supplier L:

$$\pi_l(T_l, Q_l, P_l) = \max_{z \geq 0} \left\{ T_l - k_l z - \boldsymbol{E}_\rho \left\{ \min_{y \geq 0} \left[P_l (Q_l - y)^+ + b_l (y - \rho z)^+ \right] \right\} \right\}. \tag{2}$$

Proposition 1. *For a given contract (T_l, Q_l, P_l), supplier L's optimal regular production z^*, delivery quantity y^* and expected profit π_l are given in Table 2.*

Table 2: Details of Proposition 1

Region	z^*	y^*	$\pi_l(T_l, Q_l, P_l)$
1) $P_l > b_l, b_l < k_l/\theta$	0	Q_l	$T_l - b_l Q_l$
2) $P_l > b_l, b_l \geq k_l/\theta$	Q_l	Q_l	$T_l - k_l Q_l - (1-\theta) b_l Q_l$
3) $b_l \geq P_l, P_l \geq k_l/\theta$	Q_l	ρQ_l	$T_l - k_l Q_l - (1-\theta) P_l Q_l$
4) $b_l \geq P_l, P_l < k_l/\theta$	0	0	$T_l - P_l Q_l$

In particular, in Region 1) of Proposition 1, supplier L's backup production cost is smaller than its expected regular production cost, treating it more economical to use backup production than regular production. However, in Region 2), suppler L's backup production cost is moderate, being larger than its expected regular production cost and smaller than the possible maximal margin that it could obtain, and the unit penalty is relatively large. Therefore, the supplier fully utilizes regular production and adopts backup production to cover the difference induced by supply disruption. Similarly, Region 3) shows that a relatively high backup cost and low penalty cost induce supplier L to adopt full regular production and pay penalty for the shortfall. In Region 4), however, supplier L makes no effort to produce. As we will see below, the case in Region 4) never arises under the optimal contract.

3.2 Suppliers' contracts design problem

Recall that we model the two suppliers' decisions as a mechanism design problem, using a standard information-economics approach (e.g., Mirrlees 1981). Additionally, According to the revelation principle, we focus on the direct revelation, incentive-compatible contracts. To maximize each own expected profit, supplier M and supplier L solve the following two optimization problems, respectively.

$$\max_{(T_m(\cdot), Q_m(\cdot))} \boldsymbol{E}[\pi_m(T_m(\xi), Q_m(\xi))] \tag{3}$$

subject to:

$$r\boldsymbol{E}_\varepsilon[\min(x+\varepsilon, y^*)] - T_m(x) - t_l(Q_m(x)) + P_l(x)\boldsymbol{E}_\rho\left[(Q_m(x) - y^*)^+\right] \geq 0, \tag{4}$$

$$r\boldsymbol{E}_\varepsilon[\min(x+\varepsilon, y^*)] - T_m(x) - t_l(Q_m(x)) + P_l(x)\boldsymbol{E}_\rho\left[(Q_m(x) - y^*)^+\right] \geq \tag{5}$$

$$r\boldsymbol{E}_\varepsilon[\min(x+\varepsilon, y^*)] - T_m(x') - t_l(Q_m(x')) + P_l(x)\boldsymbol{E}_\rho\left[(Q_m(x') - y^*)^+\right],$$

where supplier M's profit $\pi_m(T_m(x), Q_m(x)) = T_m(x) - k_m Q_m(x)$,

and

$$\max_{(T_l(\cdot),Q_l(\cdot),P_l(\cdot))} \boldsymbol{E}[\pi_l(T_l(\xi), Q_l(\xi), P_l(\xi))] \tag{6}$$

subject to:

$$r\boldsymbol{E}_\varepsilon[\min(x+\varepsilon, y^*)] - t_m(Q_l(x)) - T_l(x) + P_l(x)\boldsymbol{E}_\rho\left[(Q_l(x) - y^*)^+\right] \geq 0, \tag{7}$$

$$r\boldsymbol{E}_\varepsilon[\min(x+\varepsilon, y^*)] - t_m(Q_l(x)) - T_l(x) + P_l(x)\boldsymbol{E}_\rho\left[(Q_l(x) - y^*)^+\right] \geq \tag{8}$$

$$r\boldsymbol{E}_\varepsilon[\min(x+\varepsilon, y^*)] - t_m(Q_l(x')) - T_l(x') + P_l(x')\boldsymbol{E}_\rho\left[(Q_l(x') - y^*)^+\right],$$

where supplier L's profit is given in Table 2.

Note that we have assumed that $Q_m(x) = Q_l(x)$, which is practically reasonable. We also assume that the second mover can observe the first one's contract menu, but cannot observe the assembler's choice of contract (Kalkancı and Erhun; Yan et al. 2017), and thus the second mover cannot infer perfectly the assembler's demand type, while enforcing $Q_m(x) = Q_l(x)$. Furthermore, supplier M's and L's transfer payments $t_m(Q_m)$ and $t_l(Q_l)$ in each optimization problem can be represented as direct mechanisms by the revelation principle, denoted by $(T_m(x), Q_m(x))$ and $(T_l(x), Q_l(x), P_l(x))$, respectively. However, supplier M's and L's transfer payments $t_m(Q_l)$ and $t_l(Q_m)$ in supplier L and M's optimization problem remain unchanged. These notations are used throughout the paper. Inequalities (4) and (7) are the assembler's participation constraints when trading with suppliers M and L, respectively, which guarantee that each type of assembler earns at least its reservation profit. As commonly used in both economics literature (Myerson 1981, Che 1993) and operations management literature (Taylor and Xiao 2009, Wang et al. 2019), we presume that the assembler's reservation profits for trading with suppliers M and L are the same, normalized to zero. Constraints (5) and (8) denote the assembler's incentive constraints when trading with suppliers M and L, respectively, ensuring that the assembler obtains a higher (and at least no less) profit by telling the true type x to the suppliers than by misreporting about its type as x'.

4 Optimal Contracts when Supplier M Moves First

In this section, we consider the scenario in which supplier M moves first. The timing of events is shown in Figure 2. The problem can be divided into two stages: contracting and execution. At the beginning of the contracting stage, the assembler's type is not revealed to the two suppliers. Then supplier M moves first and designs a menu of contracts, $(T_m(\cdot), Q_m(\cdot))$, from which the assembler selects a contract (reports its type). After supplier M's contracting with the assembler, supplier L offers a menu of contracts, $(T_l(\cdot), Q_l(\cdot), P_l(\cdot))$. The assembler then selects a contract, ending the contracting stage. In the execution stage, assuming random demand fluctuation, the suppliers receive their transfer payments from the assembler, engage in production and delivery, while supplier L executes a penalty for the delivery shortfall.

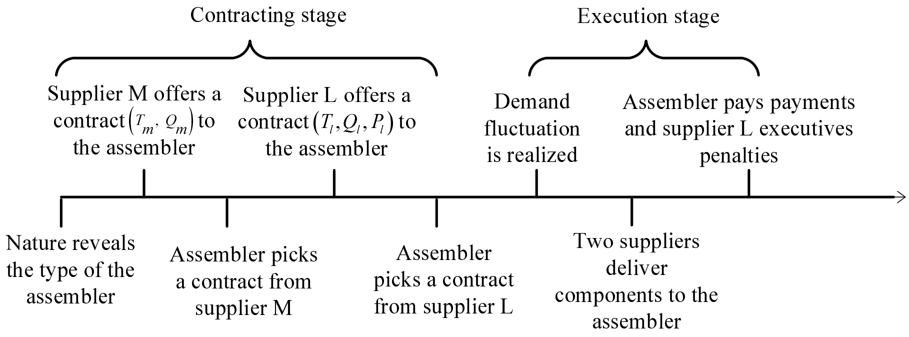

Figure 2: Timing of events when supplier M moves first

With backward induction, we can identify supplier L's best response to a payment scheme proposed by supplier M, by resolving supplier L's problem (6)–(8) first. Once supplier L's best response is characterized, supplier M's objective can be rewritten as

$$\max_{Q_{li}^*(x)} \int_a^b (t_m(Q_{li}^*(x)) - k_m Q_{li}^*(x))g(x)\mathrm{d}x$$

$$= \begin{cases} \displaystyle\max_{Q_{li}^*(x)} \int_a^b \left(r\boldsymbol{E}_\varepsilon\left[\min(x+\varepsilon, Q_{li}^*(x))\right] - \bar{h}_g(x) rF\left(Q_{li}^*(x) - x\right) - k_i Q_{li}^*(x) - \Pi_{li}^m(x)\right) g(x)\mathrm{d}x, i = 1,2 \\ \displaystyle\max_{Q_{l3}^*(x)} \int_a^b \left(r\theta\boldsymbol{E}_\varepsilon\left[\min(x+\varepsilon, Q_{l3}^*(x))\right] - \bar{h}_g(x) r\theta F\left(Q_{l3}^*(x) - x\right) - k_3\theta Q_{l3}^*(x) - \Pi_{l3}^m(x)\right) g(x)\mathrm{d}x, \end{cases}$$

where $\Pi_{li}^m(x)$ is supplier L's valuation of a type x assembler in Region i), $i = 1,2,3$, in the case of supplier M moving first, which equals to its profit less the information rent that it must give the assembler to ensure its participation. The closed forms for these terms are in the Appendix.

4.1 Optimal contracts in Case MS

To explore the impact of asymmetric information, as a benchmark we first derive the optimal contract menu when the assembler's demand forecast is common knowledge in the case of supplier M moving first. Under symmetric information, the assembler's true demand forecast information is revealed to suppliers M and L simultaneously. Thus, the incentive compatibility constraints (5) and (8) are no longer required. At optimality, the participation constraints (4) and (7) must be binding; otherwise, suppliers M and L can each increase profits by increasing $T_m(x)$ and $T_l(x)$, respectively. This is formulated in Theorem 1 below which describes the optimal menu of contracts and resulting profits.

Theorem 1. *When supplier M moves first, the two suppliers' optimal contracts and the supply chain members' optimal profits under symmetric information are given in Tables 3 and 4, respectively.*

This theorem shows that the optimal contract terms and the supply chain members' optimal profit vary in response to the Region. A detailed analysis is provided in the following.

Table 3: Suppliers M's and L's optimal contracts in Case MS

Region	Quantity	Penalty	Supplier M's transfer payment	Supplier L's transfer payment
1) $b_l < k_l/\theta$	Q_1^{MS}	P_1^{MS}	t_{M1}^{MS}	t_{L1}^{MS}
2) $k_l/\theta \le b_l < r - k_m$	Q_2^{MS}	P_2^{MS}	t_{M2}^{MS}	t_{L2}^{MS}
3) $r - k_m \le b_l$	Q_3^{MS}	P_3^{MS}	t_{M3}^{MS}	t_{L3}^{MS}

where $Q_i^{MS}(x) = F^{-1}\left(\frac{r-k_i}{r}\right) + x,\quad t_{Li}^{MS}(Q_l) = (k_i - k_m)Q_l, t_{Mi}^{MS}(Q_l) = r\boldsymbol{E}_\varepsilon[\min(x+\varepsilon, Q_l)] - (k_i - k_m)Q_l,$

$$i = 1, 2,\quad P_1^{MS}(x) \in (b_l, k_l/\theta),\quad P_2^{MS}(x) \in (b_l, r - k_m),$$

$$Q_3^{MS}(x) = F^{-1}\left(\tfrac{r-k_3}{r}\right) + x,\quad P_3^{MS}(x) \in [k_l/\theta, r - k_m),\quad t_{L3}^{MS}(Q_l) = k_l Q_l + (1-\theta)P_3^{MS}Q_l,$$

$$t_{M3}^{MS}(Q_l) = r\theta\boldsymbol{E}_\varepsilon[\min(x+\varepsilon, Q_l)] - k_l Q_l - (1-\theta)P_3^{MS}Q_l.$$

Table 4: Supply chain members' optimal profits in Case MS

Region	Assembler's profit	Supplier M's profit	Supplier L's profit
1) $b_l < k_l/\theta$	0	$\mathcal{B}_1$	0
2) $k_l/\theta \le b_l < r - k_m$	0	$\mathcal{B}_2$	0
3) $r - k_m \le b_l$	0	$\mathcal{B}_3$	0

where $\mathcal{B}_i = (r - k_i)(F^{-1}(\frac{r-k_i}{r}) + x) - r\int_a^{F^{-1}(\frac{r-k_i}{r})} F(y)\mathrm{d}y, i = 1, 2,$

$$\mathcal{B}_3 = (r - k_3)\theta(F^{-1}(\tfrac{r-k_3}{r}) + x) - r\theta\int_a^{F^{-1}(\frac{r-k_3}{r})} F(y)\mathrm{d}y.$$

1) In each Region, the assembler's optimal order quantity increases in relation to both the assembler's demand forecast and the supply chain's net profit rate $\frac{r-k_i}{r}, i \in \{1, 2, 3\}$. That is, a higher demand forecast and supply chain efficiency lead to a higher order quantity. Further, the assembler's optimal order quantity is independent on supplier L's reliability θ in Region 1) and increasing in Regions 2) and 3). This is because in Region 1), backup production is cheap relative to the product's market revenue, and thus, supplier L prefers to use backup production entirely rather than regular production, leading to no supply risk. However, in Regions 2) and 3), the relatively higher backup production costs lead to supplier L's use of risky regular production, thereby leading to the situation where the optimal order quantity is related to supplier L's reliability; in particular, the more reliable supplier L is, the more the assembler orders. If supplier L is perfectly reliable ($\theta = 1$), the assembler's optimal order quantities in Regions 2) and 3) degenerate to that in Kalkancı and Erhun (2012). This is because the high reliability of supplier L allows the assembler to more easily balance the order quantities of the two suppliers and increase the order quantity; however, the assembler's optimal order quantity in Region 1) remains different from that in Kalkancı and Erhun (2012) because supplier L uses backup production as a quantity-risk-management tool.

2) From Table 3, in Regions 1) and 2), backup production is cheap relative to the product's market revenue, and thus, supplier L uses backup production in the event of disruption. In Region 3), backup production is costly, and hence supplier L prefers to pay a penalty in the event of disruption.

3) When both Suppliers M and L know the assembler's demand forecast information, they extract the assembler's expected revenue through the payments, leaving the assembler a reservation profit of zero. Thus, inefficiencies due to double marginalization are eliminated. In addition, due to the assembler's selection of quantities, those taken from both suppliers will be identical, and hence, the suppliers' decisions are coordinated. From this, inefficiencies arising from horizontal decentralization are also eliminated. Therefore, both suppliers sell the first-best quantity, which heavily favors the suppliers because the assembler makes zero expected profit. Furthermore, Table 4 shows that supplier M, as the first mover, captures all the profit of supplier L. The direct reason for this may be that the first mover can maximize his or her profit by first designing a contract on the price and order quantity, provided that the contract parameters guarantee the second mover's participation and leave the second mover with a reservation profit of zero. (Kalkancı and Erhun 2012).

4.2 Optimal contracts in Case MA

Here we consider the case that the assembler's demand forecast is private information and supplier M moves first. The solution is presented in Theorem 2 below. We then compare the optimal contract with that under symmetric demand information.

Theorem 2. *In Region i), $i = 1, 2, 3$, the assembler's optimal buying quantity $Q_i^{MA}(x)$ satisfies*

$$Q_i^{MA}(x) = \begin{cases} x + \underline{\varepsilon} & \text{if} \quad \Gamma_i^{MA}(x + \underline{\varepsilon}) \leq 0 \text{ or } \kappa_{i2}(x) > \kappa_{i1}(x) \\ \{Q_{li}(x) | \Gamma_i^{MA}(Q_{li}(x)) = 0\} & \text{otherwise.} \end{cases} \tag{9}$$

Supplier L's optimal unit penalties for delivery shortfall in Regions 1), 2) and 3) respectively satisfy

$$P_1^{MA}(x) \in (b_l, k_l/\theta), P_2^{MA}(x) \in (b_l, r - k_m), P_3^{MA}(x) \in [k_l/\theta, r - k_m).$$

The suppliers' transfer payments from the assembler in Region i), $i = 1, 2$, satisfy the following conditions

$$t\left(Q_i^{MA}(x)\right) = t_m\left(Q_i^{MA}(x)\right) + t_l\left(Q_i^{MA}(x)\right) = r\boldsymbol{E}_\varepsilon\left[\min\left(x + \varepsilon, Q_i^{MA}(x)\right)\right] - \int_a^x rF\left(Q_i^{MA}(m) - m\right)\mathrm{d}m,$$

$$t_m\left(Q_i^{MA}(x)\right) = r\boldsymbol{E}_\varepsilon\left[\min\left(x + \varepsilon, Q_i^{MA}(x)\right)\right] - \bar{h}_g(x)rF\left(Q_i^{MA}(x) - x\right) - (k_i - k_m)Q_i^{MA}(x) - \Pi_{li}^m(x),$$

and in Region 3), they satisfy the following conditions:

$$\begin{aligned} &t\left(Q_3^{MA}(x)\right) = t_m\left(Q_3^{MA}(x)\right) + t_l\left(Q_3^{MA}(x)\right) \\ &= r\boldsymbol{E}_{\varepsilon,\rho}\left[\min\left(x + \varepsilon, \rho Q_3^{MA}(x)\right)\right] + (1 - \theta)P_3^{MA}(x)Q_3^{MA}(x) - \int_a^x r\theta F\left(Q_3^{MA}(m) - m\right)\mathrm{d}m, \end{aligned}$$

$$t_m\left(Q_3^{MA}(x)\right) = r\boldsymbol{E}_{\varepsilon,\rho}\left[\min\left(x + \varepsilon, \rho Q_3^{MA}(x)\right)\right] - \bar{h}_g(x)r\theta F\left(Q_3^{MA}(x) - x\right) - k_l Q_3^{MA}(x) - \Pi_{l3}^m(x),$$

where $\Gamma_i^{MA}(Q_{li})$ is defined as the derivative of supplier M's objective function with respect to the quantity at type x in Region i) when $Q_{li} > x + \underline{\varepsilon}$, and $\kappa_{i1}(x)$ and $\kappa_{i2}(x)$ denote the value of supplier M's objective function *in Region i), $i = 1, 2, 3$, if its sales quantity is strictly above $x + \underline{\varepsilon}$ and that if the quantity is equal to $x + \underline{\varepsilon}$, respectively. The closed-form expressions for all these terms are in the Appendix.*

Note that supplier M's optimal transfer payment is a function of supplier L's valuation. That is, supplier interactions play an important role in determining the equilibrium. Not only should the suppliers encourage the assembler with a high demand forecast to increase the order quantities, but supplier M should also incentivize supplier L, as shown by the next proposition.

Proposition 2. *In an equilibrium, $\Pi^m_{li}(x) = 0$ for $a \leq x < \hat{x_i}$ and is strictly increasing in x when $x \geq \hat{x_i}$, where $\hat{x_i} = \sup\left\{x | Q_i^{MA}(x) = x + \underline{\varepsilon}\right\}, i = 1, 2, 3$ and $\hat{x_1} \leq \min\{\hat{x_2}, \hat{x_3}\}$, specifically, when $r - k_m < \frac{k_l + k_m}{\theta}$, $\hat{x_1} \leq \hat{x_2} \leq \hat{x_3}$.*

Generally, Proposition 2 indicates that when supplier M wishes to provide more components to the assembler with a high demand forecast, it must ensure that the assembler is also able to pay supplier L for a higher order quantity. If suppler M fails to do so, supplier L will sell a lower quantity. Thus, supplier M might decrease its selling quantity by alienating supplier L. In other words, although supplier L moves second, it may pose a "threat" to supplier M while benefitting from the assembler's private information. In particular, Proposition 2 also shows that there exists a threshold of the assembler's demand forecast for supplier L's profit in each Region. If the assembler's demand forecast is less than the threshold, supplier L will obtain no profit; otherwise, it can make a positive profit. Due to the different cost efficiencies of the three Regions, supplier L is more likely to be better off in Region 1) because it can sell higher quantities.

5 Optimal Contracts when Supplier L Moves First

In this section, we model the cases in which supplier L moves first under symmetric information (LS) and asymmetric information (LA), and propose methods to solve the resulting models.

The timing of events is herein similar to that previously given in Figure 2, except swapping the orders of the two suppliers' contracting. By backward induction, we identify supplier L's best response to a payment scheme proposed by supplier M, by solving supplier M's problem (3)–(5) first. Once supplier M's best response is characterized, supplier L's objective can be rewritten as

$$\max_{Q^*_{mi}(x)} \int_a^b (\pi_l(Q^*_{mi}(x))g(x)\mathrm{d}x$$

$$= \begin{cases} \displaystyle\max_{Q^*_{mi}(x)} \int_a^b \left(r\boldsymbol{E}_\varepsilon\left[\min(x+\varepsilon, Q^*_{mi}(x))\right] - \bar{h}_g(x) rF\left(Q^*_{mi}(x) - x\right) - k_i Q^*_{mi}(x) - \Pi^l_{mi}(x)\right) g(x)\mathrm{d}x, i = 1, 2 \\ \displaystyle\max_{Q^*_{m3}(x)} \int_a^b \left(r\theta\boldsymbol{E}_\varepsilon\left[\min(x+\varepsilon, Q^*_{m3}(x))\right] - \bar{h}_g(x) r\theta F\left(Q^*_{m3}(x) - x\right) - k_3\theta Q^*_{m3}(x) - \Pi^l_{m3}(x)\right) g(x)\mathrm{d}x, \end{cases}$$

where $\Pi^l_{mi}(x)$ is supplier M's valuation of a type x assembler in Region i), $i = 1, 2, 3$, when supplier L moves first. This equals to its profit less the information rent that it must give the assembler in an effort to ensure its participation. Again, the closed forms for these terms are in the Appendix.

5.1 Optimal contracts in Case LS

In this subsection, we consider the case in which supplier L moves first and the assembler's demand forecast information is known to both suppliers M and L. This is formulated in Theorem 3 below, which describes the optimal menu of contracts and the resulting profits.

Theorem 3. *When supplier L moves first, the suppliers' optimal contracts and the supply chain members' profits given symmetric information are listed in Tables 5 and 6.*

Table 5: Suppliers M's and L's optimal contracts in Case LS

Region	Quantity	Penalty	Supplier M's transfer payment	Supplier L's transfer payment
1) $b_l < k_l/\theta$	Q_1^{LS}	P_1^{LS}	t_{M1}^{LS}	t_{L1}^{LS}
2) $k_l/\theta \leq b_l < r - k_m$	Q_2^{LS}	P_2^{LS}	t_{M2}^{LS}	t_{L2}^{LS}
3) $r - k_m \leq b_l$	Q_3^{LS}	P_3^{LS}	t_{M3}^{LS}	t_{L3}^{LS}

where $Q_i^{LS}(x) = F^{-1}\left(\frac{r-k_i}{r}\right) + x$, $i = 1, 2, 3$,

$P_1^{LS}(x) \in (b_l, k_l/\theta)$, $P_2^{LS}(x) \in (b_l, r - k_m)$, $P_3^{LS}(x) \in [k_l/\theta, r - k_m)$,

$t_{Mi}^{LS}(Q_i^{LS}) = k_m Q_i^{LS}$, $i = 1, 2, 3$, $t_{Li}^{LS}(Q_i^{LS}) = r\boldsymbol{E}_\varepsilon \left[\min\left(x + \varepsilon, Q_i^{LS}\right)\right] - k_m Q_i^{LS}$, $i = 1, 2$,

$t_{L3}^{LS}(Q_3^{LS}) = r\boldsymbol{E}_\varepsilon \left[\min\left(x + \varepsilon, \rho Q_3^{LS}\right)\right] - k_m Q_3^{LS}$.

Table 6: Participants' profit under symmetric information in Case LS

Region	Assembler's profit	Supplier L's profit	Supplier M's profit
1) $b_l < k_l/\theta$	0	$\mathcal{B}_1$	0
2) $k_l/\theta \leq b_l < r - k_m$	0	$\mathcal{B}_2$	0
3) $r - k_m \leq b_l$	0	$\mathcal{B}_3$	0

where $\mathcal{B}_i, i = 1, 2, 3$ are as defined in Table 6.

It is interesting to analyze the relationship between the optimal contracts and supply chain members' profits in Case MS and Case LS. One result from Theorem 3 may suggest that the assembler's optimal order quantity is equal for supplier M and supplier L and that both suppliers' corresponding transfer payments in Case MS are equal to their corresponding transfer payments in Case LS. This indicates that the moving sequence has no effect on the assembler's optimal order quantity but induces the first mover's transfer payments to exchange, thereby allowing the first mover to extract the entire system's profit (see Table 6).

By using Theorems 1 and 3, we can analyze the influence of supplier L's moving sequence on supplier M's pricing action given symmetric information, with the difference highlighted in Figure 3. Note that as the influence of supplier M's moving sequence on supplier L's pricing action is similar, we omit repetitively showing it explicitly. In Case MS, due to the moving advantage and supplier L's supply risk, supplier M will set a different price that allows it to extract the entire system's profit in each region, leaving supplier L only with its own reservation profit. However, in Case LS, without a moving advantage, supplier M must set the price equal to its marginal cost which is lower than that in Case MS while securing its participation. Consequently, in Case LS, the prices set by supplier M in Regions 1), 2) and 3) are equal. However, in Case MS, supplier M will set a higher price in Region 1) than those in Regions 2) and 3). Basically, the first mover will set a price to extract the entire supply chain's profit, while the second mover can only set a price equal to its marginal cost. Particularly, in Region 1), backup production is cheap relative to the product's market revenue, and thus, the first mover prefers to use backup production entirely rather than regular production, thereby imposing a higher price than those in Regions 2) and 3) in an attempt to sell more.

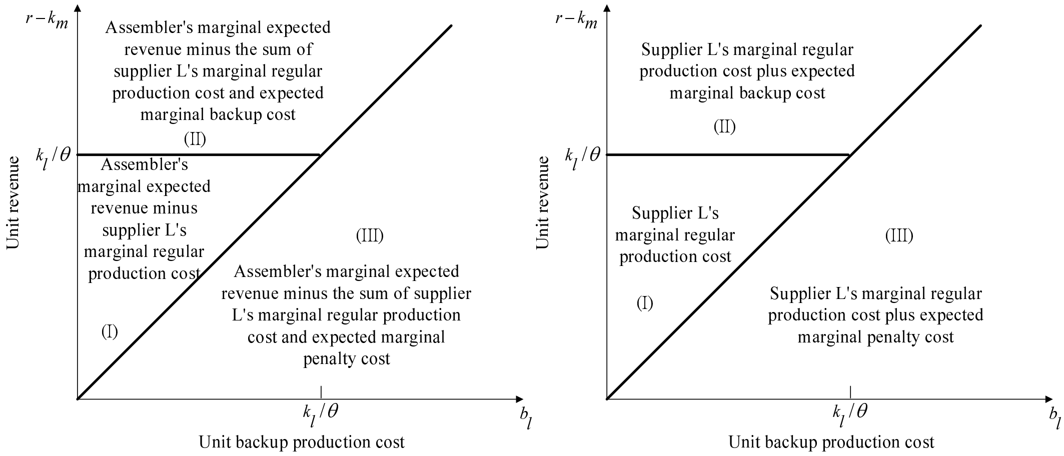

Figure 3: Influence of supplier L's moving sequence on supplier M's pricing action given symmetric information (Left panel: Case MS; Right panel: Case LS)

5.2 Optimal contracts in Case LA

Here, we consider the case in which supplier L moves first and the assembler's demand forecast information is unknown to suppliers M and L, and compare the optimal contracts with those in Cases LS and MA.

Theorem 4. *In Region i), $i \in \{1, 2, 3\}$, the assembler's optimal buying quantity $Q_i^{LA}(x)$ satisfies*

$$Q_i^{LA}(x) = \begin{cases} x + \underline{\varepsilon} & \text{if} \quad \Gamma_i^{LA}(x + \underline{\varepsilon}) \leq 0 \text{ or } \kappa_{i2}(x) > \kappa_{i1}(x) \\ \{Q_{mi}(x) | \Gamma_i^{LA}(Q_{mi}(x)) = 0\} & \text{otherwise.} \end{cases} \tag{10}$$

Supplier L's optimal unit penalties for delivery shortfall in Regions 1), 2) and 3) satisfy

$$P_1^{LA}(x) \in (b_l, k_l/\theta), P_2^{LA}(x) \in (b_l, r - k_m), P_3^{LA}(x) \in [k_l/\theta, r - k_m).$$

The suppliers' payments in Region i), $i = 1, 2$, satisfy the following conditions:

$$t\left(Q_i^{LA}(x)\right) = t_m\left(Q_i^{LA}(x)\right) + t_l\left(Q_i^{LA}(x)\right) = r\boldsymbol{E}_\varepsilon\left[\min\left(x+\varepsilon, Q_i^{LA}(x)\right)\right] - \int_a^x rF\left(Q_i^{LA}(m) - m\right)\mathrm{d}m,$$

$$t_l\left(Q_i^{LA}(x)\right) = r\boldsymbol{E}_\varepsilon\left[\min\left(x+\varepsilon, Q_i^{LA}(x)\right)\right] - \bar{h}_g(x) rF\left(Q_i^{LA}(x) - x\right) - k_m Q_i^{LA}(x) - \Pi_{mi}^l(x),$$

and in Region 3), they satisfy the following conditions

$$\begin{aligned} & t\left(Q_3^{LA}(x)\right) = t_m\left(Q_3^{LA}(x)\right) + t_l\left(Q_3^{LA}(x)\right) \\ & = r\boldsymbol{E}_{\varepsilon,\rho}\left[\min\left(x+\varepsilon, \rho Q_3^{LA}(x)\right)\right] + (1-\theta)P_3^{LA}(x)Q_3^{LA}(x) - \int_a^x r\theta F\left(Q_3^{LA}(m) - m\right)\mathrm{d}m, \end{aligned}$$

$$\begin{aligned} t_l\left(Q_3^{LA}(x)\right) = r\boldsymbol{E}_{\varepsilon,\rho}&\left[\min\left(x+\varepsilon, \rho Q_3^{LA}(x)\right)\right] + (1-\theta)P_3^{LA}(x)Q_3^{LA}(x) \\ &-\bar{h}_g(x) r\theta F\left(Q_3^{LA}(x) - x\right) - k_m Q_3^{LA}(x) - \Pi_{m3}^l(x). \end{aligned}$$

Comparing the assembler's optimal order quantities, transfer payments and profits in Cases MA, LA and LA, we can make the following observations:

1) In Case LA, the assembler's optimal order quantity is less than that in Case LS, benefiting from information advantage, but the supply chain's profit is stochastically less than that in Case LS. In other words, asymmetric information leads to a lower supply chain performance.

2) In Cases MA and LA, the assembler's optimal order quantity for both suppliers is equal. In other words, the moving sequence has no effect on the assembler's optimal order quantity. Moreover, the two suppliers' total payments from the assembler are also equal, leading to the assembler's attaining the same profit.

3) Interestingly, the results under asymmetric information herein form a sharp contrast with those previous results under symmetric information as given in Theorems 1 and 3. That is, supplier M and supplier L equally extract the entire system's profits in Cases MS and LS, respectively. However, under asymmetric information, in our newsvendor setting, the first mover may not benefit from moving advantage, namely, being the first does not always offer a supplier the best strategy.

6 Optimal Contracts when Suppliers M and L Move Simultaneously

In this section, we consider the scenario in which suppliers M and L simultaneously sign a contract with the assembler and cannot observe each other's decision. They make the decisions simultaneously through a Nash equilibrium. The timing of events is shown in Figure 4.

6.1 Optimal contracts in Case SS

In this subsection, we first present the optimal solution for Case SS as Theorem 5, and then compare the resulting optimal contract with those in Cases MS and LS.

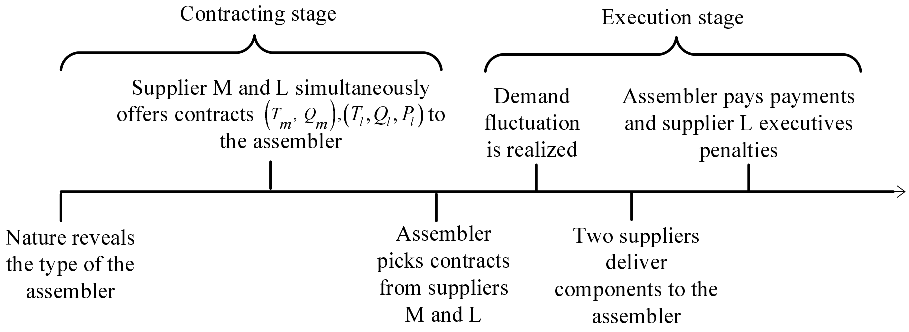

Figure 4: Timing of events when suppliers move simultaneously

Theorem 5. *When the two suppliers move simultaneously, their optimal contracts and profits are determined to be those as listed in Tables 7 and 8, respectively.*

Table 7: Suppliers' optimal contracts in Case SS

Region	Quantity	Penalty	Supplier M's transfer payment	Supplier L's transfer payment
1) $b_l < k_l/\theta$	Q_1^{SS}	P_1^{SS}	t_{M1}^{SS}	t_{L1}^{SS}
2) $k_l/\theta \le b_l < r - k_m$	Q_2^{SS}	P_2^{SS}	t_{M2}^{SS}	t_{L2}^{SS}
3) $r - k_m \le b_l$	Q_3^{SS}	P_3^{SS}	t_{M3}^{SS}	t_{L3}^{SS}

where for $i = 1, 2, 3$, $Q_i^{SS}(x) = F^{-1}\left(\frac{r-k_i}{r}\right) + x$, $\quad P_1^{SS}(x) \in (b_l, k_l/\theta)$, $\quad P_2^{SS}(x) \in (b_l, r - k_m)$, for $i = 1, 2$,

$$t_{Mi}^{SS}(Q_i^{SS}) = \frac{1}{2}\left(r\boldsymbol{E}_\varepsilon\left[\min\left(x+\varepsilon, Q_i^{SS}\right)\right] + (2k_m - k_i)Q_i^{SS}\right),$$

$$t_{Li}^{SS}(Q_i^{SS}) = \frac{1}{2}\left(r\boldsymbol{E}_\varepsilon\left[\min\left(x+\varepsilon, Q_i^{SS}\right)\right] + (k_i - 2k_m)Q_i^{SS}\right),$$

$$P_3^{SS}(x) \in [k_l/\theta, r - k_m),\ t_{M3}^{SS}(Q_3^{SS}) = \frac{1}{2}\left(r\theta\boldsymbol{E}_\varepsilon\left[\min\left(x+\varepsilon, Q_3^{SS}\right)\right] + (k_m - k_l)Q_3^{SS}\right),$$

$$t_{L3}^{SS}(Q_3^{SS}) = \frac{1}{2}\left(r\theta\boldsymbol{E}_\varepsilon\left[\min\left(x+\varepsilon, Q_3^{SS}\right)\right] + (k_l - k_m)Q_3^{SS}\right).$$

Table 8: Participants' profits in Case SS

Region	Assembler's profit	Supplier L's profit	Supplier M's profit
1) $b_l < k_l/\theta$	0	$\frac{\mathcal{B}_1}{2}$	$\frac{\mathcal{B}_1}{2}$
2) $k_l/\theta \le b_l < r - k_m$	0	$\frac{\mathcal{B}_2}{2}$	$\frac{\mathcal{B}_2}{2}$
3) $r - k_m \le b_l$	0	$\frac{\mathcal{B}_3}{2}$	$\frac{\mathcal{B}_3}{2}$

where $\mathcal{B}_i, i = 1, 2, 3$ are defined in Table 4.

Theorems 1, 3 and 5 jointly show that in Case SS, the assembler's optimal order quantity is equal to that in either case of the two suppliers moving sequentially. In other words, neither sequentially contracting nor simultaneously contracting prevails in the optimal order quantity. These theorems also show that in the three cases MS, LS and SS, the assembler can obtain only its reservation profit under symmetric information. However, the suppliers' profits are different. In particular, when the two suppliers are involved in a moving sequence, the first mover extracts the entire system's profit and leaves the second mover with just its reservation profit. however, under simultaneous contracting, due to the two suppliers' equal status, supplier M and supplier L equally obtain one-half of the entire system's profit (see Table 8). This result is quite intuitive. Indeed, the components sold by both suppliers are equally essential to assemble the final product. Thus, the differences in their production costs are irrelevant for the purpose of profit allocation. On the other hand, we also know from Table 7 that everything else being equal, a higher fixed cost supplier always provides a higher price for the component. The ending result is that a supplier with a high fixed cost compensates for the cost disadvantage. Such an equal profit allocation result has been shown in Wang (2006) and Granot and Yin (2008).

6.2 Optimal contracts in Case SA

In this subsection, we characterize the optimal contracts of suppliers M and L in a decentralized assembly system, and compare them with those in Cases SS, MA and LA.

Theorem 6 (**Simultaneous contracting**). *In Region i)* $i \in \{1, 2, 3\}$*, the assembler's optimal buying quantity* $Q_i^{SA}(x)$ *satisfies*

$$Q_i^{SA}(x) = \begin{cases} x + \underline{\varepsilon} & \text{if} \quad \Gamma_i^{SA}(x + \underline{\varepsilon}) \leq 0 \\ \{Q_i(x) | \Gamma_i^{SA}(Q_i(x)) = 0\} & \text{otherwise.} \end{cases}$$

Supplier L's optimal unit penalties for delivery shortfall in Regions 1), 2) and 3) satisfy

$$P_1^{SA}(x) \in (b_l, k_l/\theta), P_2^{SA}(x) \in (b_l, r - k_m), P_3^{SA}(x) \in [k_l/\theta, r - k_m).$$

The suppliers' payments in Region i), $i = 1, 2$*, satisfy the following conditions:*

$$t_m(Q_i^{SA}(x)) = \frac{1}{2}\left(r\boldsymbol{E}_\varepsilon\left[\min\left(x+\varepsilon, Q_i^{SA}(x)\right)\right] - \int_a^x rF\left(Q_i^{SA}(m) - m\right) \mathrm{d}m + (2k_m - k_i)Q_i^{SA}(x)\right),$$

$$t_l(Q_i^{SA}(x)) = \frac{1}{2}\left(r\boldsymbol{E}_\varepsilon\left[\min\left(x+\varepsilon, Q_i^{SA}(x)\right)\right] - \int_a^x rF\left(Q_i^{SA}(m) - m\right) \mathrm{d}m + (k_i - 2k_m)Q_i^{SA}(x)\right),$$

and in Region 3), they satisfy the following conditions:

$$t_m(Q_3^{SA}(x)) = \frac{1}{2}\left(r\theta\boldsymbol{E}_\varepsilon\left[\min\left(x+\varepsilon, Q_3^{SA}(x)\right)\right] - \int_a^x r\theta F\left(Q_3^{SA}(m) - m\right) \mathrm{d}m + (k_m - k_l)Q_3^{SA}(x)\right),$$

$$t_l(Q_3^{SA}(x)) = \frac{1}{2}\left(r\theta\boldsymbol{E}_\varepsilon\left[\min\left(x+\varepsilon, Q_3^{SA}(x)\right)\right] - \int_a^x r\theta F\left(Q_3^{SA}(m) - m\right) \mathrm{d}m + (k_l - k_m)Q_3^{SA}(x)\right).$$

By comparing the suppliers' optimal contract parameters and the assembler's optimal profit in Case SA with those in Case SS, we can derive the following corollary.

Corollary 1. *The assembler's optimal order quantities, transfer payments from the assembler and the assembler's optimal profit in Case SA are less than those in Case SS.*

Intuitively, in Case SA, private information about the demand forecast makes the low-type assembler better able to exaggerate its demand forecast. To be able to mitigate such an adverse incentive, the suppliers must pay the information rent to induce the assembler to report the demand forecast truthfully, and as a result the optimal order quantities are distorted downward. This information rent leads to a higher profit for the assembler than that in Case SS. Furthermore, supplier M's and supplier L's transfer payments from the assembler in Case SA are less than those in Case SS, because their transfer payments are both strictly increasing in relation to the order quantity. Interestingly, the two suppliers' respective differences in transfer payments between Case SS and Case SA are equal. In other words, in Case SA, the two suppliers ought to pay an identical information rent to the assembler to achieve their optimal benefits.

In what follows, we compare the optimal contract parameters in Case SA with those in Case MA, which leads to the observation as given in Table 9. The comparison result for Cases SA and LA is similar, and thus, we omit it to avoid repetition. This observation indicates that the relationships between the suppliers' optimal contract parameters, including order quantity and transfer payments, in Cases SA and MA are not certain, but are determined in part by the demand structure.

Table 9: Comparison results of contract parameters in Cases SA and MA for specified distributions

Distribution $G(x)$	Distribution $F(u)$	Sign of $Q^{MA}-Q^{SA}$	Sign of $t_m(Q^{MA})+t_l(Q^{MA})-t_m(Q^{SA})-t_l(Q^{SA})$
Exponential	Normal	+	+
Any	Uniform	0	0
Uniform	Any	–	–
Exponential	Extreme Value	– when $u>0$, + when $u<0$	– when $u>0$, + when $u<0$

7 Value of Information (VOI)

Here, we systematically compare the six cases previously analyzed in Sections 4–6, and examine the impact of the information on the assembler's demand upon the profits of suppliers M and L.

Recall that for Cases MS, LS and SS, the suppliers' profits depend on the demands of the types of the assembler.

Supplier M's expected profit in Region i) of Case jp is

$$\pi_{mi}^{jp}=\int_a^b\Big(t_m(Q_i^{jp}(x))-k_mQ_i^{jp}(x)\Big)\,g(x)\mathrm{d}x, i\in\{1,2,3\}, j\in\{M,L,S\}, p\in\{S,A\}. \tag{11}$$

Supplier L's expected profit in Region i), $i\in\{1,2\}$, of Case jp is

$$\pi_{li}^{jp}=\int_a^b\Big(t_l(Q_i^{jp}(x))-k_iQ_i^{jp}(x)\Big)\,g(x)\mathrm{d}x, j\in\{M,L,S\}, p\in\{S,A\} \tag{12}$$

and in Region 3) is

$$\pi_{l3}^{jp}=\int_a^b\Big(t_l(Q_3^{jp}(x))-k_3\theta Q_3^{jp}(x)\Big)\,g(x)\mathrm{d}x, j\in\{M,L,S\}, p\in\{S,A\}. \tag{13}$$

We define the expected values of information of supplier M and supplier L on the assembler's demand information as

$$\mathrm{VOI}^j_{mi} = \pi^{jS}_{mi} - \pi^{jA}_{mi}, i \in \{1,2,3\}, j \in \{M, L, S\} \tag{14}$$

and

$$\mathrm{VOI}^j_{li} = \pi^{jS}_{li} - \pi^{jA}_{li}, i \in \{1,2,3\}, j \in \{M, L, S\}, \tag{15}$$

respectively.

Theorem 7. *The relationships between the expected values of information for supplier M and supplier L on the assembler's demand information are as follows.*

(i) $\mathrm{VOI}^M_{li} = \mathrm{VOI}^L_{mi} < 0$, $|\mathrm{VOI}^L_{mi}| < \mathrm{VOI}^M_{mi}$, $|\mathrm{VOI}^M_{li}| < \mathrm{VOI}^L_{li}$, $i \in \{1,2,3\}$;

(ii) $\mathrm{VOI}^S_{mi} = \mathrm{VOI}^S_{li} > 0, i \in \{1,2,3\}$;

Theorem 7(i) indicates that, under symmetric information, the second mover earns only the reservation profit, and hence the second mover's expected value of information is negative. That is, the second mover is always better off when the assembler has an informational advantage. For the first mover, the expected value of information is positive, namely the first mover is more reliant upon the existence of less asymmetric information in the trade. From this regard, the first mover can extract the entire system's profit given symmetric information. However, given asymmetric information, the first mover has to pay a part of its profits to the assembler to induce truth telling, and to the second mover to ensure participation. Under such circumstances, the suppliers are willing to invest in acquiring better demand information. For example, many suppliers in the semiconductor industry resort to the services of market research companies, such as VLSI Research, to obtain demand forecasts of the market (Kalkancı and Erhun 2012). Additionally, the second mover's expected values of information are equal in sequential contracting. This is because given asymmetric information, regardless of whether supplier M or supplier L acts as the second mover, they obtain the same profit. As asymmetric information results in reduced expected supply chain's profit, the sum of the first and second mover's expected values of information are positive, and the second mover's absolute expected value of information (which is itself negative) is less than the first mover's (which is positive). This demonstrates that asymmetric information has a far greater impact upon the first mover.

Theorem 7(ii) implies that the expected values of information for suppliers M and L are equal and both are positive. This is because in the case of simultaneous contracting, supplier M and supplier L equally extract one-half of the entire supply chain's profits under symmetric information and one-half of the entire supply chain's profits minus the assembler's profit with asymmetric information. The reason that the expected value of information is positive is that asymmetric information leads to a reduction in the supply chain's expected profit. Thus, in the case of simultaneous contracting, suppliers M and L are both of equal status and are always better off when given more information.

In general, the relative preference for sequential versus simultaneous contracting for the suppliers is not immediate. However, under distributional assumptions, we can draw the following observation.

Proposition 3. *If* $\varepsilon \sim U[\underline{\varepsilon}, \overline{\varepsilon}]$, $|\mathrm{VOI}_{li}^{M}| = |\mathrm{VOI}_{mi}^{L}| < \mathrm{VOI}_{mi}^{S}, i \in \{1, 2, 3\}$.

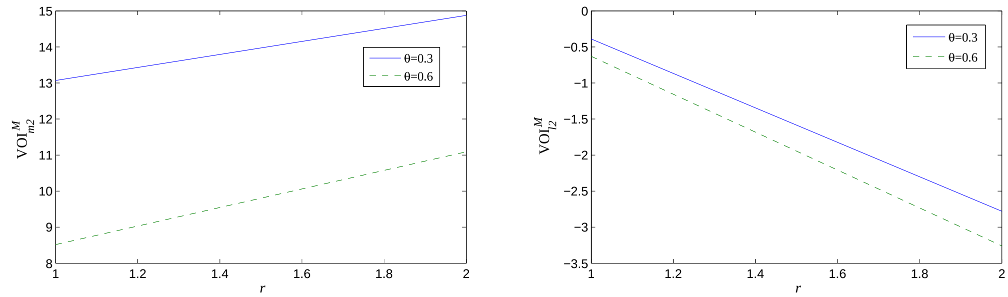

Figure 5: The impacts of r and θ on VOI_{m2}^{M} and VOI_{l2}^{M}, $\xi \sim U[3,6]$, $\varepsilon \sim U[-2,8]$, $k_m = 0.15$, $k_l = 0.05$, $b_l = 0.8$

In order to explain the results we have obtained and show the effects of supplier L's reliability θ and the market price r on the values of information and contracting sequence, we consider illustrative examples as shown in Figures 5–7. Specifically, we set supplier M's unit production cost $k_m = 0.15$, supplier L's unit production cost $k_l = 0.05$ and supplier L's unit cost of backup production $b_l = 0.8$. The setting of the parameter values consists with production practice that the backup production cost is larger than the regular one, and the production cost of the more reliable supplier is usually larger than the less reliable one. We assume that the random fluctuation of demand $\varepsilon \sim U[-2,\ 8]$ and the supplier's assessment about the assembler's demand forecast $\xi \sim U[3,\ 6]$, satisfying the distribution assumptions made in Section 3 as well as the condition that the realized demand is always nonnegative. Figure 5 illustrates how the market price and supplier L's reliability affect the values of information for the first mover and the second mover, respectively. We observe that the value of information for the first mover is high when supplier L's reliability is low (a small θ) or the market price is high. When supplier L's reliability is low, the assembler faces a higher supply risk, and hence decreases the order quantity. In this situation, the first mover has more incentive to acquire demand information, as the benefit from the first-mover right dominates the payment for information. Similarly, as the assembler's market price increases, there is much room for the first-mover to better understand the demand information. Hence, the value of information for the first mover is higher when supplier L's reliability is low and market price is high. The opposite results hold for the second mover.

8 Value of Contracting Sequence (VOCS)

In this section, we analyze the three different contracting sequences' effects upon the assembler and the two asymmetric suppliers' profits given either symmetric information or asymmetric information. We refer to the difference in profits between the optimal expected profit under sequential contracting and that under simultaneous contracting as the *value of contracting sequence* for an entity of the supply chain. We define the value of the contracting sequence as an expected value to facilitate comparison. In particular, we define the values of contracting sequence for the assembler, supplier M, supplier L and the supply chain, respectively, as follows:

$$\mathrm{VOCS}_{ai}^{jp} = \pi_{ai}^{jp} - \pi_{ai}^{Sp}, i \in \{1,2,3\}, j \in \{M, L\}, p \in \{S, A\}, \tag{16}$$

$$\mathrm{VOCS}_{mi}^{jp} = \pi_{mi}^{jp} - \pi_{mi}^{Sp}, i \in \{1,2,3\}, j \in \{M, L\}, p \in \{S, A\}, \tag{17}$$

$$\mathrm{VOCS}_{li}^{jp} = \pi_{li}^{jp} - \pi_{li}^{Sp}, i \in \{1,2,3\}, j \in \{M, L\}, p \in \{S, A\}, \tag{18}$$

and

$$\begin{aligned} \mathrm{VOCS}_{ci}^{jp} &= \mathrm{VOCS}_{ai}^{jp} + \mathrm{VOCS}_{mi}^{jp} + \mathrm{VOCS}_{li}^{jp} \\ &= \sum_{q=m,l,a} \left(\pi_{qi}^{jp} - \pi_{qi}^{Sp} \right), i \in \{1,2,3\}, j \in \{M, L\}, p \in \{S, A\}. \end{aligned} \tag{19}$$

Theorem 8. *When the assembler's demand information is public,*

(i) $\mathrm{VOCS}_{ai}^{MS} = \mathrm{VOCS}_{ai}^{LS} = 0$ *for* $i \in \{1,2,3\}$*;*

(ii) $\mathrm{VOCS}_{mi}^{MS} = \mathrm{VOCS}_{li}^{LS} = -\mathrm{VOCS}_{li}^{MS} = -\mathrm{VOCS}_{mi}^{LS} = \frac{1}{2}\pi_w$

$$= \frac{1}{2} \begin{cases} r\boldsymbol{E}_{\varepsilon}\left[\min\left(x+\varepsilon, Q_i^{MS}(x)\right)\right] - k_i Q_i^{MS}(x), & if \quad i = 1,2 \\ r\theta \boldsymbol{E}_{\varepsilon}\left[\min\left(x+\varepsilon, Q_i^{MS}(x)\right)\right] - k_i \theta Q_i^{MS}(x), & if \quad i = 3; \end{cases}$$

Particularly, the following results hold:

$$\mathrm{VOCS}_{m(l)1}^{M(L)S} > \max\left\{\mathrm{VOCS}_{m(l)2}^{M(L)S}, \mathrm{VOCS}_{m(l)3}^{M(L)S}\right\}$$

and

$$\mathrm{VOCS}_{m(l)1}^{L(M)S} < \min\left\{\mathrm{VOCS}_{m(l)2}^{L(M)S}, \mathrm{VOCS}_{m(l)3}^{L(M)S}\right\};$$

(iii) $\mathrm{VOCS}_{ci}^{MS} = \mathrm{VOCS}_{ci}^{LS} = 0$ *for* $i \in \{1,2,3\}$.

It follows from Theorem 8(i) that regardless of supplier M or supplier L moving first, the expected values of the contracting sequence for the assembler in Cases MS and LS are always equal to zero. This is intuitive because given symmetric information, the assembler only obtains a reservation profit in Cases MS, LS and SS.

Recall that Theorems 1, 3 and 5 show that with symmetric information, when the two suppliers form a moving sequence, the first mover will attain the entire supply chain's profit; however, when they move simultaneously, each supplier can achieve one-half of the entire supply chain's profit. Consequently, as Theorem 8(ii) indicates, the value of contracting sequence for the first mover is equal to one-half of the entire supply chain's profit. In other words, the first mover benefits better from the moving advantage, while the value of contracting sequence for the second mover is negative, equaling the negative value of half of the entire supply chain's profit. Thus, the second mover always refers simultaneous contracting to sequential contracting.

Theorem 8(iii) reveals that for the entire supply chain, the expected values of contracting sequence in Cases MS and LS are also always equal to zero, as with the corresponding assembler's expected value. This is intuitive because under symmetric information, there exists no profit loss in Cases MS, LS and SS.

Theorem 9. *When the assembler's demand information is private,*

(i) $\mathrm{VOCS}_{ai}^{MA} = \mathrm{VOCS}_{ai}^{LA}$ *for* $i \in \{1, 2, 3\}$*;*

(ii) $\mathrm{VOCS}_{mi}^{MA} = \mathrm{VOCS}_{li}^{LA}$ *and* $\mathrm{VOCS}_{li}^{MA} = \mathrm{VOCS}_{mi}^{LA}$ *for* $i \in \{1, 2, 3\}$*;*

(iii) $\mathrm{VOCS}_{ci}^{MA} = \mathrm{VOCS}_{ci}^{LA}$ *for* $i \in \{1, 2, 3\}$.

Similar to Theorem 8(i), Theorem 9(i) reveals that regardless of who moves first, the expected values of contracting sequence for the assembler in Cases MA and LA are always equal; however, the sign of the value is not certain depending on assumptions regarding the distribution of the demand. This is because with asymmetric information, the assembler attains an equally positive profit in Cases MA and LA. Thus, we can draw the conclusion of Theorem 9(i) by subtracting the assembler's expected profit in Case SA.

Different from the results presented in Theorem 8(ii) is that with symmetric information, the first and second movers' values of contracting sequence are equal in absolute value. Under asymmetric information, the first mover's expected values of contracting sequence in Cases MA and LA are identical, as are the second mover's. However, the expected values of contracting sequence for the first and second mover may not be equal. This is because, under asymmetric information, regardless of whether supplier M or supplier L acts as the first mover, they obtain the same profit. Consequently, as Theorem 9(ii) indicates, the value of contracting sequence for the first and the second mover is equal. However, under asymmetric information, as illustrated in Figure 6, both the first and second mover may benefit from, or be harmed by, the first-mover right. Interestingly, this result contrasts with the existing results within the operations management literature regarding assumed use of complete information. In particular, Wang (2006) and Jiang and Wang (2007) reported that, compared to simultaneous contracting, sequential contracting would lead to higher total profits. The primary difference among all of these models is the profit function of the suppliers, which is determined in part by the demand structure, meaning that the results regarding the contracting sequence are not robust to demand assumptions.

Intuitively, because the total expected supply chain profits in Cases MA and LA are equal given asymmetric information, subtracting the total expected supply chain profit in Case SA yields the result in Theorem 9(iii).

Therefore, it can be concluded that sequential contracting has no impact upon the total expected supply chain value or the value of contracting sequence for the overall supply chain.

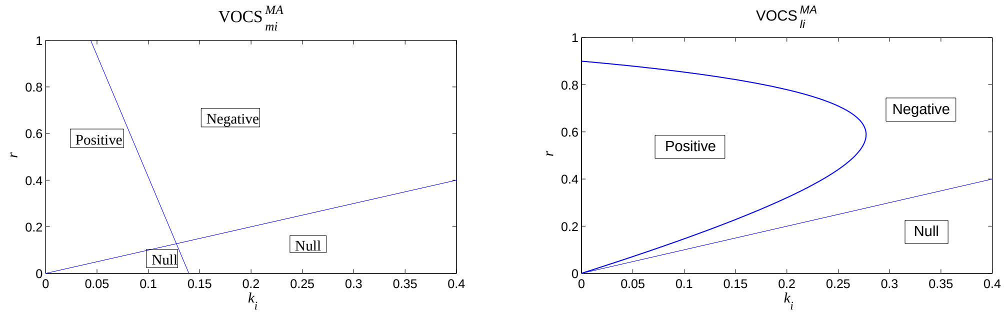

Figure 6: The values of contracting sequence VOCS_{mi}^{MA} and VOCS_{li}^{MA}, $\xi \sim U[3,6]$, $\varepsilon \sim U[-2,8]$

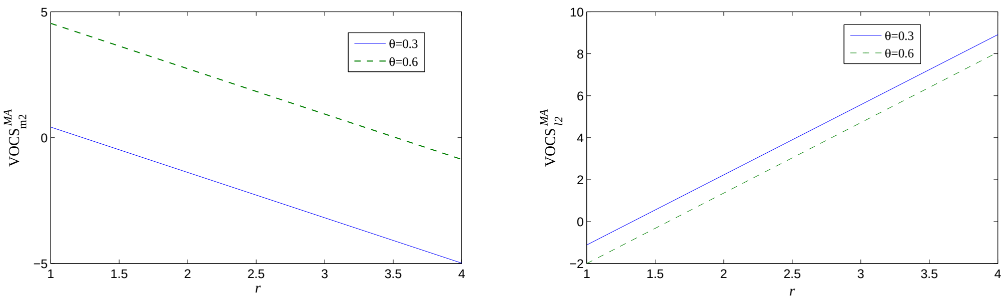

Figure 7: The impacts of r and θ on VOCS_{m2}^{MA} and VOCS_{l2}^{MA}, $\xi \sim U[3,6]$, $\varepsilon \sim U[-2,8]$, $k_m = 0.15$, $k_l = 0.05$, $b_l = 0.8$

Figure 7 illustrates how the market price and supplier L's reliability affect the values of contracting sequence for the first mover and the second mover, respectively. We observe that the value of contracting sequence for the first mover is high when supplier L's reliability is high (a big θ) or the market price is low, i.e., either a lower supply risk or a lower market price induces both suppliers to forego moving first. This is because when supplier L's reliability is high, the assembler faces a lower supply risk which induces the assembler to order more. In this situation, the benefit from the first-mover right dominates the loss from supply risk, encouraging the supplier to make use of the first-mover right. As the assembler's market price decreases, there is little room for the use of first-mover right, i.e., the loss from lower market price cannot outweigh the benefit from the first-mover right. Hence, the value of contracting sequence for the first mover is higher when the market price is low. The opposite results hold for the second mover.

9 Conclusion

We have studied the pricing and risk management strategies of two heterogeneous suppliers, one is more reliable with no supply risk and the other is less reliable with supply risk, for outsourcing by an assembler who is better informed about the demand relative to the suppliers. We have addressed this problem with an aim of designing appropriate menus of contracts that would resolve the asymmetry of demand information between the assembler and suppliers, in addition to maximizing the two suppliers' expected profits. We have systematically investigated the cases where the more reliable supplier or the less reliable supplier moves first as well as cases in which they move simultaneously.

By comparing the results of these cases, we have explored the *value of contracting sequence* to different players and the overall supply chain. We have also examined the values of the assembler's demand forecast, or the *value of information* to different suppliers, as well as the interactions between heterogeneous suppliers, specifically under different contracting sequences and information structures (asymmetric and symmetric information). The results have shown that in the case of sequential contracting, with asymmetric information, the assembler's optimal order quantities and the first moving supplier's transfer payments are both distorted downward from those under symmetric information, and the second mover's transfer payment's distortion is uncertain and dependent on the distribution of demand forecast. While in the case of simultaneous contracting, the assembler's optimal order quantity is distorted downward from that under symmetric information, and the two suppliers' total payments from the assembler are equal. Given asymmetric information, the overall supply chain suffers from a loss as the suppliers offer the low type assembler contracts differing from what an integrated supply chain may offer.

Whether to acquire demand information in a supply chain has considerable influence on suppliers' decisions and profitability and the system's efficiency. We find that in the case of sequential contracting, the first mover benefits more from the first-mover advantage under symmetric information but may benefit or be harmed by the first-mover advantage under asymmetric information. In addition, the first mover is shown to be more desperate for the existence of less asymmetric information in the trade; by contrast, the second mover is always better off when the assembler has an information advantage. Asymmetric information harms the overall supply chain because the suppliers offer the low type assembler contracts that differ from what an integrated supply chain could offer. Furthermore, in the case of simultaneous contracting, both suppliers are of equal status and are always better off with more information.

Our work also touches upon the issue of how the less reliable supplier's reliability affects the values of information and contracting sequence. We find that a low reliability of the less reliable supplier enlarges the value of information for the first mover, and discourages the supplier from making use of the first-mover right. These results provide useful guidelines for firms to make their decisions on information acquisition and selection of contracting timing.

Several important extensions of our paper could be pursued. Specifically, it is important to extend the analysis to a more general demand distribution as well as to consider the case when the retail price is determined endogenously. It would also be interesting to extend the model to incorporate supplier competition by including multiple suppliers producing the same component. Additionally, we have assumed that the supplier's disruption risk is exogenously given. It would be interesting and important to investigate the value of risk information for each individual firm when their disruption risk is asymmetric information. Finally, we have assumed that the suppliers are independent; therefore, it would be worth applying cooperative game theory to see how individual firms may behave if they cooperate. Given the complexity of the current model, we suspect that these extensions would complicate the analysis substantially; hence, we leave them for significant future research.

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