SUPPLY RISKS AND ASYMMETRIC INFORMATION

by

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To Mom and Dad
For giving me life

To my wife, Yunyan Tao
For her support, understanding and patience

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Chapter 1

Introduction

One of the foremost concerns of supply chain managers today is building supply chains that can handle supply disruptions. There are a number of reasons why supply chain managers are becoming increasingly preoccupied with supply risk. First, supply disruptions are more likely than before, because the widespread use of outsourcing is not only stretching supply chains further geographically, but it is also turning supply networks into intricate webs of highly interdependent players. In fact, in a 2008 survey of 138 companies, 58% reported that they suffered financial losses within the last year due to a supply disruption.[1] Second, outsourcing to external vendors is making supply risks harder to foresee and, therefore, harder to prepare for. Third, the consequences of supply risks have arguably become more costly than before. Successful initiatives such as lean manufacturing, quick response, and postponement proved beneficial in maintaining high fill rates while squeezing inventory out of the pipeline, but they also reduced the buffers that a firm could fall back on in the case of a supply disruption, thus accentuating the costly effects of disruptions.

This dissertation focuses on supply-risk management in decentralized supply chains, in which suppliers may have private information about their odds of experiencing a disruption. In the Introduction (this chapter), we first illustrate several types of supply risk, and then briefly review operational tools used to manage those risks. Next,

[1] For more details, see `http://www.infoworld.com/article/08/09/17/Most_companies_lag_in_supply_chain_risk_management_1.html`.

we discuss the challenges in supply-risk management arising from the decentralized nature of the supply chain. In particular, we focus on asymmetric information about supply disruption risk, and highlight how it influences the interactions among firms in the supply chain. Lastly, we define the research questions and outline this dissertation.

1.1. Types of Supply Risk

When a buyer experiences a supply disruption, the key ramification is the inability to meet customer demand, resulting in costs ranging from loss of customer goodwill to non-performance penalties, from loss of revenue to reduced market capitalization. Within these fairly large boundaries, supply risks come in many forms. In particular, the causes for supply disruptions are myriad: an accident at a supplier's facility, natural disasters, bankruptcy of a key supplier, defective parts or components, labor strikes, etc. Despite the diversity of causes, supply risks by and large fall into four categories depending on how they manifest themselves.

Shortage of a critical part or the product itself: Oftentimes a buyer experiences a supply risk in the form of a shortage of a critical part (or a shortage of the product itself in cases where the entire product is outsourced). For example, in late 1990s, Boeing had trouble keeping up with the demand and missed several delivery deadlines. The poor delivery performance was blamed mainly on shortages of parts such as tie rods and bearings (Biddle, 1997b).

Loss of finished goods inventory due to the use of a defective part: Another form of supply risk is the use of a defective input, which results in finished goods that do not meet standards. Such supply risks can have very serious consequences and can result in the recall of the entire finished goods inventory. For example, following the deaths of numerous pets in 2007, pet food producer Menu Foods Corp. had to recall more than 60 million cans and pouches of dog and cat foods for more than 100 pet-food brands (Myers, 2007). The deaths were later linked to melamine, a poisonous industrial chemical. The melamine was traced to wheat gluten, which Menu Foods (a Canadian firm) had bought from ChemNutra (a U.S.-based supplier), who, unbeknownst to Menu Foods, had decided to outsource it to Xuzhou Anying Biologic Technology Development Co. Ltd. (a Chinese supplier). In the past few years there have been many other similar recalls: the spinach recall in the US upon the discovery of batches contaminated with e.coli (Wall Street Journal, 2007), Mattel's recall of toys due to the use of lead paint (Casey, 2007), several brands recalling their laptops due to defective batteries produced by Sony (Morse, 2006).

Loss of supplier capacity: The loss of supplier capacity can stem from a variety of reasons such as a shift in the supplier's business strategy, supplier bankruptcy, and accidents or natural disasters. An example of the former is the medical device manufacturer Beckman Coulter's loss of its supplier Dovatron, who produced customized chips for Beckman Coulter.[2] After Dovatron was acquired by Flextronics in 2000, the company was restructured to focus on higher volume products, and Flextronics decided it would no longer serve Beckman Coulter, who was purchasing a low-volume specialty product. There are abundant examples of supplier bankruptcies that threatened to cut the supply of critical parts, e.g., the bankruptcy of UPF-Thompson, the sole provider of chassis for Land Rover's Discovery model (Jennings, 2002); the bankruptcy of automotive supplier Collins & Aikman, which led to a halt in the shipment of parts to Ford's Fusion plant (McCracken, 2006). Likewise, there are several examples of accidents and natural disasters resulting in temporary loss of suppliers' facilities, e.g., the 1999 earthquake in Taiwan, causing disruptions at semi-conductor plants, which made 70% of the world's graphic chips and 10% of the world's memory chips (Savage, 1999; Papadakis, 2003); the fire at a plant of Aisin Seiki, the sole supplier of a key component used in the brake system of many Toyota models (Nishiguchi and Beaudet, 1998); the fire at a Phillips chip plant, which served

[2]For more details, see `http://www.callahan-law.com/verdicts-settlements/fraud-beckman-coulter/index.html`.

both Nokia and Ericsson, exposing the competitive advantage that Nokia had over Ericsson thanks to the robustness of its supply chain (Sheffi, 2005).

Supply cost risk: Another type of supply risk is related to the uncertainty about the cost of inputs. For example, a part that is procured from a distant supplier may quickly become more expensive if rising oil prices lead to a hike in shipping costs. Supply costs risks can also arise in connection with shortages. For instance, in 2000, the price of palladium increased sharply when Russia, who is the main source of this precious metal, held up its supply. Consequently, automotive manufacturers, who use palladium in catalytic converters, suffered a $100 increase in the productions cost per vehicle (White, 2000).

1.2. Operational Tools to Deal with Supply Risk

Firms use several operational tools to manage the risk of supply disruptions. We next discuss them briefly.

Multi-sourcing: In many cases a buyer will have the option to source the same part from not one, but multiple suppliers. When such an option is exercised, i.e., when the buyer diversifies, the buyer is less vulnerable to risks associated with any one supplier. As such, diversification can help make the buyer more resilient to supply risks such as shortages, defective parts or loss of supplier capacity. On the other hand, when the buyer chooses not to diversify, having multiple suppliers results in increased supplier competition, thus yielding benefits to the buyer.

Creating external or internal backup sources of supply: In the face of a disruption, the buyer can scramble to create an alternate source of supply. For example, when the fire at Aisin Seiki threatened to halt the production of many Toyota models, the two companies worked together with many other suppliers to create an alternate source. Likewise, when Beckman Coulter lost its supply of chips from Dovatron, it chose to replace the lost supply by building an in-house production line.

Using non-performance penalties: Most supply contracts include provisions for penalties that will be imposed on a supplier in the event that the supplier fails to deliver on its promises. As a last resort, a buyer can choose to sue the supplier to enforce such penalty clauses.

There are other tools that the buyer can employ to reduce risk: a buyer can perform qualification screening when selecting a new supplier or can audit its existing suppliers; the buyer may induce the supplier to invest in itself to reduce the odds of a disruption. In this dissertation, however, we focus on the use of dual-sourcing, backup sources of supply and non-performance penalties.

1.3. Asymmetric Risk Information in Decentralized Supply Chains

In a decentralized supply chain, the supplier's priorities and interests are not necessarily well aligned with those of the buyer's. Such misalignments may result in increased supply risks. For example, the parts shortage that resulted in Boeing's troubles was partly due to suppliers not keeping up with Boeing's major overhaul of its production process to improve its cycle times (Biddle, 1997a). Likewise, in the case of Beckman Coulter, the part which was highly critical to Beckman Coulter was simply an unprofitable specialty product for Dovatron, which is why Flextronics dropped the part after acquiring Dovatron.

As a consequence of misalignment of interests, the supplier will not necessarily volunteer to the buyer the information about the supplier's vulnerability to a disruption. When dealing with the buyer, the supplier is unlikely to reveal the details of its true financial status, operational capability, or the identities of its own suppliers.

Not having access to the supplier's reliability information may be very detrimental to a buyer. It is interesting to note, for example, that Land Rover was not aware of the looming bankruptcy of its supplier UPF-Thompson. Hence, once the bankruptcy arrived, Land Rover was unprepared and had few options (Jennings, 2002). Likewise, Menu Foods was not aware of the second-tier supplier utilized by its first-tier supplier ChemNutra and, eventually, it was this second-tier supplier's product that resulted in the contamination of pet food (Myers, 2007).

Such asymmetric information about supply risk affects how the buyer manages its supply risk. For example, Menu Foods would likely have heightened its risk-management measures, had it known in advance that its first-tier supplier in U.S. had outsource production of wheat gluten to a Chinese supplier.

1.4. Research Questions and the Plan of the Dissertation

Most research in the extant supply-risk management literature assumes that the buyer and the supplier are equally knowledgeable about the likelihood of a supply disruption. This dissertation contributes to the literature by studying the effects of asymmetric information regarding supplier reliability. In particular, this dissertation explores the interaction between asymmetric information about the supplier's probability of disruption and a manufacturer's (buyer's) use of supply-risk management tools, namely, backup production option, dual-sourcing option and non-delivery penalty.

We explore the following research questions:

- What is the effect of asymmetric risk information on the manufacturer's use of risk management tools?
- What is the value of information about the supplier's reliability?
- What is the value of risk management tools under asymmetric information?

The dissertation consists of three essays. In Chapter 2, we model a supply chain with one manufacturer and one unreliable supplier, in which the supplier's reliability is either high or low and is the supplier's private information. Upon disruption, the supplier chooses between paying a penalty to the manufacturer for the shortfall and exercising its backup production option to fill the manufacturer's order. Using a game-theoretic approach (mechanism design theory), we derive the optimal contracts offered by the manufacturer. We find that asymmetric information about the supplier's reliability may cause the manufacturer to stop using backup production with the low-reliability type of the supplier while the manufacturer continues to use it with the high-reliability type. Consequently, asymmetric information makes the backup production option less valuable for the manufacturer when backup production is moderately expensive. However, the converse is true when backup production is cheap. Hence, information and the backup production option can be either substitutes or complements. Surprisingly, under asymmetric information the value of the backup production option may increase even as the probability of drawing the more reliable supplier type increases. In addition, information about the supplier's reliability could become more valuable for the manufacturer even as both supplier types become more reliable. Thus, higher supplier reliability need not be a substitute for better information.

In Chapter 3, we examine the manufacturer's strategic use of a dual-sourcing option, which enables a precautionary approach (diversification) to managing supply disruption risks. We find that asymmetric information about the suppliers' reliabilities effectively makes diversification more expensive and pushes the manufacturer towards sole-sourcing to leverage competition. Consequently, information becomes more valuable for the manufacturer when the underlying business environment changes in ways that encourage diversification, such as higher product revenue, lower correlation between the suppliers' disruption processes, and smaller reliability gap between supplier types. Surprisingly, the additional cost that asymmetric information imposes on diversification may cause the manufacturer to cease diversifying, even as the supply base reliability erodes. Furthermore, the dual-sourcing option may be more or less valuable under asymmetric information, compared to under symmetric information.

In Chapter 4, we study a problem where the manufacturer delegates its procurement of a part to one of two unreliable suppliers, who form a coalition to fulfill the manufacturer's requirement. Under delegation, the manufacturer loses some control over the procurement process. Hence, if the manufacturer wants to reduce its supply disruption risk, it can only indirectly induce both suppliers to produce by imposing a high non-performance penalty on the coalition. The results show that, compared to direct contracting, delegation may encourage the manufacturer to induce diversification with one high-type and one low-type, but may discourage the manufacturer from doing so with two low-type suppliers. We find that delegation may decrease or increase the manufacturer's profit, depending on the modeling parameters such as the cost of disruption and the probability of drawing a high-type supplier. In contrast, delegation would not change the manufacturer's profit, if the suppliers' reliabilities were common knowledge in the supply chain.

Chapter 5 summarizes the findings and discusses future directions.

Chapter 2

Supply Disruptions, Asymmetric Information and a Backup Production Option

2.1. Introduction

In March of 2007, following the deaths of numerous pets, Menu Foods Corp., a producer of pet food, had to recall more than 60 million cans and pouches of dog and cat foods for more than 100 pet-food brands. Myers (2007) reports that the deaths were linked to melamine, an industrial chemical suspected of causing kidney and liver failure. The melamine was traced to wheat gluten, which Menu Foods (a Canadian firm) had bought from ChemNutra (a U.S.-based supplier), who, unbeknownst to Menu Foods, had outsourced it to Xuzhou Anying Biologic Technology Development Co. Ltd. (a Chinese supplier). This example illustrates that, as supply chains are extended by outsourcing and stretched by globalization, disruption risks and lack of visibility into a supplier's status can both worsen. The possible causes for supply disruptions are myriad, for instance, supplier bankruptcy, labor strikes and machine breakdown (Sheffi, 2005).

As supply risks increase, it is crucial for manufacturers to learn how to anticipate, prepare for, and manage potential supply disruptions. The losses due to supply disruptions can be huge. For example, shortly after initial recalls were issued on March 16, 2007, the market capitalization of Menu Foods Corp. lost about half of its value, dropping to $70 Million. Generally, Hendricks and Singhal (2003, 2005a,b) find that firms that experienced supply glitches suffer from declining operational performance and eroding shareholder value (e.g., the abnormal return on stock of such firms is negative 40% over three years).

A manufacturer has a number of choices when managing its supply risk, including supplier qualification screening, multi-sourcing, flexibility, and penalties levied for supplier non-performance. Intuitively, the effectiveness of risk-management tools used by a manufacturer depends on information the manufacturer has about the supplier. For example, risk-management measures put into place by Menu Foods would likely have been different, had it known that ChemNutra was outsourcing to a Chinese supplier. In practice, suppliers are often privileged with better information about their likelihood of experiencing a production disruption than the manufacturers they serve, because of the suppliers' private knowledge of their financial status, state of operations, or input sources. However, most of the extant research on supply disruptions assumes that the manufacturer and supplier are equally knowledgeable about the likelihood of supply disruptions. The majority of papers that incorporate asymmetric information do so in the context of suppliers' costs, and only a few model asymmetric information about supply disruptions. There is a crucial difference between asymmetric information about suppliers' costs and asymmetric information about supply disruptions. Supply disruptions affect not only the manufacturer's cost, but also the manufacturer's risk profile (risk-return tradeoff). As a consequence, to handle uncertainty about supply disruptions, the manufacturer can not only design information-eliciting contracts (as considered in the economics literature), but can also avail itself of various operational risk-management tools.

To address these gaps in the current literature, in this chapter we investigate the interaction between risk-management strategies and asymmetric information about supplier reliability. We address the following questions:

Research Question 1 How do a manufacturer's risk-management strategies change in the presence of asymmetric information about supply reliability?

Research Question 2 How much would the manufacturer be willing to pay to eliminate information asymmetry?

Research Question 3 Are risk-management tools more, or less, valuable when there is information asymmetry?

Research Question 4 How do answers to the above questions depend on changes in the underlying business environment, such as supply base heterogeneity, or the manufacturer's contracting flexibility?

In answering these questions, we limit our consideration within the set of possible risk-management strategies. We examine penalties for non-delivery, and an ability of the manufacturer to offer contract alternatives to a supplier. Penalty clauses in contracts are a common means for buyers to recover damages for non-delivery.[1] The penalty amount is mutually agreed upon at the time of contracting as a proactive way to avoid costly litigation for damages in the event of non-delivery. We assume that, had litigation occurred, the supplier would have been found to be at fault for the disruption.[2] As an alternative to the penalty clause, one could use a canonical, two-part tariff (fixed plus variable payment) contract and obtain the same equilibrium outcome as in our contract with penalty clause. Either the variable payment or the penalty provides an incentive to the supplier to look for alternative means of satisfying its obligations. In our model, we call such alternatives *backup production*. Backup production could take many forms. For the Menu Foods Corp. example, upon disruption a supplier like ChemNutra might re-source its wheat gluten from a different second-tier supplier (not Xuzhou Anying, who was the culprit of the disruption),

[1] What we call penalties in this chapter are known, in precise legal terms, as "liquidated damages." To be court-enforceable, liquidated damages must not exceed damages that the buyer reasonably expects to suffer as a result of supplier non-performance (Corbin, 2007). The penalties studied in this chapter satisfy this requirement. For more on non-performance remedies and contract law, see Plambeck and Taylor (2007) and references therein.

[2] An example of this is the suit brought by medical device manufacturer Beckman Coulter against its circuit board supplier Flextronics, after Flextronics exited the medical device circuit board business without delivering the units promised to Beckman Coulter (Beckman Coulter v. Flextronics, OCSC Case No. 01CC08395, September 24, 2003 Orange County Superior Court), described at `http://www.callahan-law.com/verdicts-settlements/fraud-beckman-coulter/index.html`.

install different quality controls, produce the wheat gluten itself, or perhaps use a combination thereof. Backup production sometimes involves heroic efforts by the supplier. For example, in 1997, when a fire at one of Toyota's suppliers — Aisin Seiki, threatened to halt production at many Toyota plants, Aisin Seiki was able to avert disruption by shifting production to its own suppliers and other firms (including some outside of automotive industry, see Nishiguchi and Beaudet, 1998). Where backup production is infeasible or implausible, we capture this by including in the model the possibility that backup production is prohibitively expensive and hence never used. In addition, we extend our analysis to the case where the manufacturer has access to its own backup production option.

We use a single-period, single-supplier, single-manufacturer model where the supplier is subject to a random production disruption, the likelihood of which is the supplier's private information. There are two supplier types, according to their reliability: high and low. In case of a production disruption, the supplier has two choices: use a perfectly reliable (but costly) backup production option to fulfill the manufacturer's order or pay the manufacturer a penalty. Using mechanism design theory, we find the optimal menu of contracts offered by the manufacturer to the supplier, and obtain answers to our research questions. We emphasize a few of our results below.

Because backup production at the supplier improves the chances of products being delivered to the manufacturer, one might intuitively expect that the manufacturer is more likely to encourage the use of this tool when working with a less reliable supplier. However, under information asymmetry, we observe that this need not be true, addressing *research question 1*. In an effort to correctly set incentives for a more reliable supplier, the manufacturer may force a less reliable supplier to pay penalties in case of a disruption, while asking a more reliable supplier to use backup production.

Addressing *research question 2*, the value of perfect information for the manufacturer depends on the cost of the supplier's backup production option. Where backup production is cheap, the value of information is small. The value of information is the greatest for moderately costly backup production, where the manufacturer, in an attempt to control the incentives of a more reliable supplier, decides to deviate from the risk-management strategy optimal under symmetric information. Furthermore, jumping to *research question 4*, as the reliability gap between the two supplier types increases, the value of information for the manufacturer increases as well. Interestingly, the value of information may also increase as supplier types become uniformly more reliable. Thus, higher reliability need not be a substitute for better information.

Intuitively, the better the manufacturer's information about the supplier's reliability, the more precisely it can execute risk-management actions such as ensuring the supplier would exercise its backup production option, and the more valuable the presence of such an option is for the manufacturer. In contrast to this intuition, we find that the supplier's backup production option may become less valuable if better information about the supplier becomes available, addressing *research question 3*.

The chapter is organized as follows. We briefly review related literature in the next section. The model is described in §2.3. In §2.4, we present the optimal contracts under symmetric information as a benchmark for our study of asymmetric information. The optimal menu of contracts under asymmetric information is presented in §2.5. Value of information, value of backup production and the interaction between them are explored in §2.6. We conduct a sensitivity analysis in §2.7. In §2.8 we extend our model to allow for the manufacturer's backup production option. §2.9 summarizes managerial implications, discusses model limitations, and suggests future research directions. Proofs can be found in the chapter's appendix.

2.2. Literature Review

Supply chain risk management has attracted interest from both researchers and practitioners of Operations Management. Chopra and Sodhi (2004) and Sheffi (2005) provide a diverse set of supply disruption examples. Various operational tools that deal with supply disruptions have been studied: multi-sourcing (e.g., Anupindi and Akella, 1993; Tomlin, 2005; Babich et al., 2005, 2007), alternative supply sources and backup production options (e.g., Serel et al., 2001; Kouvelis and Milner, 2002; Babich, 2006), flexibility (e.g., Van Mieghem, 2003; Tomlin and Wang, 2005), and supplier selection (e.g., Deng and Elmaghraby, 2005). For a recent review of supply-risk literature see Tang (2006b).

These, and the majority of other papers in the supply-risk literature, assume that the distribution (likelihood) of supply disruptions is known to both the suppliers and the manufacturer. In contrast, we assume that the supplier is better informed about the likelihood of disruption. There are few papers that consider the issue of the manufacturer not knowing the supplier reliability distribution. For instance, Tomlin (2008) studies a model where the manufacturer faces two suppliers, one with known and the other with unknown reliability. The manufacturer learns about the latter supplier's reliability through Bayesian updating. In our model, information is also revealed, but through a contract choice rather than through repeated interactions. In Gurnani and Shi (2006), a buyer and supplier have differing estimates of the supplier's reliability. Unlike our setting, the buyer's beliefs about reliability are not affected by knowing the supplier's self-estimate. Depending on whose estimate is larger, the authors employ contract terms incorporating either downpayment or non-delivery penalty.

Disruptions in supply chains could be caused by quality problems and several papers have examined information asymmetry in quality control. For instance, Baiman et al. (2000) study a moral hazard issue surrounding the fact that both the supplier and the manufacturer can exert costly effort to prevent (requiring supplier effort) or weed out defective items. Lim (1997) examines a problem where the manufacturer can inspect incoming units at a cost to identify defects. If inspection is not done and a defective unit is passed on to the consumer, the channel incurs warranty costs.

The central theme in this literature is how to allocate quality-related costs among the channel partners and/or how to motivate several parties to exert costly quality improvement efforts.

In the operations contracting literature, prior work has examined situations in which cost information is private, be it the manufacturer's cost (Corbett et al., 2004) or the supplier's cost (Corbett, 2001). In addition, the latter is extensively studied in the literature on procurement auctions under asymmetric information (Rob, 1986; Dasgupta and Spulber, 1989; Che, 1993; Beil and Wein, 2003; Elmaghraby, 2004; Chen et al., 2005; Kostamis et al., 2009; Wan and Beil, 2008). However, as we discussed in the introduction, there is a crucial difference between asymmetric information about suppliers' costs (studied in those papers) and asymmetric information about supply disruptions (studied here).

2.3. Model

We model a stylized supply chain, in which a manufacturer purchases a product from a supplier to satisfy market demand. The supplier is unreliable in that its regular production is subject to a random disruption. We assume there are two types of suppliers in the market: high reliability and low reliability. These types differ from each other in their likelihood of a disruption and their cost of regular production. Let the fraction of high-reliability suppliers in the market be $\alpha \in (0,1)$. We hereafter refer to high- and low-reliability suppliers as high-type and low-type, and distinguish them with labels H and L. For a type-i supplier, $i \in \{H, L\}$, we represent the random yield of its regular production as a Bernoulli random variable ρ_i having success probability θ_i, that is,

$$\rho_i = \begin{cases} 1 & \text{with probability } \theta_i \\ 0 & \text{with probability } 1-\theta_i, \end{cases} \tag{2.1}$$

where probability θ_i can be interpreted as a measure of the supplier's reliability. The success probabilities are $\theta_H = h$ and $\theta_L = l$, where $1 > h > l > 0$. We assume that it costs a type-i supplier c_i (per unit) to run regular production, regardless of whether the run is disrupted or not. Although we allow c_H and c_L to be different, the high-type is assumed to be the more cost-efficient supplier, that is, the expected cost of successfully producing one unit using regular production is smaller for the high-type supplier:[3]

Assumption 1. *$c_L/l > c_H/h$.*

In addition to a regular production run, the supplier has access to a backup production option in case of disruption. We assume that backup production is perfectly reliable, with unit cost b.[4] We make the following assumption on b:

Assumption 2. *$b > c_H/h$.*

In other words, the cost of backup production is greater than the high-type supplier's expected cost of successfully producing one unit using regular production. As explained in §3.3.1, this assumption avoids the uninteresting situation in which neither type of supplier uses regular production before running backup production.

To focus on the effects of supply risk without additional complications due to demand uncertainty, we assume the manufacturer faces a deterministic demand, D, for the product. In other words, demand is known at the time the manufacturer places its order. The demand is infinitely divisible, and without loss of generality, we normalize it to $D = 1$. The manufacturer collects a revenue of r per unit sold. We restrict r as follows:

Assumption 3. *$r > c_H/h$.*

[3] Note that, for one unit of input going into regular production, the expected output of a type-i supplier is θ_i. Hence, were repeated regular production attempts allowed, the expected cost of successfully producing one unit using regular production would be c_i/θ_i.

[4] The analysis would go through if one assumed that the unit cost of backup production were a random variable, whose value is realized after the supplier commits to using it. In such a case, the parameter b would represent the expected value of the random unit backup production cost.

If this assumption does not hold, the manufacturer would not order from either supplier type, because the unit revenue would be less than the expected cost of producing one unit.

To capture the manufacturer's lack of visibility into the supplier's reliability and cost, we assume that the supplier's type is its private information. All other information is common knowledge. The manufacturer designs a contract menu without knowing the type of the supplier, who can act strategically and take advantage of its private information. We find the manufacturer's optimal menu of contracts using mechanism design theory. This approach dates back to the seminal work by Myerson (1981). Invoking the *Revelation Principle* (Dasgupta et al., 1979; Myerson, 1979), the mechanism design problem can be solved by focusing on incentive compatible, direct revelation mechanisms. Therefore, the manufacturer offers two contracts, one for each type of supplier, and the supplier truthfully reports its type. In our model, a contract consists of three terms: an upfront transfer payment, $X_i \geq 0$, an order quantity, $q_i \geq 0$, and, because of the possibility of supplier non-delivery, a unit penalty, $p_i \geq 0$, for delivery shortfall, where $i \in \{H, L\}$.

The timing of events is shown in Figure 3.1. The problem can be divided into two stages: contracting and execution. At time zero, at the beginning of the contracting stage, nature reveals the supplier type to the supplier, but not to the manufacturer. Then, the manufacturer designs a menu of two contracts, (X_i, q_i, p_i), $i \in \{H, L\}$. The supplier then selects a contract (signals its type), concluding the contracting stage. In the execution stage, the supplier receives its transfer payment from the manufacturer, runs regular and/or backup production, makes delivery, and pays a penalty, if necessary.

We solve the problem by working backward from the execution stage. The next subsection presents the analysis of the supplier's execution stage decisions.

2.3.1 Supplier's Production Decisions

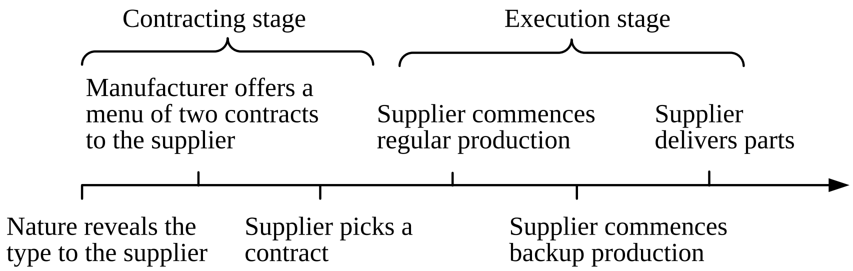


Figure 2.1: Timing of events.

For notational convenience, in this subsection we suppress the supplier's subscript i from the parameters ρ_i, c_i, θ_i, X_i, q_i, and p_i. In the execution stage, given a contract (X, q, p) offered by the manufacturer, the supplier chooses its regular production size and delivery quantity to maximize its expected profit. The supplier first decides on z, the size of its regular production run. After the completion of regular production, which has yielded $\rho\, z$, the supplier decides the total quantity to be delivered to the manufacturer, y. Subsequently, the supplier engages backup production to make up the difference, $(y - \rho\, z)^+$, and/or pays a penalty for the shortfall $(q - y)^+$. The $^+$ operator is defined such that $x^+ = x$ if $x > 0$ and $x^+ = 0$ if $x \leq 0$. The following is the optimization problem of the supplier whose probability of successful regular production is θ:

$$\pi_S(X, q, p|\theta) = \max_{z \geq 0} \left\{ X - c\, z - E \left\{ \min_{y \geq 0} \left[b\, (y - \rho\, z)^+ + p\, (q - y)^+ \right] \right\} \right\}. \tag{2.2}$$

Let z^* and y^* denote the optimal decisions. Solving this problem, we observe that, when deciding how much to deliver, the supplier either uses backup production (i.e., $y^* = q$), if $b < p$, or pays a penalty (i.e., $y^* = \rho\, z^*$), if $b \geq p$. When choosing z^*, the supplier trades off the cost of regular production, $c\, z$, against the cost of recourse (backup production cost or penalty). The supplier will run regular production only if its expected cost of successfully producing one unit using regular production, c/θ, is lower than both backup production cost, b, and unit penalty, p. The following proposition formalizes the above discussion.

Proposition 1. *For a given contract (X, q, p), the size of the supplier's optimal regular production run, z^*, the delivery quantity, y^*, and the supplier's expected profit, π_S, are:*

Case	z^*	y^*	$\pi_S(X, q, p\vert\theta)$
(1) $p > b$, $b < c/\theta$	0	q	$X - b\,q$
(2) $p > b$, $b \geq c/\theta$	q	q	$X - c\,q - (1-\theta)b\,q$
(3) $b \geq p$, $p < c/\theta$	0	0	$X - p\,q$
(4) $b \geq p$, $p \geq c/\theta$	q	$\rho\,q$	$X - c\,q - (1-\theta)p\,q$

Notice that in case (3) of Proposition 1 the supplier makes no effort to produce. As we will see later, this situation never arises under the manufacturer's optimal contracts. In case (1) of Proposition 1 the supplier does not use regular production, instead finding it more economical to use backup production to produce and deliver q units. Note that, per Assumption 2, this situation does not arise with the high-type supplier, who will always give regular production a try. However, Assumption 2 does not rule out the possibility that $b \leq c_L/l$, in which case the low-type supplier would bypass regular production.

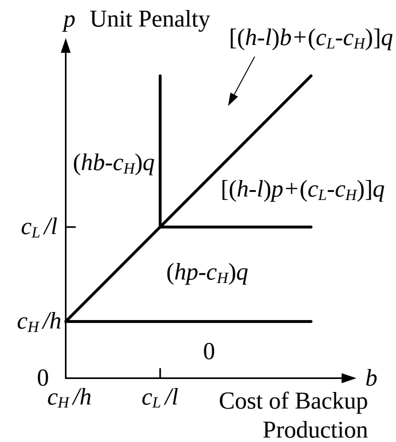
Proposition 1 shows that the supplier's profit is increasing in its reliability, θ. (In this chapter, we use increasing and decreasing in the weak sense.) We extend this observation and show that, given the same contract, a high-type supplier would earn a larger profit in expectation than a low-type supplier. We denote the difference between the high- and low-types' optimal profits, given the manufacturer's contract, by Γ.

Definition 1. $\Gamma(q, p) \triangleq \pi_S(X, q, p|h) - \pi_S(X, q, p|l)$ *is the benefit of being a high-type supplier over a low-type supplier, given the manufacturer's contract,* (X, q, p).

Notice that Γ is not a function of the transfer payment, X, because the transfer payment term cancels out in the calculation. Applying Proposition 1 to the definition yields the expression for $\Gamma(q,p)$.

Corollary 1. *For given q and p, the expression for $\Gamma(q,p)$ is given by the following table and illustrated in the accompanying figure. Moreover, $\Gamma(q,p)$ is always non-negative.*

Case		$\boldsymbol{\Gamma(q,p)}$
$p > b$	$b < c_L/l$	$(h\,b - c_H)q$
	$b \geq c_L/l$	$[(h-l)\,b + (c_L - c_H)]q$
$b \geq p$	$p < c_H/h$	0
	$c_L/l > p \geq c_H/h$	$(h\,p - c_H)q$
	$p \geq c_L/l$	$[(h-l)\,p + (c_L - c_H)]q$



$\Gamma(q,p)$ reflects the high-type supplier's reliability advantage over the low-type supplier. We will carefully consider this advantage when solving the manufacturer's contract design problem, as described in the next subsection. With Corollary 1, $\Gamma(q,p)$ can be shown to be increasing in b, p, q, and h, and decreasing in l. These properties of $\Gamma(q,p)$ will be instrumental in developing insights about the effects of asymmetric information on the manufacturer's optimal contract.

2.3.2 Manufacturer's Contract Design Problem

Recall that we model the manufacturer's decisions as a mechanism design problem, using a standard information-economics approach (e.g., see Laffont and Martimort, 2002), and, by the *Revelation Principle*, we focus on incentive-compatible, direct revelation contracts.

For shorthand, we define $\pi_H(X,q,p) \triangleq \pi_S(X,q,p|h)$ and $\pi_L(X,q,p) \triangleq \pi_S(X,q,p|l)$. In addition, given contract (X_i, q_i, p_i), we denote the optimal delivery of the type-i

supplier by $y_i^*(X_i, q_i, p_i)$, $i \in \{H, L\}$. Where convenient, we suppress the explicit dependence of y_i^* on the contract terms. The expressions of π_H, π_L and y_i^* can be obtained from Proposition 1.

Using these definitions, we present the manufacturer's contract design problem as the following optimization program:

$$\max_{\substack{(X_H, q_H, p_H)\\(X_L, q_L, p_L)}} \left\{ \begin{array}{l} \alpha\, \left[r\, E\min(y_H^*, D) - X_H + p_H\, E(q_H - y_H^*)^+\right] \\ + (1-\alpha)\left[r\, E\min(y_L^*, D) - X_L + p_L\, E(q_L - y_L^*)^+\right] \end{array} \right\} \tag{2.3a}$$

subject to

$$\text{(I.C. H)} \quad \pi_H(X_H, q_H, p_H) \geq \pi_H(X_L, q_L, p_L), \tag{2.3b}$$

$$\text{(I.C. L)} \quad \pi_L(X_L, q_L, p_L) \geq \pi_L(X_H, q_H, p_H), \tag{2.3c}$$

$$\text{(I.R. H)} \quad \pi_H(X_H, q_H, p_H) \geq 0, \tag{2.3d}$$

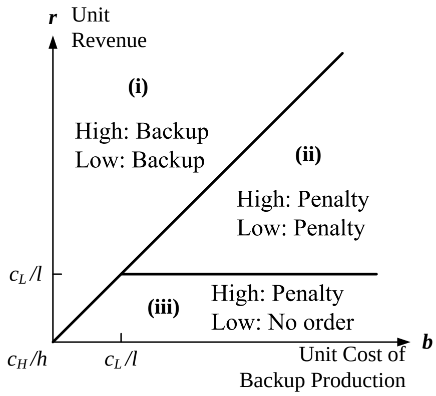
$$\text{(I.R. L)} \quad \pi_L(X_L, q_L, p_L) \geq 0, \tag{2.3e}$$

$$X_H \geq 0,\; X_L \geq 0,\; q_H \geq 0,\; q_L \geq 0,\; p_H \geq 0, p_L \geq 0. \tag{2.3f}$$

The objective function (2.3a) of this problem is the sum of the manufacturer's expected profits from the high and low supplier types, each weighted by the probability of drawing that type of supplier. Constraints (I.C. H) are (I.C. L) are *incentive compatibility* constraints, which ensure that a supplier does not benefit from lying about its type to the manufacturer. Constraints (I.R. H) and (I.R. L) are *individual rationality* constraints, which reflect the fact that a supplier accepts the contract only if its reservation profit is met. We assume that both supplier types have the same reservation profit, normalized to zero. This assumption is common in mechanism design problems, and has been used in both the economics literature (e.g., Myerson, 1981; Che, 1993) and the operations management literature (e.g. Lim, 1997; Corbett et al., 2004).

2.4. Optimal Contracts under Symmetric Information

To explore the influence of asymmetric information, as a benchmark we first derive the optimal menu of contracts when the manufacturer knows perfectly the reliability type of the supplier. We refer to this case as *symmetric information*.



Legend

"High" and "Low" refer to the supplier's type.

"Penalty" and "Backup" refer to the manufacturer's choice of inducing the supplier to pay a penalty or use backup production in case of disruption.

"No order" indicates that the manufacturer does not order from the supplier.

Figure 2.2: Supplier's actions induced by the manufacturer's optimal menu of contracts under symmetric information.

Under symmetric information, nature reveals the supplier type to the supplier and the manufacturer simultaneously. Thus, the incentive compatibility constraints (2.3b) and (2.3c) in the manufacturer's problem (2.3) are no longer required, and the manufacturer's choice of the contract for one supplier type does not interfere with the choice for the other type. At optimality, the individual rationality constraints in the manufacturer's optimization problem will be binding, and either type of supplier earns zero profit. This is formalized in Proposition 2 below, which describes the optimal menu of contracts and resulting profits.[5] Let $\breve{\pi}_{M|i}(X_i, q_i, p_i)$ and $\breve{\pi}_i(X_i, q_i, p_i)$ denote the manufacturer's and supplier's profits, given that nature draws a supplier of type i, $i \in \{H, L\}$, and the manufacturer offers contract (X_i, q_i, p_i) to the supplier of type i. Thus, $\alpha\, \breve{\pi}_{M|H} + (1 - \alpha)\, \breve{\pi}_{M|L}$ is the manufacturer's expected profit prior to nature drawing the supplier type, where we have suppressed the contract terms. Let

[5] The legal requirement that penalties (or "liquidated damages") do not exceed a reasonable estimate of the buyer's damages translates to $p \leq r$ in our model. This condition is satisfied by the buyer's optimal contracts derived in this chapter.

$\breve{\pi}^*_{M|i}$ and $\breve{\pi}^*_i$ denote the manufacturer's and supplier's profits under the manufacturer's optimal contract. Figure 2.2 illustrates the following proposition.

Proposition 2. *The manufacturer's optimal contract under symmetric information is*

Region	Penalty	Quantity	Transfer Payment
(i): $r > b$	any $p_H \in (b, r)$	$q_H = 1$	$X_H = c_H + (1 - h)b$
	any $p_L \in (b, r)$	$q_L = 1$	$X_L = \begin{cases} b & b < c_L/l \\ c_L + (1 - l)b & b \geq c_L/l \end{cases}$
(ii): $b \geq r > c_L/l$	any $p_H \in [c_H/h, b]$	$q_H = 1$	$X_H = c_H + (1 - h)p_H$
	any $p_L \in [c_L/l, b]$	$q_L = 1$	$X_L = c_L + (1 - l)p_L$
(iii): $b \geq r,\ c_L/l \geq r$	any $p_H \in [c_H/h, b]$	$q_H = 1$	$X_H = c_H + (1 - h)p_H$
	any $p_L \in [0, r)$	$q_L = 0$	$X_L = 0$

Furthermore, the supplier's profit is zero, that is, $\breve{\pi}^*_H = \breve{\pi}^*_L = 0$, and the manufacturer extracts the entire channel profit ($\breve{\pi}_{M|i}$ is the manufacturer's profit if the supplier is of type i, $i \in \{H, L\}$), given in the following table:

Region	$\breve{\pi}^*_{M\|H}$	$\breve{\pi}^*_{M\|L}$
(i) and $b < c_L/l$	$r - c_H - (1 - h)\, b$	$r - b$
(i) and $b \geq c_L/l$	$r - c_H - (1 - h)\, b$	$r - c_L - (1 - l)\, b$
(ii)	$h\, r - c_H$	$l\, r - c_L$
(iii)	$h\, r - c_H$	0

From Proposition 2, in region (i), backup production is cheap relative to the product's market revenue, so the manufacturer uses backup production with both types of suppliers. In the sequel, if the manufacturer's contract induces the supplier to use backup production in case of disruption, we will refer to this by the shorthand term "using backup production". In region (ii), backup production is costly, and the manufacturer induces both types to pay a penalty in case of disruption. In the sequel, if the manufacturer's contract induces the supplier to pay penalties, we will refer to this by the shorthand term "paying penalty". In region (iii), the unit revenue, r, is too low to justify ordering from the low-type supplier.

Per Proposition 2, under symmetric information, the manufacturer extracts all channel profit. Let $\pi_{C|i}(X_i, q_i, p_i)$, $i \in \{H, L\}$, denote the channel's profit when nature draws a supplier of type i and the manufacturer offers this supplier contract (X_i, q_i, p_i), and let $\pi^*_{C|i}$ denote the channel's optimal profit. Hence, $\pi^*_{C|i}$ is given by $\breve{\pi}^*_{M|i}$, and the optimal contract under symmetric information also maximizes the channel's profit. It will be of interest in the following section to examine the channel's profit loss when the manufacturer offers a contract different from the contract in Proposition 2. In particular, we define the following.

Definition 2. $\Delta(X, q, p) \triangleq \pi^*_{C|L} - \pi_{C|L}(X, q, p)$ *is the channel loss given that nature draws a low-type supplier and the manufacturer offers this supplier contract* (X, q, p)*.*

2.5. Optimal Contracts under Asymmetric Information

In this section, we first overview the procedure of solving the manufacturer's problem (2.3) by describing the tradeoffs involved in the solution. The solution is presented in Proposition 3 below. We then compare the optimal contract with that under symmetric information.

The fundamental tradeoff. We first notice from re-arranging equation (3.2) that $-X_i + p_i\, E(q_i - y_i^*)^+ = -\pi_i(X_i, q_i, p_i) - c_i\, z_i^* - b\, E(y_i^* - \rho_i\, z_i^*)^+$ for $i \in \{H, L\}$, where z_i^* is the optimal size of the regular production run for the type-i supplier. We suppress the dependence of z_i^* on the contract terms (X_i, q_i, p_i) for notational convenience. Using this, we rewrite the manufacturer's objective (2.3a) as

$$\max_{\substack{(X_H, q_H, p_H)\\(X_L, q_L, p_L)}} \left\{ \begin{array}{l} \alpha \left[r\, E \min(y_H^*, D) - \pi_H(X_H, q_H, p_H) - c_H\, z_H^* - b\, E(y_H^* - \rho_H\, z_H^*)^+ \right] \\ \quad + (1-\alpha) \left[r\, E \min(y_L^*, D) - \pi_L(X_L, q_L, p_L) - c_L\, z_L^* - b\, E(y_L^* - \rho_L\, z_L^*)^+ \right] \end{array} \right\}. \tag{2.4}$$

Second, as an outcome of the mechanism design problem (see the proof of Proposition 3 in the appendix of this chapter), at the optimal solution, the high-type supplier's incentive compatibility constraint is binding, that is $\pi_H(X_H, q_H, p_H) = \pi_H(X_L, q_L, p_L)$. Combining this observation with the definition of $\Gamma(q,p)$ (Definition 3), we have $\pi_H(X_H, q_H, p_H) = \pi_L(X_L, q_L, p_L) + \Gamma(q_L, p_L)$. At the same time, the low-type supplier's individual rationality constraint (2.3c) is also binding, that is $\pi_L(X_L, q_L, p_L) = 0$. Therefore, at optimality, the profit of the high-type supplier, $\pi_H(X_H, q_H, p_H)$, equals $\Gamma(q_L, p_L)$, which is a function of the contract terms offered to the low-type supplier. In addition, at the optimal solution, the individual rationality constraint for the high-type supplier (2.3d) and the incentive compatibility constraint for the low-type supplier (2.3c) turn out to be non-binding. Hence, we can roll binding constraints (2.3b) and (2.3e) into the objective function (2.4) by substituting $\pi_H(X_H, q_H, p_H) = \Gamma(q_L, p_L)$ and $\pi_L(X_L, q_L, p_L) = 0$ into (2.4) and separating terms that depend on (X_H, q_H, p_H) and (X_L, q_L, p_L) to obtain

$$\max_{(X_H, q_H, p_H)} \left\{ \alpha \, \left[r\, E \min(y_H^*, D) - c_H\, z_H^* - b\, E(y_H^* - \rho_H\, z_H^*)^+ \right] \right\} \tag{2.5a}$$

$$+ \max_{(X_L, q_L, p_L)} \left\{ (1-\alpha) \, \left[r\, E \min(y_L^*, D) - c_L\, z_L^* - b\, E(y_L^* - \rho_L\, z_L^*)^+ \right] - \alpha\, \Gamma(q_L, p_L) \right\}. \tag{2.5b}$$

Third, we observe that the bracketed expressions in (2.5a) and (2.5b) are the same as the profit of the channel with a high-type and low-type supplier, respectively. Therefore, when the manufacturer chooses (X_H, q_H, p_H) to maximize (2.5a), the resulting profit equals $\pi^*_{C|H}$. Furthermore, applying the definition of Δ (Definition 4), we can rewrite the manufacturer's objective function (2.5) as

$$\alpha\, \pi^*_{C|H} + (1-\alpha)\, \pi^*_{C|L} - \min_{(X_L, q_L, p_L)} \left\{ \alpha\, \Gamma(q_L, p_L) + (1-\alpha)\, \Delta(X_L, q_L, p_L) \right\}. \tag{2.6}$$

Observe from (2.6) that the manufacturer's profit is the optimal channel profit under symmetric information minus two types of losses due to asymmetric information: $\Gamma(q_L, p_L)$, which can be interpreted as the incentive payment to the high-type supplier to represent itself truthfully, and $\Delta(X_L, q_L, p_L)$, the loss in the channel profit. Thus, the manufacturer's decision boils down to selecting a contract, (X_L, q_L, p_L), offered to the low-type supplier, to minimize the sum of these two losses. To mitigate the loss due to the incentive payment, the manufacturer deviates from the contract that is optimal with the low-type supplier under symmetric information, causing channel loss (per Definition 4). This tradeoff between $\Gamma(q_L, p_L)$ and $\Delta(X_L, q_L, p_L)$ is the *fundamental tradeoff* in our analysis.

Optimal contracts under asymmetric information. Following the steps outlined above, we derive the optimal solution to problem (2.3). We divide the (b, r) plane into five regions using five lines, as illustrated on the right panel of Figure 2.3. See Lemma 1 in the appendix of this chapter for a formal definition of these five regions.

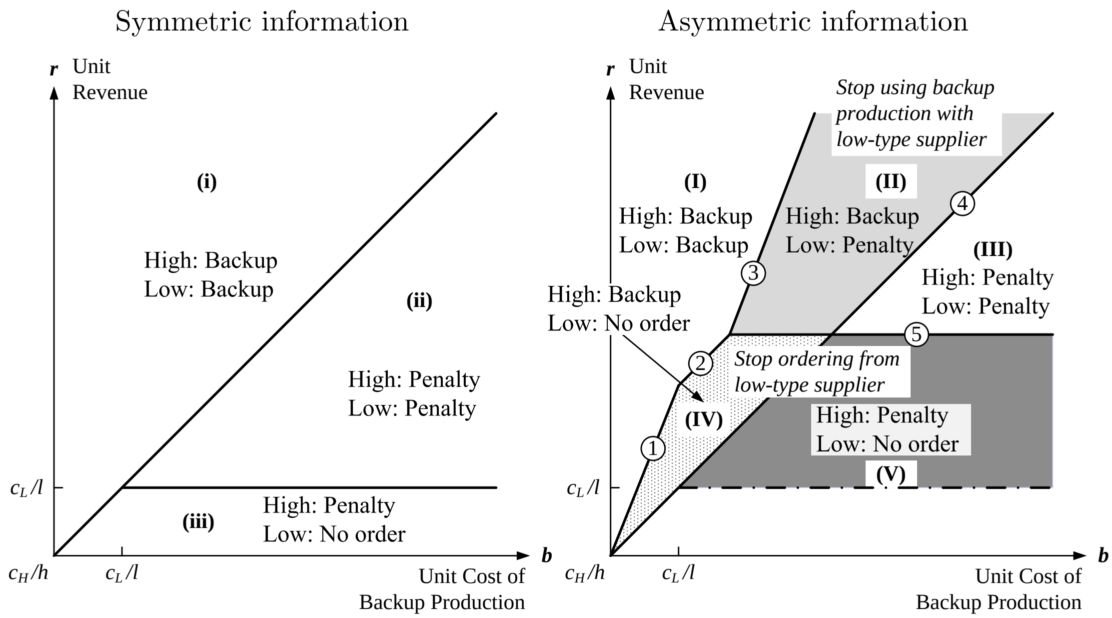


Figure 2.3: The supplier's actions induced by the manufacturer's optimal menu of contracts under symmetric information (left panel) and asymmetric information (right panel). The effects of asymmetric information are indicated on the right panel. Region (i) is the union of regions (I), (II) and (IV); region (ii) is the union of region (III) and the shaded portion of region (V); and region (iii) is the unshaded portion of region (V).

The right panel of Figure 2.3 shows the salient features of the menu of optimal contracts under asymmetric information. The optimal contract terms vary by region, and details are provided in the following proposition.

Proposition 3. *Under asymmetric information, the optimal unit penalties, p_H and p_L, order quantities, q_H and q_L, and transfer payments, X_H and X_L, offered to the high- and low-type suppliers are:*

Region	Penalty	Quantity	Transfer payment
(I)	any $p_H \in (b, r)$ any $p_L \in (b, r)$	$q_H = 1$ $q_L = 1$	$X_H = X_L = \begin{cases} b & b < c_L/l \\ c_L + (1-l)\,b & b \geq c_L/l \end{cases}$
(II)	any $p_H \in (b, r)$ $p_L = c_L/l$	$q_H = 1$ $q_L = 1$	$X_H = h\,(c_L/l) + (1-h)\,b$ $X_L = c_L/l$
(III)	any $p_H \in [c_L/l, b]$ $p_L = c_L/l$	$q_H = 1$ $q_L = 1$	$X_H = h\,(c_L/l) + (1-h)\,p_H$ $X_L = c_L/l$
(IV)	any $p_H \in (b, r)$ any $p_L \in [0, r)$	$q_H = 1$ $q_L = 0$	$X_H = c_H + (1-h)\,b$ $X_L = 0$
(V)	any $p_H \in [c_H/h, b]$ any $p_L \in [0, r)$	$q_H = 1$ $q_L = 0$	$X_H = c_H + (1-h)\,p_H$ $X_L = 0$

Furthermore, the low-type supplier's profit is zero, $\pi^*_L = 0$. The high-type supplier's profit, π^*_H, and the manufacturer's expected profits of sourcing from the high- and low-type suppliers, $\pi^*_{M|H}$ and $\pi^*_{M|L}$, are provided in the following table:

Region		Manufacturer's profit	High-type supplier's profit
(I)	$b < c_L/l$	$\pi^*_{M\|H} = \pi^*_{M\|L} = r - b$	$\pi^*_H = h\,b - c_H$
	$b \geq c_L/l$	$\pi^*_{M\|H} = \pi^*_{M\|L} = r - c_L - (1-l)\,b$	$\pi^*_H = (h-l)\,b + (c_L - c_H)$
(II)		$\pi^*_{M\|H} = r - h(c_L/l) - (1-h)b$ $\pi^*_{M\|L} = l\,r - c_L$	$\pi^*_H = (h-l)(c_L/l) + (c_L - c_H)$
(III)		$\pi^*_{M\|H} = h(r - c_L/l)$, $\pi^*_{M\|L} = l(r - c_L/l)$	$\pi^*_H = (h-l)(c_L/l) + (c_L - c_H)$
(IV)		$\pi^*_{M\|H} = r - c_H - (1-h)\,b$, $\pi^*_{M\|L} = 0$	$\pi^*_H = 0$
(V)		$\pi^*_{M\|H} = h\,r - c_H$, $\pi^*_{M\|L} = 0$	$\pi^*_H = 0$

Effect of asymmetric information on the optimal contract. Using Propositions 2 and 3, we compare the manufacturer's optimal risk-management policies under symmetric and asymmetric information and highlight the difference in Figure 2.3, addressing *research question 1.* Specifically, in region (II), under asymmetric information, the manufacturer induces the high-type supplier to use backup production in case of disruption, but (unlike the optimal contract under symmetric information) makes the low-type supplier pay a penalty. This is, perhaps, counterintuitive, because the manufacturer uses backup production as a quantity-risk management tool. Therefore, one might expect that the less reliable the supplier is, the more the manufacturer prefers that the supplier uses backup production. In regions (IV) and (V), as in the symmetric-information case, the manufacturer orders from the high-type supplier. However, in region (IV) and the shaded portion of region (V), information asymmetry causes the manufacturer to stop ordering from the low-type supplier.

To gain intuition for this behavior, note that the manufacturer deviates from the symmetric-information risk-management policies in order to reduce the incentive payment to the high-type supplier. Specifically, in region (II), had the low-type supplier used backup production, the resulting transfer payment to the low-type supplier would have been large, because backup production is relatively expensive. Consequently, the incentive payment to the high-type supplier would have been large as well. Therefore, the manufacturer curtails this large incentive payment by forcing the low-type supplier to pay penalty (less than the cost of backup production). Similarly, in region (IV) and the shaded portion of region (V) the incentive payment is avoided by simply not ordering from the low-type supplier.

As a consequence of the deviation from the symmetric-information contract, we have the following result.

Corollary 2. *The quantity received by the manufacturer from the supplier under symmetric information is stochastically larger than the quantity received under asymmetric information.*

The manufacturer deviates from the symmetric-information risk-management policies in order to reduce incentive payments. In doing so it incurs channel loss, as captured by the fundamental tradeoff in equation (2.6).

Informational rent and channel loss. Using the optimal contract terms from Proposition 3, we can evaluate the incentive payment to the high-type supplier, $\Gamma(q_L, p_L)$, and channel loss, $\Delta(X_L, q_L, p_L)$, at the optimal contract (X_L, q_L, p_L) offered to the low-type supplier. Hereafter, we denote the incentive payment at the optimal contracts by γ and refer to it as informational rent, as is customary in information economics. In addition, let δ denote the channel loss under the optimal contracts. The expressions of γ and δ are provided in Table 2.1.

Table 2.1 reveals that under the optimal contract, in all regions except region (II), the manufacturer incurs either informational rent or channel loss, but not both. Intuitively, the manufacturer chooses the less onerous type of loss. For example, in regions (IV) and (V), revenue is so low that the channel loss due to not ordering from the low-type supplier is small. In return for this sacrifice, the manufacturer avoids paying what would have been relatively high informational rent. In region (I), backup production is so cheap that the channel loss due to not using backup production with the low-type supplier is large. On the other hand, in region (III), backup production

Region		Informational rent, γ	Channel loss, δ
(I)	$b < c_L/l$	$h\,b - c_H$	0
	$b \geq c_L/l$	$(h-l)\,b + (c_L - c_H)$	0
(II)		$(h-l)(c_L/l) + (c_L - c_H)$	$(1-l)(r-b)$
(III)		$(h-l)(c_L/l) + (c_L - c_H)$	0
(IV)	$b < c_L/l$	0	$r - b$
	$b \geq c_L/l$	0	$r - c_L - (1-l)\,b$
(V)	$r > c_L/l$	0	$l\,r - c_L$
	$r \leq c_L/l$	0	0

Table 2.1: Informational rent, γ, and channel loss, δ, at the optimal contracts under asymmetric information.

is so costly that it would not be used with symmetric or asymmetric information, while high unit revenue entices the manufacturer to order from either supplier type. Therefore, there is no channel loss incurred in regions (I) and (III). In region (II) the manufacturer incurs a mixture of informational rent and channel loss.

2.6. Values of Information and Backup Production

In this section, we address *research questions 2* and *3*, examining how the value of information and the value of backup production depend on important problem parameters: backup production cost b and unit revenue r. As in the previous sections, all the figures in this section represent analytically derived results.

Value of information for an entity of the supply chain is the difference between its optimal expected profits under symmetric and asymmetric information.

The manufacturer earns the entire channel profit under symmetric information. However, under asymmetric information, it loses informational rent, γ, if the supplier is of high-type and suffers a channel loss, δ, if the supplier is of low-type (see the fundamental tradeoff in equation (2.6)). Therefore, the value of information for the manufacturer equals $\alpha\gamma + (1-\alpha)\delta$ (where expressions for γ and δ are provided in Table 2.1).

The supplier makes no profit under symmetric information, regardless of its type.

Under asymmetric information, the low-type supplier continues to make zero profit. Therefore, the value of information is zero for the low-type supplier. In contrast, the high-type supplier earns an informational rent, γ, under asymmetric information. Hence, the value of information for the high-type supplier is $-\gamma$.

The channel loses a profit, δ, under asymmetric information, when the manufacturer offers the low-type supplier a contract that differs from what an integrated channel would offer, as discussed earlier. The value of information for the channel (prior to nature choosing supplier type) is $(1-\alpha)\,\delta$, where $1-\alpha$ is the probability of drawing a low-type supplier.

Value of information and the cost of backup production. We first study how the value of information for the manufacturer, channel, and supplier change in the unit backup production cost, b. The results are shown on the left panel of Figure 2.4, which follows from Table 2.1 with unit revenue fixed at $r = r_0$ above line 5 (marked on the right panel). The behavior for smaller values of r (below line 5) is similar.

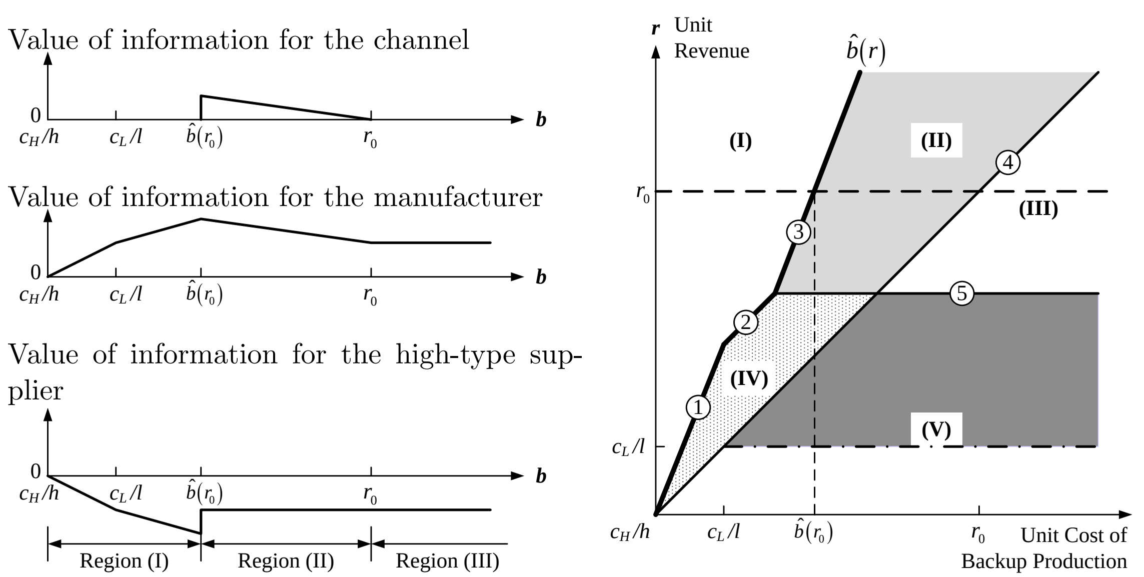


Figure 2.4: Value of information reaches its peak at the rightmost border of region (I), given a fixed r. $\hat{b}(r)$ is the union of line segments 1, 2, and 3.

For the manufacturer, the channel, and the supplier, the effect of information is most pronounced for moderate values of b. To gain intuition for this, consider a large r (above line 5). For small values of b, backup production is so cheap that the manufacturer would like both supplier types to use it. Similarly, if b is very expensive the manufacturer does not want either type of supplier to use it. At these extreme values of b, the manufacturer does not care to distinguish between supplier types and can offer them the same contract, as formalized in the following corollary.

Corollary 3. *Per Proposition 3, under asymmetric information, in regions (I) and (III) the manufacturer can offer the same optimal contract to the two supplier types by letting* $p_H = p_L$.

In contrast, at medium values of b, the tradeoffs are more intricate and the manufacturer may choose to stop using backup production with the low-type. Therefore, this is the region where the manufacturer benefits the most from knowing the supplier's type.

Value of information and the unit revenue. We now study how the value of information for the manufacturer, channel, and supplier changes in the unit revenue, r. The results are shown on the left panel of Figure 2.5, leveraging Table 2.1. We examine the value of information at a fixed backup production cost $b = b_0$, where b_0 is marked on the right panel of Figure 2.5. The behavior for other values of b is similar.

From Figure 2.5, observe that the value of information for the channel and the high-type supplier is non-monotone with jumps at $\bar{r}$ and $\hat{r}$, where $\bar{r}$ corresponds to line 5 and $\hat{b}(\hat{r}) = b_0$. Each discontinuity coincides with a strategic decision by the manufacturer to change whether it incurs informational rent, channel loss, or both, as captured by Table 2.1. For example, for $r \leq \bar{r}$ the manufacturer avoids paying an informational rent by not ordering from the low-type supplier, but once $r > \bar{r}$ the low-type receives an order and informational rent is incurred (along with channel loss). Finally, observe that the value of information is always increasing

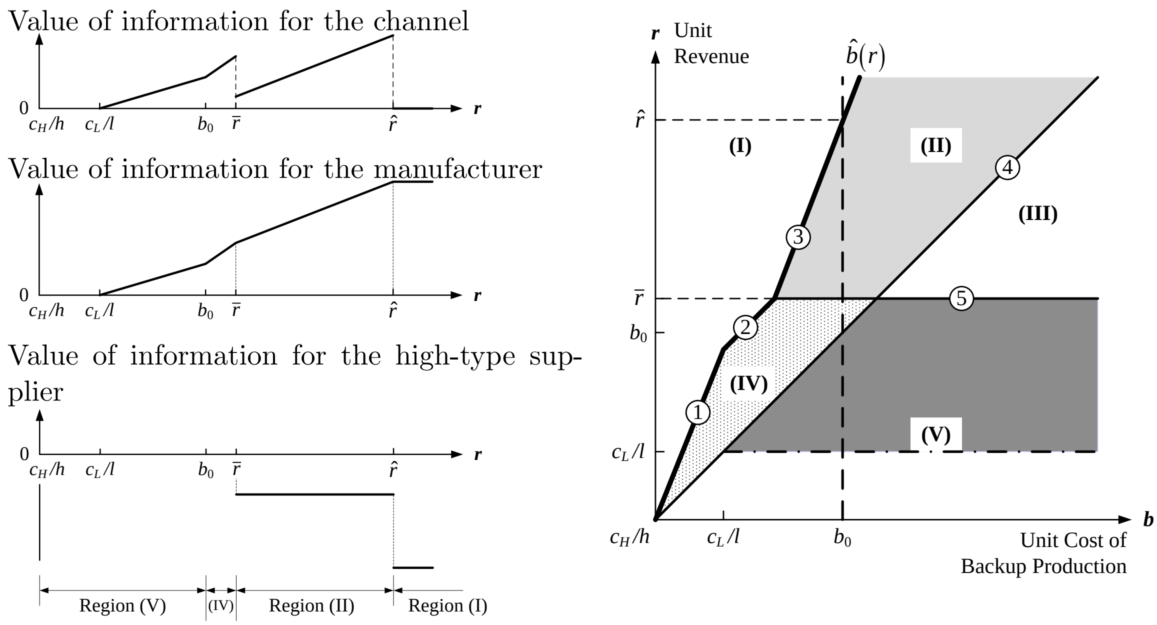


Figure 2.5: Value of information versus unit revenue, r. $\hat{b}(r)$ is the union of line segments 1, 2, and 3.

for the manufacturer, and is increasing within each region for the channel. From Corollary 2, the quantity received by the manufacturer and hence the quantity sold are stochastically smaller under asymmetric information. The larger the unit revenue, the larger loss the manufacturer would suffer due to the reduction of sales. Similar reasoning applies for the channel, within each region.

Value of backup production. For the manufacturer, supplier and channel, we examine the *value of the backup production option*, defined to be the difference between profits with and without backup production (where the latter can be computed by setting $b = r$, making backup production economically unattractive). The expressions for the value of backup production in Table 2.2 (see the Appendix) are derived from Proposition 3. It can be verified using Table 2.2 that the value of backup production for the manufacturer and the value for the channel are decreasing in the backup production cost b, increasing in the revenue r, and nonnegative under asymmetric information.

As shown in Figure 2.6, the value of backup production for the high-type supplier

Region		Manufacturer	High-type supplier
(I) $(r > \bar{r})$	$b < c_L/l$	$(r-b) - \bar{\theta}\,(r - c_L/l)$	$h\,(b - c_L/l)$
	$b \geq c_L/l$	$[r - c_L - (1-l)\,b] - \bar{\theta}\,(r - c_L/l)$	$(h-l)(b - c_L/l)$
(I) $(r \leq \bar{r})$	$b < c_L/l$	$(r-b) - \alpha\,h\,(r - c_H/h)$	$h\,b - c_H$
	$b \geq c_L/l$	$[r - c_L - (1-l)\,b] - \alpha\,h\,(r - c_H/h)$	$(h-l)\,b + (c_L - c_H)$
(II), (IV)		$\alpha\,(1-h)(r-b)$	0
(III), (V)		0	0

Table 2.2: Value of backup production for the manufacturer and high-type supplier under asymmetric information. $\bar{\theta} = \alpha h + (1-\alpha) l$ is the average reliability of suppliers and $\bar{r}$ is defined by line 5 in Figure 2.3.

is non-monotone in backup production cost, b, and could be negative. Recall that the profit of the high-type supplier comes from informational rent. For small r (i.e., $r \leq \bar{r}$), the high-type supplier earns zero informational rent in the absence of backup production, because the low-type supplier receives no orders. Therefore, for such r the value of adding backup production can only be positive. On the other hand, for large r (i.e., $r > \bar{r}$), the high-type supplier earns informational rent even in the absence of a backup production option. Introducing a cheap backup production option of unit cost $b < c_L/l$ reduces the economic advantage of being a high-type supplier, by allowing disruptions to be cheaply remedied. This diminishes the high-type supplier's informational rent. Therefore, for small b and large r, the value of backup production is negative for the high-type supplier.

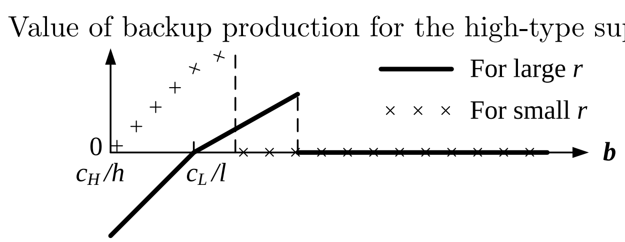


Figure 2.6: Value of backup production for the high-type supplier is negative for large r (i.e., $r > \bar{r}$) and small b ($b < c_L/l$), but is always non-negative for small r (i.e., $r \leq \bar{r}$).

Effect of information on the value of backup production. Intuition might suggest that, if information asymmetry regarding supplier reliability is eliminated, then the manufacturer will make better use of the backup production option to manage the supply risk. Hence, one may expect the value of backup production to be larger under symmetric information. However, as shown on the left panel of Figure 2.7, the value of backup production may be larger or smaller under symmetric information. Under information asymmetry, the presence of a backup option with a small unit cost, b, results in a decrease in the informational rent paid to the high-type supplier. This additional benefit of backup production does not exist under symmetric information. As a result, under small b the value of backup production is greater under asymmetric information. In contrast, when b is moderate, under asymmetric information the backup option increases the informational rent paid to the high-type supplier, thus diminishing the value of backup production.

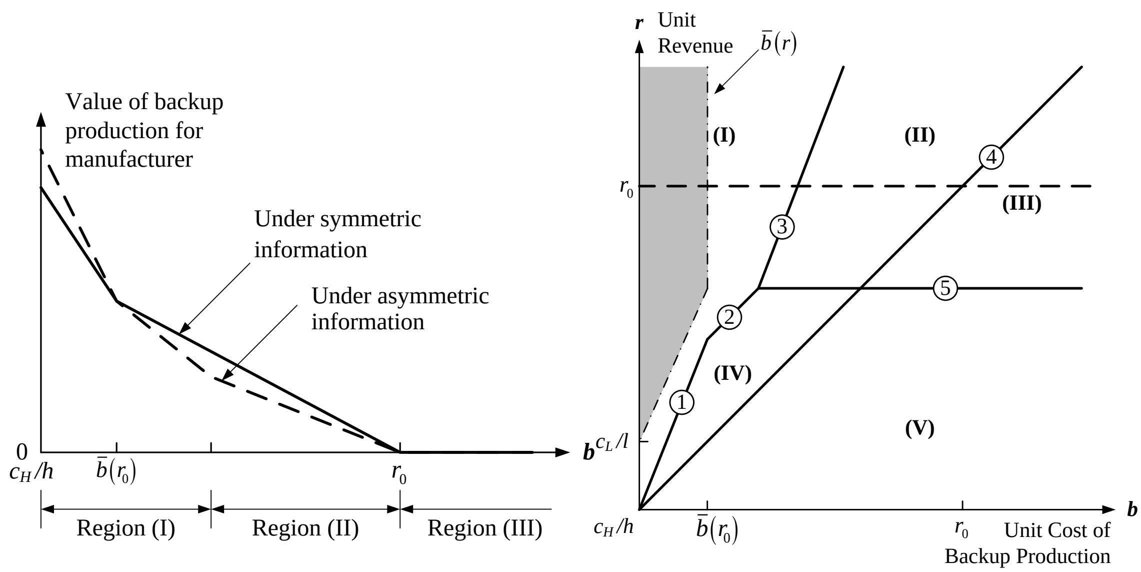


Figure 2.7: Value of backup production under symmetric and asymmetric information. The left panel plots the values of backup production for $r = r_0$ (marked on the right panel). On the right panel the shaded portion of region (I) indicates (b, r) pairs for which the value of backup production is greater under asymmetric information. The right panel also shows the line $\bar{b}(r)$, used on the left panel and defined as follows: for $r > \bar{r}$, $\bar{b}(r) = \frac{c_L}{l}$; for $r \in \left(\frac{c_L}{l}, \bar{r}\right]$, $\bar{b}(r) = \frac{(1-\alpha)l}{\alpha h}\left(r - \frac{c_L}{l}\right) + \frac{c_H}{h}$.

2.7. Sensitivity Analysis

In this section, we address *research question 4* by investigating the sensitivity of our earlier results to changes in the underlying business setting, including reliability parameters, h and l, the fraction of high-type suppliers in the market, α, and the manufacturer's contracting flexibility.

Sensitivity to supplier reliabilities, h and l. Suppose we increase h and l simultaneously, fixing the difference, $h - l$. This corresponds to the case in which all suppliers in the market become more reliable while the reliability gap between the two supplier types remains constant. While one might expect that the value of information should always decrease as suppliers become more reliable, the following corollary shows that when unit revenue is relatively small, or backup production is relatively cheap, the value of information for the manufacturer can actually increase with supplier reliability.

Corollary 4 (Sensitivity of value of information to supplier reliability)**.** *Per Table 2.1, if the supplier reliabilities l and h increase to $l + \epsilon$ and $h + \epsilon$, respectively (while $h - l$ remains constant), then in the interior of regions (I), (IV) and (V) the value of information for the manufacturer increases, while in the interiors of regions (II) and (III) the value of information for the manufacturer decreases.*

The intuition for the behavior in regions (I), (IV) and (V) can be gleaned from Table 2.1. In regions (IV) and (V), only channel loss is incurred due to the manufacturer not ordering from the low-type supplier. The more reliable the low-type supplier becomes, the larger this channel loss and, hence, the larger the value of information. On the other hand, in region (I), only informational rent is incurred. In the part of region (I) where backup production is very cheap ($b < c_L/l$), the low-type supplier does not utilize regular production at all, and its unit production cost is fixed at the cost of backup production. As the high-type supplier's reliability, h, increases, its reliability advantage also increases, which drives up the informational rent and, hence, the value of information.

Using Table 2.2, we next examine how the value of backup production changes. The next corollary follows from the fact that the manufacturer's need for backup production diminishes as suppliers become more reliable.

Corollary 5 (Sensitivity of value of backup production to supplier reliability)**.** *Per Table 2.2, if the supplier's reliabilities h and l increase to $h+\epsilon$ and $l+\epsilon$, respectively* (*while $h-l$ remains constant*)*, then the value of backup production for the manufacturer decreases.*

Sensitivity to reliability gap, $\boldsymbol{h-l}$. Here, we fix the low-type's reliability, l, and increase the high-type's reliability, h. This corresponds to an increase in the reliability gap, with the high-type supplier becoming more reliable. The following corollary describes how the value of information and value of backup production depend on the reliability gap.

Corollary 6 (Sensitivity to supplier reliability gap)**.** *Per Proposition 3 and Table 2.1, if h increases and l is fixed, then*

1. *The value of information for the manufacturer increases.*
2. *The value of backup production for the manufacturer decreases, and the absolute value of backup production for the high-type supplier increases.*

Intuitively, as the two supplier types become increasingly different, information about the supplier's type becomes more critical. In addition, as the high-type supplier becomes even more reliable, the probability that backup production is used to fulfill the order decreases. Consequently, the value of backup production for the manufacturer diminishes.

Sensitivity to the fraction of high-type suppliers in the market, $\boldsymbol{\alpha}$. Recall that the value of information for the manufacturer is $\alpha\gamma+(1-\alpha)\delta$, where informational rent γ and channel loss δ do not depend on α, the probability of drawing a high-type supplier (see Table 2.1). In regions (I) and (III), where only informational rent is incurred (channel loss is zero), the effect of informational rent is magnified due to an increase in α, and the value of information becomes larger. In regions (IV) and (V), where only channel loss is incurred (informational rent is zero), the effect of channel loss is diminished due to a decrease in $1-\alpha$, and the value of information decreases. In region (II), value of information can move either way in α, depending on whether channel loss or informational rent is larger. These observations are formalized in the following corollary.

Corollary 7 (Sensitivity of value of information to α)**.** *Per Table 2.1, if α increases to $\alpha+\epsilon$, then in the interior of regions (I) and (III), the value of information for the manufacturer increases, while in the interiors of regions (IV) and (V) the value of information for the manufacturer decreases. In region (II) the value of information increases if $(h-l)(c_L/l)+(c_L-c_H)>(1-l)(r-b)$ and decreases otherwise.*

Using Table 2.2, we examine how the value of backup production changes with α. One may expect that, if the fraction of more reliable suppliers in the market increases, disruptions will become less likely and, hence, the value of backup production will decrease. This intuition holds under symmetric information, but not necessarily under asymmetric information, as Corollary 8 illustrates.

Corollary 8 (Sensitivity of value of backup production to α)**.** *Per Table 2.2, as α increases to $\alpha+\epsilon$, the value of backup production for the manufacturer decreases in region (I) and increases in regions (II) and (IV).*

To understand why the value of backup production increases in the fraction of high-type suppliers when the cost of backup production is moderate (in regions (II) and (IV)), recall that the manufacturer asks only the high-type supplier to use backup production in these regions. Therefore, in these regions, the benefit of backup production is realized only if a high-type supplier is drawn, and an increase in the fraction of high-type suppliers, α, enhances the value of backup production for the manufacturer.

Sensitivity to manufacturer's contracting flexibility. We now discuss the effects of the manufacturer's contracting flexibility on its contracting decisions and its profit, using three types of manufacturers:

1. *Informed* manufacturer, who knows the supplier's type prior to contracting. The informed manufacturer's problem is the symmetric-information problem (discussed in §2.4).
2. *Partially-informed and discriminating* manufacturer, who does not know the supplier's type prior to contracting, but knows that there are two supplier types and has the flexibility of offering a menu of contracts. This manufacturer's problem is the asymmetric-information problem (discussed in §2.5).
3. *Partially-informed and non-discriminating* manufacturer, who is identical to the *partially informed and discriminating* manufacturer, except for being constrained to offer a single contract. The manufacturer could either be legally bound to offer a single contract or limited by its procurement department's resources to monitor and enforce multiple supplier-specific contacts.

As shorthand, we will refer to the latter two manufacturer types as *discriminating* and *non-discriminating*, respectively. We have already defined mathematical models for the *informed* and *discriminating* manufacturer types. The *non-discriminating* manufacturer's problem is

$$\max_{\substack{(X,q,p):\\ X\geq 0,\ q\geq 0,\ p\geq 0}} \left\{ \begin{array}{l} \alpha\, E\left[r\, \min(y_H^*, D) - X + p\,(q - y_H^*)^+\right] \mathbb{I}_{\{\pi_H(X,q,p)\geq 0\}} \\ \;+ (1-\alpha)\, E\left[r\, \min(y_L^*, D) - X + p\,(q - y_L^*)^+\right] \mathbb{I}_{\{\pi_L(X,q,p)\geq 0\}} \end{array} \right\}. \quad (2.7)$$

In the above expression, $\mathbb{I}_{\{A\}}$ is the indicator of an event A. The manufacturer offers a single contract (X, q, p). A type-i supplier, $i \in \{H, L\}$, chooses to participate if $\pi_i(X, q, p) \geq 0$. The optimal contract is stated in Proposition 4 and is characterized on the left panel of Figure 2.8.

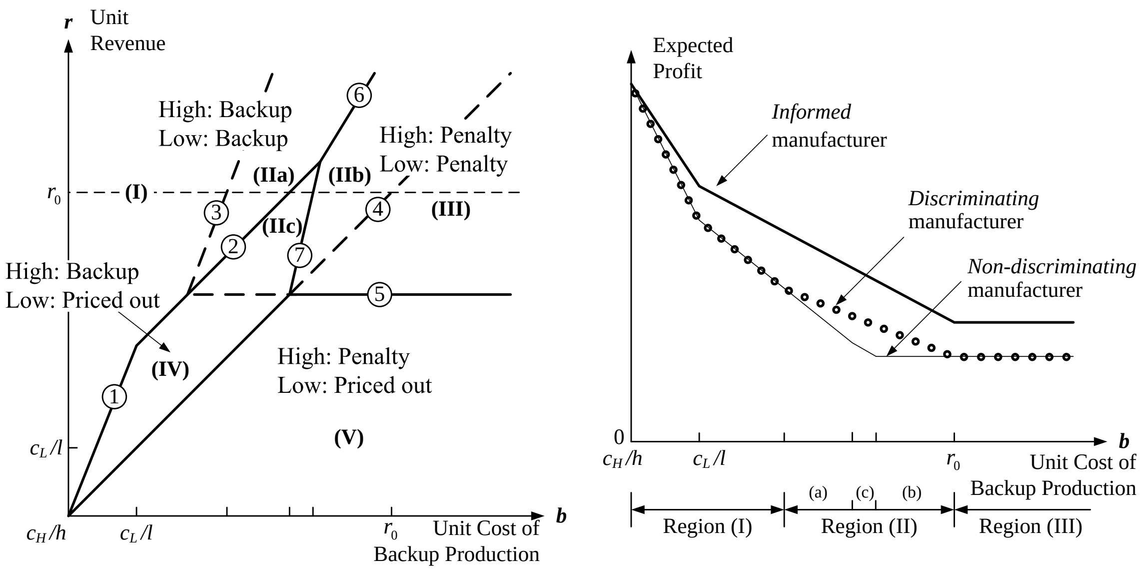


Figure 2.8: Left panel: optimal contract offered by the *non-discriminating* manufacturer. Right panel: expected profits of the three manufacturer types (r is fixed to be r_0, marked on the left panel). The *non-discriminating* manufacturer earns a smaller profit than the *discriminating* manufacturer only when b is moderate (i.e., (b, r) is in region (II)).

Proposition 4. *The optimal contract offered by the non-discriminating manufacturer is summarized in the following table*

Region	Penalty	Quantity	Transfer payment
(I) and (IIa)	any $p \in (b, r)$	$q = 1$	$X = \begin{cases} b & b < c_L/l \\ c_L + (1-l)\,b & b \geq c_L/l \end{cases}$
(III) and (IIb)	any $p = c_L/l$	$q = 1$	$X = c_L/l$
(IV) and (IIc)	any $p \in (b, r)$	$q = 1$	$X = c_H + (1-h)\,b$
(V)	any $p \in [c_H/h, b]$	$q = 1$	$X = c_H + (1-h)\,p$

By comparing Propositions 3 and 4 and using Corollary 3, we notice that the optimal contracts offered by the *discriminating* and *non-discriminating* manufacturers coincide in regions (I) and (III). Furthermore, the contracts offered by the two manufacturer types coincide for the high-type supplier in regions (IV) and (V). In these two regions, the low-type supplier does not participate with either manufacturer type.

In region (II), where the discriminating manufacturer does use its power to discriminate between the two supplier types, the *non-discriminating* manufacturer does not have that option and falls back on one of three kinds of contracts: the contracts in subregions (IIa), (IIb), and (IIc) coincide, respectively, with the contracts offered by the *discriminating* manufacturer in regions (I), (III), and (IV).

The right panel of Figure 2.8 shows the expected profits of the three manufacturer types. The difference between the profits of the *discriminating* and *informed* manufacturer types equals the value of information for the manufacturer, discussed in §2.6. Interestingly, the profits of the *discriminating* and *non-discriminating* manufacturer types are different only in region (II). This happens because only in region (II) the *discriminating* and *non-discriminating* manufacturers induce suppliers to take different actions. It follows that, in our model, the ability to discriminate pays off for the manufacturer only if the backup production option is moderately expensive. The reasoning for this is akin to that provided after Figure 2.4 to explain why information is most valuable when backup production is moderately expensive.

2.8. Extension: Manufacturer's Backup Production Option

So far, we have assumed that only the supplier has access to backup production capacity. It is also possible that the manufacturer has its own backup production option, the implications of which we investigate in this section.[6]

To the model we have been using so far, we add the ability of the manufacturer to use its own backup production at unit cost b_M. If both the supplier and the manufacturer have access to the same third-party backup source, then the manufacturer's cost of accessing this source, b_M, may be higher or lower than the supplier's cost, b, depending, for example, on the relative bargaining powers of the supplier and the manufacturer versus the third party. For example, if the manufacturer has more

[6]For example, in the Beckman Coulter v. Flextronics example we cited earlier, after Flextronics failed to deliver the promised units, Beckman Coulter was able to convert one of its existing prototype production lines for full-scale production.

bargaining power than the supplier when negotiating the contract for the alternative supply source, it can secure a lower price, resulting in $b_M < b$. It is also possible that, instead of having its own backup production option, the manufacturer asks the supplier to run the supplier's backup production even if the original contract did not call for it. For instance, in region (II), if the low-type supplier experiences a disruption and according to the contract would not deliver, perhaps the manufacturer could simply pay the supplier b and ask the supplier to run backup production. In such a case, b_M could be equal to b, but it is more likely that $b_M > b$ due to administrative costs, for instance, the cost of verifying that a disruption indeed occurred. Verification prevents the supplier from claiming to have had a disruption, and consequently demanding the b payment from the manufacturer for backup production, regardless of whether there was actually a disruption or not.

As before we assume that the cost of backup production exceeds the effective cost of regular production for the high-type supplier, $b_M \geq c_H/h$. To the contracting and execution stages of the original problem (see the timeline in Figure 3.1), we append a *manufacturer recourse* stage in which the manufacturer may run its backup production. In the recourse stage, the manufacturer chooses s_i, $i = H, L$, the total product supply that will be available to it at the stage's conclusion. In the execution stage, given a contract from the manufacturer, (X_i, q_i, p_i) $i = H, L$, the supplier's production decisions, y_i^* and z_i^*, are unaffected by the manufacturer's backup production option and are the same as those described in Proposition 1. In the contracting stage the manufacturer designs the contract menu (X_i, q_i, p_i), $i = H, L$, and offers it to the supplier.

To find the optimal contract menu we invoke the following intuitive observations. Suppose the unit revenue for the product is fixed at some $r = r_0$. First, if the manufacturer's backup production cost is greater than the revenue, $b_M > r_0$, the manufacturer's backup production option is economically infeasible and none of this chapter's previous results change. Second, if $b_M \leq r_0$, the optimal contracts under symmetric and asymmetric information are, respectively, given by Propositions 2 and 3, where r is replaced by b_M. Consequently, all of the subsequent analysis (value of information, value of supplier backup production, etc.) goes through with b_M playing the role of r. To understand why, we observe that if the quantity delivered by the supplier, y, is less than demand, D, the manufacturer pays $b_M(D-y)^+$ when the manufacturer's backup production option is available, and "pays" $r(D-y)^+$ (via lost revenue) when such an option is absent. Thus, mathematically, b_M plays the same role in this model as r played in equations (2.3a) and (2.4). (Proposition 5 in the appendix of this chapter formalizes this argument.)

Addressing *research question 1* we notice from Corollary 2 that asymmetric information increases the risk of non-delivery from the supplier. This effect increases the manufacturer's reliance on its own backup production option.

Addressing *research question 2* we examine how introducing the manufacturer's backup production option affects the manufacturer's value of information. Recall from Figure 2.5 that the value of information increases in r, the unit shortfall cost in the absence of the manufacturer's backup production option. As pointed out earlier, the presence of the manufacturer's backup production option reduces the manufacturer's unit shortfall cost from r to $b_M < r$. By making the manufacturer less sensitive to shortfall, the manufacturer's backup production option reduces the value of information. Thus, addressing *research question 3*, the manufacturer's backup production option is a substitute for information. In particular, this means that the value of the manufacturer's backup production option is greater under asymmetric information. This is in contrast to the supplier's backup production option, which can be either a substitute or a complement for information. Intuitively, the supplier's backup production option can increase the high-type supplier's reliability advantage, thus increasing the informational rent, whereas the manufacturer's backup production option has no such effect.

Similarly, the manufacturer's backup production option is a substitute for the supplier's backup production option. This is because the value of the supplier's backup production option increases in the unit shortfall cost (see Table 2.2, where the shortfall cost equals r). The introduction of the manufacturer's backup production option reduces this shortfall cost from r to $b_M < r$, thereby reducing the value of the supplier's backup production option.

2.9. Concluding Remarks

In a supply chain, lack of visibility into supplier reliability impedes the manufacturer's ability to manage supply risk effectively. This chapter examines a situation where the supplier's reliability is either high or low and is its private information, and the supplier has two options to respond to a disruption: use backup production, or pay a penalty to the manufacturer for non-delivery. When designing a procurement contract, the manufacturer must anticipate which of these options the supplier would choose, and how this would affect the manufacturer's expected procurement costs, use of its own backup production option, and sales revenues. To our knowledge, this chapter is among the first in operational risk management to consider asymmetric information about supplier reliability.

We model the manufacturer's contracting decisions as a mechanism design problem, and derive closed-form expressions for the optimal menu of contracts that elicits the supplier's private information. We observe that the manufacturer faces a key tradeoff when designing the contract for the low-type supplier: pay high informational rent to the high-type supplier, or suffer channel loss. Informational rent comes from the high-type supplier's incentive to exploit its reliability advantage over the low-type supplier, and it depends on the low-type supplier's actions in response to a disruption. In controlling this incentive, the manufacturer offers to the low-type supplier a contract that would be suboptimal under symmetric information, resulting in the channel loss. This tradeoff between informational rent and channel loss determines how the manufacturer manages its supply risk.

We answered four main research questions in this chapter. Addressing *research question 1* (*How do a manufacturer's risk-management strategies change in the presence of asymmetric information about supply reliability?*), we find that asymmetric information can have a pronounced effect on the manufacturer's risk-management strategy. While information asymmetry encourages the use of the manufacturer's backup production option, it discourages the use of the supplier's backup production option. In particular, information asymmetry may cause the manufacturer to stop using the backup production of a less reliable supplier, while continuing to use the backup production of a more reliable supplier. Additionally, the manufacturer may stop ordering from the less reliable supplier altogether.

Addressing *research question 2* (*How much would the manufacturer be willing to pay to eliminate this information asymmetry?*), we obtain a closed-form expression for the value of information. We find that the manufacturer would be willing to pay the most for information — that is, asymmetric information is of the greatest concern for managers — when the supplier's backup production is moderately expensive. In this case, the manufacturer predicates the supplier's use of backup production on the supplier's type. In contrast, when the supplier's backup production is cheap or expensive, the manufacturer's decision to induce the use of backup production does not depend on the supplier's type.

Addressing *research question 3* (*Are risk-management tools more, or less, valuable when there is information asymmetry?*), asymmetric information enhances the benefits the manufacturer derives from its own backup production option. The effect of information on the value of the supplier's backup production option is more intricate. For the manufacturer, information asymmetry makes the supplier's backup production option more valuable provided it is moderately expensive, and less valuable when it is cheap, but the value is always positive. On the flip side, for the supplier, under symmetric information, the value of its backup production option is always zero. However, under asymmetric information, the value of the backup production option for the high-type supplier is positive provided backup production is moderately expensive, but is negative when it is cheap. Cheap backup production for the supplier erodes the high-type supplier's reliability advantage over the low-type by reducing the cost of remedying supply disruptions. Therefore, an already reliable supplier may be reluctant to embrace the addition of cheap backup production into the supply base.

Addressing *research question 4* (*How do answers to the above questions depend on changes in the underlying business environment, such as supply base heterogeneity, or the manufacturer's contracting flexibility?*), we find that, as the reliability gap between the two supplier types increases due to an improvement in the reliability of the high-type supplier, information becomes more valuable for the manufacturer. Interestingly, the value of information may increase even as both supplier types simultaneously become more reliable. Therefore, higher reliability need not be a substitute for better information. The high-type supplier's benefit (or disbenefit) from its backup production option is magnified as its reliability improves. In particular, an improvement in the reliability of the high-type supplier may actually enhance its benefit from backup production. Finally, we find that the flexibility to offer a menu of two contracts to the supplier benefits the manufacturer only if supplier backup production is moderately expensive. Thus, a manufacturer who does not want to exert the effort to offer a menu of contracts need not do so if supplier backup production is cheap or very expensive.

The above findings were derived through closed-form analysis, facilitated by several simplifying assumptions. We assumed the manufacturer's demand, D, is common knowledge. Maskin and Tirole (1990) (Section 4, Proposition 11) proved that if (i) the principal (the manufacturer) also has private information, (ii) the principal's information cannot directly affect the agent's payoffs, and (iii) the agent's and principal's payoffs are quasi-linear in the transfer payment, then the principal derives no benefit from its private information; in other words, without loss of optimality one can focus on the situation in which the information about the principal is public. Applied to our model, this means that when the manufacturer has private information about its demand, it can do no better than when this information is public.

Another assumption on demand is that it is deterministic. We conjecture that the main tradeoffs identified in this chapter would remain if demand were stochastic, however, the details of how these tradeoffs play out would change. This analysis would be far more complicated owing to the *monotonicity* condition and bunching (Laffont and Martimort, 2002, pages 39, 140), meaning the contract design problem cannot be separated into independent subproblems for the high and low types.

We expect that increasing the number of discrete supplier types would also not substantially change the main qualitative insights documented in answers one through four above, although it would make the analysis more tedious. Having more than two supplier types or allowing a continuum of types may again create problems with *monotonicity* conditions. For an illustration of principal-agent problems with three agent types, please refer to Laffont and Martimort (2002). For a general treatment of mechanism design with N agent types, see Lovejoy (2006). For a discussion of detailed *monotonicity* conditions under a continuum of types, see Fudenberg and Tirole (1991), pages 266 – 268.

We also assume linear backup production costs, and restrict the manufacturer to offer linear penalty schedules to the supplier. As a result, the supplier would either run backup production or pay a penalty, but not both simultaneously. We can show that under general, concave backup production costs and concave penalty schedules for shortfall, the supplier's production decisions are unchanged and, consequently, all of our results continue to hold. An example of a concave penalty schedule (backup production cost) is a fee-plus schedule, whereby the supplier pays a fixed fee plus an additional fee per unit of shortage (backup production quantity). Convex backup production costs are also possible in practice, however, incorporating them into the model makes the analysis significantly more difficult.

We modeled supply risk using a random yield framework. One could also model supply risk arising from supplier lead time uncertainty. Under certain conditions the two approaches are equivalent: For example, for a manufacturer whose selling season is short relative to the variability in supply lead times, a delay is tantamount to a disruption and the backup option corresponds to the ability of the supplier to expedite the production (and the delivery). A more general model would have to introduce the manufacturer's sensitivity to delivery delays and the ability of the supplier to speed up (at a cost) depending on the forecast of the remaining production time. One might also wish to model the supplier's decision to slow down production (at a cost savings). With such features, the supplier's problem becomes a rather intricate stochastic control problem, compounding the difficulty of finding the manufacturer's optimal menu of contracts. We leave this interesting and challenging topic for future research.

In this chapter, we assume that the cost of regular production is perfectly correlated with the supplier type and the expected backup production cost is public information. Allowing imperfect correlation between supplier reliability and its cost, or extending information asymmetry to backup production, would require solving a multi-dimensional screening problem. Such problems have been solved for rather few, special cases (see Kostamis and Duenyas, 2007). We leave the study of this problem to future research as well.

2.10. Appendix

Proof of Proposition 1. The supplier's problem is given in (3.2). We first derive the supplier's optimal delivery quantity $y^*(z)$ for a given size of regular production z by solving

$$\min_{y\geq 0}\{p\,(q-y)^+ + b\,(y-\rho\,z)^+\}.$$

Because the objective function is piecewise linear in y, we focus on the corner point solutions, $y \in \{0, \rho\,z, q\}$. If $p < b$, the optimal delivery quantity is $y^*(z) = \rho\,z$. If $b < p$, the optimal delivery quantity is $y^*(z) = q$. If $b = p$, the supplier is indifferent between the two choices. To break the tie, we assume that the supplier prefers paying a penalty, that is, $y^*(z) = \rho\,z$.

Given the optimal delivery quantity $y^*(z)$ as described above, we next derive the optimal size of the regular production run, z^*, by solving

$$\begin{aligned}
&\min_{z\geq 0}\{c\,z + E_\rho\,[p\,(q-\rho\,z)^+]\} && \text{if } b \geq p,\\
&\min_{z\geq 0}\{c\,z + E_\rho\,[b\,(q-\rho\,z)^+]\} && \text{if } p > b.
\end{aligned}$$

If $b \geq p$, by evaluating the expectation, the optimization problem reduces to

$$\min_{z\geq 0}\{c\,z + \theta\,p\,(q-z)^+\} + (1-\theta)\,p\,q.$$

From above, we observe that, if $p < c/\theta$, the optimal solution is $z^* = 0$, and, if $p > c/\theta$, we have $z^* = q$. When $p = c/\theta$, we let $z^* = q$ to break the tie. Analogously, if $p > b$, the optimal solution is $z^* = 0$ for $b < c/\theta$ and $z^* = q$ for $b \geq c/\theta$. The expressions for the supplier's expected profit are derived by substituting z^* and $y^*(z^*)$ into the objective function of problem (3.2). ■

Proof of Proposition 2. To find the optimal contract under symmetric information, we solve the following problem:

$$\max_{\substack{(X_H,q_H,p_H)\\(X_L,q_L,p_L)}} \left\{ \begin{aligned} &\alpha \left[r\, E\min(y_H^*, D) - X_H + p_H\, E(q_H - y_H^*)^+ \right] \\ &\qquad + (1-\alpha) \left[r\, E\min(y_L^*, D) - X_L + p_L\, E(q_L - y_L^*)^+ \right] \end{aligned} \right\}$$

$$\begin{aligned} \text{subject to} \quad & \pi_H(X_H, q_H, p_H) \geq 0, \pi_L(X_L, q_L, p_L) \geq 0, \\ & X_H \geq 0,\ X_L \geq 0,\ q_H \geq 0,\ q_L \geq 0,\ p_H \geq 0, p_L \geq 0. \end{aligned}$$

We apply the supplier's optimal profit function $\pi_i(X_i, q_i, p_i) = X_i - c_i\, z_i^* - p_i\, E(q_i - y_i^*)^+ - b\, E(y_i^* - \rho_i\, z_i^*)^+$, $i \in \{H, L\}$, to the manufacturer's objective function and separate the terms that depend on (X_H,q_H, p_H) and (X_L, q_L, p_L), respectively. The above problem is equivalent to

$$\alpha \max_{\substack{X_H\geq 0, q_H\geq 0, p_H \geq 0:\\ \pi_H(X_H,q_H,p_H)\geq 0}} \left\{ r\, E\min(y_H^*, D) - \pi_H(X_H, q_H, p_H) - c_H\, z_H^* - b\, E(y_H^* - \rho_H\, z_H^*)^+ \right\} \tag{2.8a}$$

$$+ (1-\alpha) \max_{\substack{X_L\geq 0, q_L\geq 0, p_L \geq 0:\\ \pi_L(X_L,q_L,p_L)\geq 0}} \left\{ r\, E\min(y_L^*, D) - \pi_L(X_L, q_L, p_L) - c_L\, z_L^* - b\, E(y_L^* - \rho_L\, z_L^*)^+ \right\}. \tag{2.8b}$$

Observe that, for $i \in \{H, L\}$, reducing X_i decreases $\pi_i(X_i, q_i, p_i)$ and increases the objective value. Therefore, for a given q_i and p_i, it is optimal to set X_i equal to its lowest possible value, which is given by $X_i = c_i\, z_i^* + p_i\, E(q_i - y_i^*)^+ + b\, E(y_i^* + \rho_i\, z_i^*)^+$, where $\pi_i(X_i, q_i, p_i) = 0$. Using this observation, we rewrite problem (2.8) as:

$$\alpha \max_{q_H \geq 0,\ p_H \geq 0} \left\{ r\, E\min(y_H^*, D) - c_H\, z_H^* - b\, E(y_H^* - \rho_H\, z_H^*)^+ \right\} \tag{2.9a}$$

$$+\ (1-\alpha) \max_{q_L \geq 0,\ p_L \geq 0} \left\{ r\, E\min(y_L^*, D) - c_L\, z_L^* - b\, E(y_L^* - \rho_L\, z_L^*)^+ \right\} \tag{2.9b}$$

$$X_i = c_i\, z_i^* + p_i\, E(q_i - y_i^*)^+ + b\, E(y_i^* + \rho_i\, z_i^*)^+,\ i = H, L. \tag{2.9c}$$

We now solve problem (2.9b), where a low-type supplier is drawn. In the following table, each combination of the constraint on p_L and the condition on b versus c_L/l corresponds to a case in Proposition 1. For each combination of constraint and condition, the following table provides the objective function obtained by substituting z_L^* and y_L^* (from Proposition 1) into (2.9b).

Constraint on p_L	**Condition**	**Objective function**
$\mathcal{A} = \{p_L : p_L > b\}$	$b < c_L/l$	$r\ \min(q_L, 1) - b\, q_L$
	$b \geq c_L/l$	$r\ \min(q_L, 1) - c_L\, q_L - (1-l)\, b\, q_L$
$\mathcal{B} = \{p_L : b \geq p_L, p_L < c_L/l\}$		0
$\mathcal{C} = \{p_L : b \geq p_L, p_L \geq c_L/l\}$	$b \geq c_L/l$	$l\, r\ \min(q_L, 1) - c_L\, q_L$

For each constraint and condition, we find the optimal q_L. Because in all cases the objective function is piecewise linear in q_L, we restrict our attention to corner-point solutions, where $q_L = 0$ or 1. When the two solutions yield the same objective function value, we let $q_L = 0$, following the convention that the manufacturer breaks the tie in favor of smaller transfer payments. For instance, if $p_L \in \mathcal{A}$ and $b \geq c_L/l$, it is optimal to set $q_L = 1$ if $r - c_L - (1-l)\, b > 0$, or $q_L = 0$ if $r - c_L - (1-l)\, b \leq 0$, and p_L can take any value in $\mathcal{A}$. The constrained optimal (q_L, p_L) and the objective function value in each of the four cases are summarized in the following table:

Constraint	**Condition**		**q_L**	**p_L**	**Constrained optimal objective**
$\mathcal{A}$	$b < c_L/l$	$r - b > 0$	1	any $p_L \in \mathcal{A}$	$r - b$
		$r - b \leq 0$	0		0
	$b \geq c_L/l$	$r - c_L - (1-l)\, b > 0$	1		$r - c_L - (1-l)\, b$
		$r - c_L - (1-l)\, b \leq 0$	0		0
$\mathcal{B}$			0	any $p_L \in \mathcal{B}$	0
$\mathcal{C}$	$b \geq c_L/l$	$r - c_L/l > 0$	1	any $p_L \in \mathcal{C}$	$l\, r - c_L$
		$r - c_L/l \leq 0$	0		0

Next, to find the optimal q_L and p_L for problem (2.9b) we first consider the case $b \geq c_L/l$ and $r > b$. In this case, we have $r > c_L/l$ and $r - c_L - (1-l)\,b > 0$. Therefore, if $p_L \in \mathcal{A}$, the objective function value is $r - c_L - (1-l)\,b$. If $p_L \in \mathcal{B}$, the objective value is 0. If $p_L \in \mathcal{C}$, the objective value is $l\,r - c_L$. Thus, by comparing the three values, we conclude that when $r > b > c_L/l$, the optimal objective value is $r - c_L - (1-l)\,b$, obtained by setting $p_L \in \mathcal{A}$ and $q_L = 1$. For other values of r and b, the analysis is similar.

The solution procedure for problem (2.9a) is analogous to that for problem (2.9b), with c_L and l being replaced by c_H and h. (Recall that we assume that $b > c_H/h$ and $r > c_H/h$.)

To derive the optimal transfer payment X_i, we substitute the type-i supplier's decisions y_i^* and z_i^* under the optimal (q_i, p_i) into equation (2.9c). Moreover, without loss of optimality, we restrict $p_H < r$ and $p_L < r$ whenever possible. This completes the solution to problem (2.9). ■

Proof of Proposition 3. To solve problem (2.3), we use the form (2.4) of the objective function (2.3a) (see §2.5). The following is the roadmap of the proof. To solve problem (2.4, 2.3b–2.3f), we first reduce it to an equivalent problem over decision variables q_H, p_H, q_L, and p_L. Then, we relax the *monotonicity* constraint in the equivalent problem and show that the optimal solution to the relaxed problem is indeed feasible.

To reduce problem (2.4, 2.3b–2.3f) to the equivalent problem, we use the following three steps.

1. *Rearrange the incentive compatibility and individual rationality constraints (2.3b–2.3e).* Recall $\Gamma(q,p)$ reflects the reliability advantage of the high-type supplier. From its definition (Definition 3),

$$\pi_H(X_L, q_L, p_L) = \pi_L(X_L, q_L, p_L) + \Gamma(q_L, p_L), \text{ and}$$

$$\pi_L(X_H, q_H, p_H) = \pi_H(X_H, q_H, p_H) - \Gamma(q_H, p_H).$$

Substituting these two equalities into incentive compatibility constraints (2.3b) and (2.3c) yields $\Gamma(q_H, p_H) \geq \pi_H(X_H, q_H, p_H) - \pi_L(X_L, q_L, p_L) \geq \Gamma(q_L, p_L)$. The latter inequality, together with $\Gamma(q_L, p_L) \geq 0$ and $\pi_L(X_L, q_L, p_L) \geq 0$, implies that the individual rationality constraint for the high-type, $\pi_H(X_H, q_H, p_H) \geq 0$, is redundant. Thus, constraints (2.3b–2.3e) are equivalent to

$$\Gamma(q_H, p_H) \geq \pi_H(X_H, q_H, p_H) - \pi_L(X_L, q_L, p_L) \geq \Gamma(q_L, p_L), \tag{2.10a}$$

$$\pi_L(X_L, q_L, p_L) \geq 0. \tag{2.10b}$$

2. *Identify a set of constraints that is equivalent to* (2.10) *at optimality.* The manufacturer's objective function (2.4) suggests that, for any given q_i and p_i, $i \in \{H, L\}$, the objective function is maximized if X_i is chosen such that the supplier's profit $\pi_i(X_i, q_i, p_i)$ is minimized. Hence, by (2.10), at optimality X_H must be chosen such that $\pi_H(X_H, q_H, p_H) - \pi_L(X_L, q_L, p_L) = \Gamma(q_L, p_L)$, and X_L must be chosen such that $\pi_L(X_L, q_L, p_L) = 0$. Constraint set (2.10) degenerates to

$$\Gamma(q_H, p_H) \geq \Gamma(q_L, p_L), \ \ \pi_H(X_H, q_H, p_H) = \Gamma(q_L, p_L), \ \ \pi_L(X_L, q_L, p_L) = 0, \tag{2.11}$$

where constraint $\Gamma(q_H, p_H) \geq \Gamma(q_L, p_L)$ is commonly called the *monotonicity* constraint in the economics literature.

3. *Replace the constraints (2.3b–2.3f) with* (2.11) *and substitute* $\pi_H(X_H, q_H, p_H) = \Gamma(q_L, p_L)$ *and* $\pi_L(X_L, q_L, p_L) = 0$ *into the objective function* (2.4). Problem (2.4,

2.3b–2.3f) becomes the following equivalent problem

$$\begin{aligned} \max_{q_H, p_H, q_L, p_L} & \left\{ \begin{array}{l} \alpha[r\, E \min(y_H^*, D) - \Gamma(q_L, p_L) - c_H\, z_H^* - b\, E(y_H^* - \rho\, z_H^*)] \\ + (1-\alpha)[r\, E \min(y_L^*, D) - c_L\, z_L^* - b\, E(y_L^* - \rho\, z_L^*)] \end{array} \right\} \\ \text{subject to} \quad & \Gamma(q_H, p_H) \geq \Gamma(q_L, p_L) \qquad (\textit{monotonicity}) \\ & q_H \geq 0,\, q_L \geq 0,\, p_H \geq 0, p_L \geq 0, \end{aligned} \tag{2.12}$$

where the optimal X_H and X_L can be found by setting $\pi_H(X_H, q_H, p_H) = \Gamma(q_L, p_L)$ and $\pi_L(X_L, q_L, p_L) = 0$, that is,

$$X_H = \Gamma(q_L, p_L) + c_H\, z_H^* + p_H\, E(q_H - y_H^*)^+ + b\, E(y_H^* - \rho_H\, z_H^*)^+, \tag{2.13a}$$

$$X_L = c_L\, z_L^* + p_L\, E(q_L - y_L^*)^+ + b\, E(y_L^* - \rho_L\, z_L^*)^+. \tag{2.13b}$$

To solve problem (2.12), we first temporarily relax its *monotonicity* constraint, hoping that the constraint is non-binding at the optimal solution. The relaxation is easier to solve in that we can rearrange the objective function and solve it as two independent maximization problems over (q_H, p_H) and (q_L, p_L), respectively, as follows:

$$\max_{q_H \geq 0,\ p_H \geq 0} \left\{ \alpha[r\, E \min(y_H^*, D) - c_H\, z_H^* - b\, E(y_H^* - \rho_H\, z_H^*)] \right\} \tag{2.14a}$$

$$+ \max_{q_L \geq 0,\ p_L \geq 0} \left\{ (1-\alpha)\, [r\, E \min(y_L^*, D) - c_L\, z_L^* - b\, E(y_L^* - \rho_L\, z_L^*)] - \alpha \Gamma(q_L, p_L) \right\}. \tag{2.14b}$$

Lemma 1 below solves problem (2.14). The lemma divides the (b, r) plane into regions (I) through (V) shown in Figure 2.3, and characterizes the optimal solution and the objective function of (2.14) in each region.

Next, to satisfy the *monotonicity* constraint, $\Gamma(q_H, p_H) \geq \Gamma(q_L, p_L)$, we choose the optimal solution in Lemma 1 to be such that $p_H \geq p_L$ whenever $q_L > 0$. The outcome satisfies the *monotonicity* constraint, because $\Gamma(q, p)$ is increasing function in both q and p (see Corollary 1), $q_H \geq q_L$ and $p_H \geq p_L$.

Finally, we calculate X_H, X_L and the manufacturer's realized profits, $\pi^*_{M|H}$ and $\pi^*_{M|L}$. X_H and X_L can be calculated using equations (2.13a) and (2.13b). $\pi^*_{M|H}$ and $\pi^*_{M|L}$ are equal to the expressions in the two pairs of square brackets, respectively, in (2.4), that is,

$$\pi^*_{M|H} = r\,E\min(y^*_H, D) - \Gamma(q_L, p_L) - c_H\, z^*_H - b\,E(y^*_H - \rho_H\, z^*_H), \text{ and}$$
$$\pi^*_{M|L} = r\,E\min(y^*_L, D) - c_L\, z^*_L - b\,E(y^*_L - \rho_L\, z^*_L). \qquad \blacksquare$$

Lemma 1. *We divide the plane of (b, r), where $b > c_H/h$ and $r > c_H/h$, into the following five regions, as shown in Figure 2.3:*

Region	**Condition**	**Defining inequalities**
(I)	$b < c_L/l$	$(1-\alpha)(r-b) - \alpha(h\,b - c_H) > 0$
	$b \geq c_L/l$	$(1-\alpha)[r - c_L - (1-l)\,b] - \alpha[(h-l)\,b + (c_L - c_H)]$ $> \{(1-\alpha)(l\,r - c_L) - \alpha[(h-l)(c_L/l) + (c_L - c_H)]\}^+$
(II)		$r > b$, $(1-\alpha)(l\,r - c_L) - \alpha[(h-l)(c_L/l) + (c_L - c_H)] > 0$ and $(1-\alpha)[r - c_L - (1-l)\,b] - \alpha[(h-l)\,b + (c_L - c_H)]$ $\leq (1-\alpha)(l\,r - c_L) - \alpha[(h-l)(c_L/l) + (c_L - c_H)]$
(III)		$r \leq b$ and $(1-\alpha)(l\,r - c_L) - \alpha[(h-l)(c_L/l) + (c_L - c_H)] > 0$
(IV)	$b < c_L/l$	$r > b$ and $(1-\alpha)(r-b) - \alpha(h\,b - c_H) \leq 0$
	$b \geq c_L/l$	$r > b$, $(1-\alpha)[r - c_L - (1-l)\,b] - \alpha[(h-l)\,b + (c_L - c_H)] \leq 0$ and $(1-\alpha)(l\,r - c_L) - \alpha[(h-l)(c_L/l) + (c_L - c_H)] \leq 0$
(V)	$b < c_L/l$	$r \leq b$
	$b \geq c_L/l$	$r \leq b$ and $(1-\alpha)(l\,r - c_L) - \alpha[(h-l)(c_L/l) + (c_L - c_H)] \leq 0$

In each of the five regions, the optimal solutions and the objective function of *problems* (2.14a) *and* (2.14b) *are:*

Region	Condition		Solutions	Objective function
(I)	$b \le c_L/l$	(2.14a)	$q_H = 1, \quad p_H \in (b, r)$	$\alpha[r - c_H - (1-h)b]$
		(2.14b)	$q_L = 1, \quad p_L \in (b, r)$	$(1-\alpha)(r-b) - \alpha(h\,b - c_H)$
	$b > c_L/l$	(2.14a)	$q_H = 1, \quad p_H \in (b, r)$	$\alpha[r - c_H - (1-h)b]$
		(2.14b)	$q_L = 1, \quad p_L \in (b, r)$	$(1-\alpha)[r - c_L - (1-l)b]$
				$- \alpha[(h-l)b + (c_L - c_H)]$
(II)		(2.14a)	$q_H = 1, \quad p_H \in (b, r)$	$\alpha[r - c_H - (1-h)b]$
		(2.14b)	$q_L = 1, \quad p_L = c_L/l$	$(1-\alpha)(l\,r - c_L)$
				$- \alpha[(h-l)(c_L/l) + (c_L - c_H)]$
(III)		(2.14a)	$q_H = 1, \quad p_H \in [c_H/h, b]$	$\alpha(h\,r - c_H)$
		(2.14b)	$q_L = 1, \quad p_L = c_L/l$	$(1-\alpha)(l\,r - c_L)$
				$- \alpha[(h-l)(c_L/l) + (c_L - c_H)]$
(IV)		(2.14a)	$q_H = 1, \quad p_H \in (b, r)$	$\alpha\,[r - c_H - (1-h)\,b]$
		(2.14b)	$q_L = 0, \quad p_L \in [0, r)$	0
(V)		(2.14a)	$q_H = 1, \quad p_H \in [c_H/h, b]$	$\alpha(h\,r - c_H)$
		(2.14b)	$q_L = 0, \quad p_L \in [0, r)$	0

Proof of Lemma 1. We first solve problem (2.14a) for the optimal (q_H, p_H). This problem is identical to problem (2.9a) under symmetric information. Please refer to Proposition 2 for the optimal q_H, p_H, and objective function value.

Now we solve problem (2.14b) for the optimal (q_L, p_L). In the following table, each combination of the constraint on p_L, and the condition on b versus c_L/l, corresponds to a case in Corollary 1 that follows Proposition 1. For each combination of constraint and condition, the following table provides the objective function obtained by substituting z_L^*, y_L^* (from Proposition 1) and $\Gamma(q_L, p_L)$ (from Corollary 1) into (2.14b).

Constraint	Condition	Objective function
$\mathcal{A} = \{p_L : p_L > b\}$	$b < c_L/l$	$(1-\alpha)[r\,\min(q_L,1) - b\,q_L] - \alpha(h\,b - c_H)\,q_L$
	$b \geq c_L/l$	$(1-\alpha)[r\,\min(q_L,1) - c_L\,q_L - (1-l)\,b\,q_L]$ $-\alpha[(h-l)\,b + (c_L - c_H)]q_L$
$\mathcal{B} = \{p_L : b \geq p_L, p_L < c_H/h\}$		0
$\mathcal{C} = \{p_L : b \geq p_L, c_L/l > p_L \geq c_H/h\}$		$-\alpha\,(h\,p_L - c_H)\,q_L$
$\mathcal{D} = \{p_L : b \geq p_L, p_L \geq c_L/l\}$	$b \geq c_L/l$	$(1-\alpha)[l\,r\,\min(q_L,1) - c_L\,q_L]$ $-\alpha[(h-l)\,p_L + (c_L - c_H)]q_L$

For each constraint and condition, we find the optimal q_L and p_L. We restrict our attention to corner-point solutions, where $q_L = 0$ or 1. The constrained optimal (q_L, p_L) and the objective function value are summarized in the following table:

	Condition		q_L	p_L	Constrained optimal objective
$\mathcal{A}$	$b < c_L/l$	$(1-\alpha)(r-b) - \alpha(h\,b - c_H) > 0$	1	any $p_L \in \mathcal{A}$	$(1-\alpha)(r-b) - \alpha(h\,b - c_H)$
		$(1-\alpha)(r-b) - \alpha(h\,b - c_H) \leq 0$	0		0
	$b \geq c_L/l$	$(1-\alpha)[r - c_L - (1-l)\,b]$ $-\alpha[(h-l)\,b + (c_L - c_H)] > 0$	1		$(1-\alpha)[r - c_L - (1-l)\,b]$ $-\alpha[(h-l)\,b + (c_L - c_H)]$
		$(1-\alpha)[r - c_L - (1-l)\,b]$ $-\alpha[(h-l)\,b + (c_L - c_H)] \leq 0$	0		0
$\mathcal{B}$			0	any $p_L \in \mathcal{B}$	0
$\mathcal{C}$			0	any $p_L \in \mathcal{C}$	0
$\mathcal{D}$	$b \geq c_L/l$	$(1-\alpha)(l\,r - c_L)$ $-\alpha[(h-l)\,(c_L/l) + (c_L - c_H)] > 0$	1	c_L/l	$(1-\alpha)(l\,r - c_L)$ $-\alpha[(h-l)\,\frac{c_L}{l} + (c_L - c_H)]$
		$(1-\alpha)(l\,r - c_L)$ $-\alpha[(h-l)\,(c_L/l) + (c_L - c_H)] \leq 0$	0	any $p_L \in \mathcal{D}$	0

To find the optimal q_L and p_L for problem (2.14b) under $b \geq c_L/l$, we compare the constrained objective function values when p_L is in $\mathcal{A}$, $\mathcal{B}$, $\mathcal{C}$, and $\mathcal{D}$. The following expression of the optimal objective function value captures the comparison:

$$\max\{0,\ (1-\alpha)[r-c_L-(1-l)\,b]-\alpha[(h-l)\,b+(c_L-c_H)],$$
$$(1-\alpha)(l\,r-c_L)-\alpha[(h-l)\,(c_L/l)+(c_L-c_H)]\}.$$

For instance, if the second element in the curly brackets is strictly greater than the other two, the optimal (q_L, p_L) under constraint $\mathcal{A}$ and condition $(1-\alpha)[r-c_L-(1-l)\,b]-\alpha[(h-l)\,b+(c_L-c_H)]>0$ is optimal for problem (2.14b). (That is, $q_L=1$, and $p_L\in\mathcal{A}$.) The analysis for the other cases are analogous. Under $b<c_L/l$, we compare the objective function values when p_L is in $\mathcal{A}$, $\mathcal{B}$, and $\mathcal{C}$. Analogously, we use the following expression to represent the optimal objective function value:

$$\max\{0,\ (1-\alpha)(r-b)-\alpha(h\,b-c_H)\}.$$

Without loss of optimality, we restrict $p_H<r$ and $p_L<r$ whenever possible. The result follows by applying the optimal solutions for problems (2.14a) and (2.14b) to all five regions defined. ■

Proof of Corollary 2. By Proposition 1, the manufacturer receives q_L if the low-type supplier uses backup production, or receives $\rho_L\,q_L$ if the low-type supplier pays a penalty in the event of a disruption. We compare the expected quantities received by the manufacturer under symmetric information and under asymmetric information in regions (I) through (V). The result follows. ■

Proof of Corollary 3. The result follows from Proposition 3. ■

Proof of Proposition 4. To solve problem (2.7), we begin by applying equalities

$$X=\pi_i(X,q,p)+c_i\,z_i^*+p\,E(q-y_i^*)^+ + b\,E(y_i^*-\rho_i\,z_i^*)^+,\ \ i=H,L \tag{2.15}$$

to the objective function. The problem becomes

$$\max_{X\geq 0,\ q\geq 0,\ p\geq 0}\Big\{\alpha[r\,E\min(y_H^*,D)-\pi_H(X,q,p)-c_H\,z_H^*-b\,E(y_H^*-\rho_H\,z_H^*)]\,\mathbb{I}_{\{\pi_H(X,q,p)\geq 0\}}$$
$$+(1-\alpha)[r\,E\min(y_L^*,D)-\pi_L(X,q,p)-c_L\,z_L^*-b\,E(y_L^*-\rho_L\,z_L^*)]\,\mathbb{I}_{\{\pi_L(X,q,p)\geq 0\}}\Big\}. \tag{2.16}$$

Proposition 1 shows that, given a contract (X, q, p), a supplier with a higher probability of success always earns a larger expected profit, that is, $\pi_H(X, q, p) \geq \pi_L(X, q, p)$. A contract (X, q, p) such that $\pi_H(X, q, p) < 0$ will induce no participation, leading to zero profit of the manufacturer. Without loss of generality, we can assume that at least the high-type supplier would participate under the optimal contract, and, therefore, we restrict our attention to feasible (X, q, p) such that $\pi_H(X, q, p) \geq 0$.

We find the optimal solution to problem (2.16) using the following procedure. We first solve the problem under constraints $\pi_L(X, q, p) \geq 0$, when both supplier types would accept the contract. We then solve it under constraint $\pi_H(X, q, p) \geq 0 > \pi_L(X, q, p)$, when only the high-type supplier would accept the contract. Finally, we compare the two maxima to identify the global optimal solution.

Lemma 2 solves problem (2.16) under constraint $\pi_L(X, q, p) \geq 0$. Let $\bar{\theta} = \alpha h + (1-\alpha)l$, the average probability of successful regular production run. The optimal objective function is π_M^{N2} (superscript "N" indicates the manufacturer is non-discriminative, and superscript "2" indicates that both supplier types would participate), where

$$\pi_M^{N2} = \begin{cases} \max\{r - c_L - (1-l)\,b,\ \alpha\,h\,(r - c_H/h),\ \bar{\theta}(r - c_L/l)\} & b \geq c_L/l \\ \max\{r - b,\ \alpha\,h\,(r - c_H/h)\} & b < c_L/l. \end{cases} \tag{2.17}$$

We next solve problem (2.16) under $\pi_H(X, q, p) \geq 0 > \pi_L(X, q, p)$. This problem is equivalent to problem (2.8a) under symmetric information, and its optimal solution is given by problem (2.9a) in the proof of Proposition 2. We denote its optimal objective value as π_M^{N1} (superscript "1" indicates only one supplier type – high-type – would participate), where

$$\pi_M^{N1} = \max\{\alpha[r - c_H - (1-h)\, b],\ \alpha\, h\,(r - c_H/h)\}. \tag{2.18}$$

To identify the global optimum of problem (2.16), we compare π_M^{N1} and π_M^{N2} (see Lemma 3 for details). The result follows. ■

Lemma 2. *The optimal solution to problem* (2.16) *subject to* $\pi_L(X, q, p) \geq 0$ *is:*
When $b \geq c_L/l$*,*

- *If* $r - c_L - (1-l)\, b > \max\{\alpha\, h\,(r - c_H/h), \bar{\theta}(r - c_L/l)\}$*, then* $X = c_L + (1-l)b$*,* $q = 1$*,* $p \in (b, \infty)$*,* $\pi_M^{N2} = r - c_L - (1-l)\, b$*.*

- *If* $\alpha\, h\,(r - c_H/h) \geq \max\{r - c_L - (1-l)\, b, \bar{\theta}(r - c_L/l)\}$*, then* $X = c_H/h$*,* $q = 1$*,* $p = c_H/h$*,* $\pi_M^{N2} = \alpha\, h\,(r - c_H/h)$*.*

- *If* $\bar{\theta}(r - c_L/l) \geq r - c_L - (1-l)\, b$ *and* $\bar{\theta}(r - c_L/l) > \alpha\, h\,(r - c_H/h)$*, then* $X = c_L/l$*,* $q = 1$*,* $p = c_L/l$*,* $\pi_M^{N2} = \bar{\theta}(r - c_L/l)$*.*

When $b < c_L/l$*,*

- *If* $r - b > \alpha\, h\,(r - c_H/h)$*, then* $X = b$*,* $q = 1$*,* $p \in (b, \infty)$*,* $\pi_M^{N2} = r - b$*.*

- *If* $\alpha\, h\,(r - c_H/h) \geq r - b$*, then* $X = c_H/h$*,* $q = 1$*,* $p = c_H/h$*,* $\pi_M^{N2} = \alpha\, h\,(r - c_H/h)$*.*

Proof of Lemma 2. The problem we are solving is

$$\max_{\substack{(X,q,p):\\ X \geq 0,\ q \geq 0,\ p \geq 0}} \left\{ \begin{array}{l} \alpha[r\, E \min(y_H^*, D) - \pi_H(X, q, p) - c_H\, z_H^* - b\, E(y_H^* - \rho_H\, z_H^*)] \\ + (1-\alpha)[r\, E \min(y_L^*, D) - \pi_L(X, q, p) - c_L\, z_L^* - b\, E(y_L^* - \rho_L\, z_L^*)] \end{array} \right\}$$

$$\text{subject to} \quad \pi_L(X, q, p) \geq 0.$$

From Definition 3, we have $\pi_H(X, q, p) = \pi_L(X, q, p) + \Gamma(q, p)$ and $\pi_L(X, q, p) = 0$

must hold at optimality. The above problem is equivalent to

$$\max_{q\geq 0,\ p\geq 0} \left\{ \begin{array}{l} \alpha[r\,E\min(y_H^*, D) - \Gamma(q,p) - c_H\, z_H^* - b\,E(y_H^* - \rho_H\, z_H^*)] \\ +\,(1-\alpha)[r\,E\min(y_L^*, D) - c_L\, z_L^* - b\,E(y_L^* - \rho_L\, z_L^*)] \end{array} \right\}. \tag{2.19}$$

Note that decision variable X vanishes from the above program, and can be evaluated using equation (2.15), with $i = L$ and $\pi_L(X, q, p) = 0$.

Now we solve problem (2.19) for the optimal (q, p). In the following table, each combination of the constraint on p, and the condition on b versus c_L/l, corresponds to a case in Corollary 1 that follows Proposition 1. For each combination of constraint and condition, the following table provides the objective function obtained by substituting z_L^*, y_L^* (from Proposition 1) and $\Gamma(q, p)$ (from Corollary 1) into (2.19).

Constraint	**Condition**	**Objective function**
$\mathcal{A} = \{p : p > b\}$	$b < c_L/l$	$r\,\min(q,1) - b\,q$
	$b \geq c_L/l$	$r\,\min(q,1) - c_L\,q - (1-l)\,b\,q$
$\mathcal{B} = \{p : b \geq p, p < c_H/h\}$		0
$\mathcal{C} = \{p : b \geq p, c_L/l > p \geq c_H/h\}$		$\alpha\,h\,[r\,\min(q,1) - p\,q]$
$\mathcal{D} = \{p : b \geq p, p \geq c_L/l\}$	$b \geq c_L/l$	$\bar{\theta}r\,\min(q,1) - \alpha(h-l)p\,q - c_L\,q$

Next, for each constraint and condition, we find the optimal q and p. We restrict our attention to corner-point solutions, where $q = 0$ or 1. The constrained optimal (q, p) and the objective function value are summarized in the following table:

Constraint	Condition		q	p	Constrained optimal objective
$\mathcal{A}$	$b < c_L/l$	$r - b > 0$	1	any $p \in \mathcal{A}$	$r - b$
		$r - b \leq 0$	0		0
	$b \geq c_L/l$	$r - c_L - (1-l)\,b > 0$	1		$r - c_L - (1-l)\,b$
		$r - c_L - (1-l)\,b \leq 0$	0		0
$\mathcal{B}$			0	any $p \in \mathcal{B}$	0
$\mathcal{C}$			1	c_H/h	$\alpha\, h\,(r - c_H/h)$
$\mathcal{D}$	$b \geq c_L/l$	$r - c_L/l > 0$	1	c_L/l	$\bar{\theta}(r - c_L/l)$
		$r - c_L/l \leq 0$	0	any $p \in \mathcal{D}$	0

To find the optimal solution to problem (2.19) and its objective function value, π_M^{N2}, we compare the constrained optimal objective function values for p in $\mathcal{A}$, $\mathcal{C}$, and $\mathcal{D}$ when $b \geq c_L/l$, and for p in $\mathcal{A}$ and $\mathcal{C}$ when $b < c_L/l$. The result follows. ■

Lemma 3. *The following is the relationship between π_M^{N1} and π_M^{N2}:*

Regions (I), (IIa), (IIb), and (III)	$\pi_M^{N2} > \pi_M^{N1}$
Region (IV) and (IIc)	$\pi_M^{N2} \leq \pi_M^{N1}$
Region (V)	$\pi_M^{N2} = \pi_M^{N1}$

Proof of Lemma 3. Region (I). Recall that region (I) is defined in Lemma 1 by

$$(1-\alpha)(r-b) - \alpha(h\,b - c_H) > 0 \qquad b < c_L/l \qquad (2.20a)$$

$$(1-\alpha)[r - c_L - (1-l)\,b] - \alpha[(h-l)\,b + (c_L - c_H)] > \{(1-\alpha)(l\,r - c_L) - \alpha[(h-l)(c_L/l) + (c_L - c_H)]\}^+ \qquad b \geq c_L/l. \qquad (2.20b)$$

We first evaluate π_M^{N1}, which is presented in (2.18). Note that region (I) satisfies inequality $r > b$, which implies

$$\alpha[r - c_H - (1-h)\,b] > \alpha\, h\,(r - c_H/h). \tag{2.21}$$

We apply this inequality to (2.18), and obtain $\pi_M^{N1} = \alpha[r - c_H - (1-h)\,b]$.

We now evaluate π_M^{N2}, which is presented in (2.17). The value of π_M^{N2} is uniquely determined by inequalities (2.20) and (2.21). To see this, we first note that, for $b < c_L/l$, [LHS (2.20a) + LHS (2.21)] $>$ [RHS (2.20a) + RHS (2.21)]. It can be verified that [LHS (2.20a) + LHS (2.21)] $= r - b$, and [RHS (2.20a) + RHS (2.21)] $= \alpha\, h\,(r - c_H/h)$. Hence, we have $r - b > \alpha\, h\,(r - c_H/h)$. Applying the above inequality to (2.17) determines the value of π_M^{N2} when $b < c_L/l$, that is, $\pi_M^{N2} = r - b$ for $b < c_L/l$. Analogously for $b \geq c_L/l$, we have [LHS (2.20b) + LHS (2.21)] $>$ [RHS (2.20b) + RHS (2.21)]. It can be verified that [LHS (2.20b) + LHS (2.21)] $= r - c_L - (1-l)\,b$ and [RHS (2.20b) + RHS (2.21)] $= \max\{\alpha\, h\,(r - c_H/h), \bar{\theta}(r - c_L/l)\}$. The second equation follows from the following equality:

$$\bar{\theta}(r - c_L/l) \equiv \alpha\, h\,(r - c_H/h) + (1-\alpha)(l\,r - c_L) - \alpha[(h-l)(c_L/l) + (c_L - c_H)].$$

Hence, we have inequality $r - c_L - (1-l)\,b > \max\{\alpha\, h\,(r - c_H/h), \bar{\theta}(r - c_L/l)$. Applying this inequality to (2.17), we identify the value of π_M^{N2} when $b \geq c_L/l$, that is, $\pi_M^{N2} = r - c_L - (1-l)\,b$ for $b \geq c_L/l$. Comparing π_M^{N1} and π_M^{N2} yields

$$\pi_M^{N2} - \pi_M^{N1} = \begin{cases} (1-\alpha)(r-b) - \alpha(h\,b - c_H) & b < c_L/l \\ (1-\alpha)[r - c_L - (1-l)\,b] & \\ \qquad -\alpha[(h-l)\,b + (c_L - c_H)] & b \geq c_L/l. \end{cases}$$

By inequalities (2.20a) and (2.20b), we must have $\pi_M^{N2} - \pi_M^{N1} > 0$.

The analysis is similar for regions (III), (IV), and (V).

Region (II). In this region, the sign of $\pi_M^{N1} - \pi_M^{N2}$ can be either positive or negative. Recall that region (II) is defined by a set of inequalities:

$$\begin{aligned}
&r > b,\ \bar{\theta}(r - c_L/l) > \alpha\, h\,(r - c_H/h),\ \text{and} \\
&(1-\alpha)[r - c_L - (1-l)\,b] - \alpha[(h-l)\,b + (c_L - c_H)] \\
&\qquad\qquad \leq (1-\alpha)(l\,r - c_L) - \alpha[(h-l)(c_L/l) + (c_L - c_H)].
\end{aligned}$$

As in the discussion for region (I), the first inequality implies $\pi_M^{N1} = \alpha[r - c_H - (1-h)\,b]$. The second inequality implies that $\pi_M^{N2} = \max\{r - c_L - (1-l)\,b,\ \bar{\theta}(r - c_L/l)\}$. To the left of line 6 in region (II) (see Figure 2.8), $\pi_M^{N2} = r - c_L - (1-l)\,b$. When (b, r) is also to the left of line 2 (region (IIa)), $\pi_M^{N2} > \pi_M^{N1}$. To the right of line 6, $\pi_M^{N2} = \bar{\theta}(r - c_L/l)$. When (b, r) is also to the right of line 7 (region (IIb)), $\pi_M^{N2} > \pi_M^{N1}$ as well. ■

Proposition 5. *If the manufacturer has access to its own backup production option at unit cost b_M, the optimal menu of contracts offered by the manufacturer is as follows:*

- *When $b_M \geq r$, the optimal menu of contracts is the same as the optimal menu of contracts in the absence of the manufacturer's backup production option. In particular, the optimal menu of contracts is given by Proposition 2 under symmetric information, and Proposition 3 under asymmetric information.*

- *When $b_M < r$, the optimal menu of contracts can be derived from the optimal menu of contracts in the absence of the manufacturer's backup production option. In particular, replacing revenue r with b_M in Propositions 2 and 3 gives the optimal menu of contracts under symmetric and asymmetric information, respectively.*

Proof. We present the proof for the asymmetric information case. The analysis is similar for the symmetric information case.

To find the optimal menu of contracts, we maximize the following objective, subject to constraints (2.3b–2.3f):

$$
\begin{aligned}
\max_{\substack{(X_H,q_H,p_H)\\(X_L,q_L,p_L)}} \Bigg\{ \alpha \Bigg\{ & \big[r\,E\min(y_H^*,D) - X_H + p_H\,E(q_H - y_H^*)^+\big] \\
& + E\max_{s_H \geq y_H^*}\{r[\min(s_H,D) - \min(y_H^*,D)] - b_M(s_H - y_H^*)\}\Bigg\} \\
+ (1-\alpha)\Bigg\{ & \big[r\,E\min(y_L^*,D) - X_L + p_L\,E(q_L - y_L^*)^+\big] \\
& + E\max_{s_L \geq y_L^*}\{r[\min(s_L,D) - \min(y_L^*,D)] - b_M(s_L - y_L^*)\}\Bigg\}\Bigg\}.
\end{aligned}
\tag{2.22}
$$

When the manufacturer's backup production option is economically infeasible, $b_M \geq r$, the manufacturer will not exercises it, that is, $s_i \equiv y_i^*$, $i = H, L$. The objective function (2.22) is then identical to the objective function (2.3a). Problem (2.22, 2.3b–2.3f) is identical to problem (2.3).

Now consider the case where the manufacturer's backup production option is economically feasible, $b_M < r$. Observe that at the optimal solution, $s_i = D$ and $D - y_i^* = D - \min\{D, y_i^*\}$. Hence, $s_i - y_i^* = D - y_i^* = D - \min\{D, y_i^*\}$ at the optimal solution. We substitute these equalities into objective function (2.22) to obtain

$$
\max_{\substack{(X_H,q_H,p_H)\\(X_L,q_L,p_L)}} \left\{ \begin{array}{l} \alpha\,[b_M\,E\min(y_H^*,D) - X_H + p_H\,E(q_H - y_H^*)^+] \\ + (1-\alpha)[b_M\,E\min(y_L^*,D) - X_L + p_L\,E(q_L - y_L^*)^+] \end{array} \right\} + (r - b_M)D. \tag{2.23}
$$

Note that the group of terms in the pair of curly brackets in (2.23) is the same as (2.3a), with r replaced by b_M. ■

Chapter 3

Supply Disruptions, Asymmetric Information, and a Dual-Sourcing Option

3.1. Introduction

The average US manufacturer spends roughly half its revenue procuring goods and services (U.S. Census Bureau, 2006). While outsourcing production of a critical component can offer cost advantages for the manufacturer, it can also introduce the risk that a supplier's failure to deliver will halt the manufacturer's production. A supplier's facility might suffer from fire, flood, or an earthquake. A labor strike or financial bankruptcy might shut down supplier operation (see Babich, 2007, for examples). Changes in a supplier's ownership status can also trigger disruptions. For example, after it purchased Dovatron in April 2000, Flextronics announced that it would completely shut down Dovatron's low-volume specialty circuit board facility in Anaheim as part of restructuring to focus on low-mix, high-volume products. As a result of Flextronics's decision, Beckman Coulter Inc., a medical device manufacturer who single-sourced a critical component from Dovatron's Anaheim facility, lost its supplier. The supply disruption cost Beckman Coulter millions of dollars.[1]

To mitigate such risks, manufacturers often employ a *dual-sourcing option*:[2] they

[1] For more details, see `www.callahan-law.com/verdicts-settlements/fraud-beckman-coulter/index.html`.

[2] In this chapter, we refer to the case in which there is only one supplier in the supply base as *single-sourcing*, and the case in which there are two suppliers as *dual-sourcing*. In the case of dual-sourcing, we refer to the manufacturer's action of ordering from only one supplier as *sole-sourcing*, and the action of ordering from both as *diversification*.

widen a critical component's supply base to include more than one supplier. Practitioner surveys (Wu and Choi, 2005) identify two main benefits of a dual-sourcing option. First, a dual-sourcing option enables the manufacturer to reduce risk by *diversifying* its supply, that is, by simultaneously ordering the component from two suppliers. Second, a dual-sourcing option encourages competition among suppliers, resulting in lower procurement costs for the manufacturer.

Previous research assumes that the manufacturer and suppliers have identical knowledge about the possibility that a supplier experiences a disruption. However, suppliers might be privileged with better information about their susceptibility to disruptions. For instance, Dovatron likely enjoyed better information than Beckman Coulter had about Dovatron's acquisition by Flextronics. A supplier might also outsource sub-components to second-tier suppliers without telling the manufacturer it is doing so, creating risks of disruptions caused by second-tier suppliers.[3]

Intuitively, asymmetric information about suppliers' reliabilities might change the way the manufacturer mitigates disruption risks. For instance, Beckman Coulter might have sought to diversify its circuit board supply had it known that Dovatron was in talks with Flextronics and that a restructuring might follow. Conversely, employing risk-mitigating strategies might make the manufacturer more or less sensitive to asymmetric information about suppliers' reliabilities. In this chapter, we seek to understand how the use of a dual-sourcing option is affected by asymmetric information about suppliers' reliabilities and how the value of information is affected by the dual-sourcing option.

To this end, we utilize a stylized, one-period model with a manufacturer and two suppliers. Each supplier privately knows whether it is a high or a low reliability-type

[3]This is what happened to Menu Foods in March 2007. Its supplier ChemNutra outsourced production of wheat gluten, an ingredient in the pet food, to a Chinese supplier Xuzhou Anying Biologic Technology Development Co. Ltd.. In an effort to increase its profit margin, Xuzhou Anying introduced melamine into wheat gluten, resulting in deaths of numerous pets. More examples are provided in Chapter 2.

supplier. The manufacturer seeks to contract with one or possibly both suppliers for production. In addition to setting quantity and payment terms, contracts ensure that the suppliers have an incentive to deliver by specifying penalties for non-delivery.[4] As an alternative to the penalty clause, one could use a canonical, two-part tariff (fixed plus variable payment) contract and obtain the same equilibrium outcome as in our contract with penalty clause. Either the variable payment or the penalty provides an incentive to the supplier to deliver. The manufacturer maximizes its expected profit, and in so doing must strategically account for each supplier's incentive to misrepresent their reliability. Using a mechanism design approach, we solve this model (detailed in §3.3), and explore the effect of asymmetric information about suppliers' reliabilities on a manufacturer's application of a dual-sourcing option to mitigating disruption risks. Next, we highlight some of our findings and briefly describe the chapter's organization.

§3.4 presents the benchmark model of symmetric information. In §3.5 we analyze how asymmetric information about suppliers' reliabilities changes the manufacturer's use of its dual-sourcing option. Asymmetric information pushes the manufacturer towards sole-sourcing (and away from diversification) as a way to leverage supplier competition and limit each supplier's ability to misrepresent its reliability. Moreover, as the reliabilities of both the high and low supplier-types decrease, a manufacturer will diversify more under symmetric information, but may diversify less under asymmetric information. Thus, even if diversification is a useful tool under symmetric information for a manufacturer facing a supply base whose overall reliability has declined, the same need not be true under asymmetric information about suppliers' reliability.

In §3.6 we study the manufacturer's value of information about suppliers' reliabilities. It is conceivable that better information about suppliers' reliabilities could

[4]In practice, such penalties are commonly referred to as "liquidated damages", e.g., Corbin (2007).

be obtained by the manufacturer, at least for risk factors the manufacturer can identify and learn about. For instance, the manufacturer might audit the suppliers for bankruptcy risk, the soundness of their fire prevention measures, structural earthquake proofing, or location relative to flood-prone coastlines. We find that information about reliability, which would likely be costly to obtain, is most beneficial for the manufacturer when the item's value is high. In such a case, the manufacturer forgoes leveraging competition and instead uses diversification to help mitigate the overall risk of non-delivery. Surprisingly, we also find that information may become more valuable even as a high-type supplier's reliability becomes closer to that of a low-type, because in such a case supply diversification becomes more important. Thus, more similarity between supplier reliability types (having "less to learn" about the suppliers' true reliabilities) should not be seen as a substitute for information.

In §3.7 we examine the value of the dual-sourcing option for the manufacturer, that is, the incremental benefit the manufacturer enjoys by having a supply base with two suppliers instead of one. Expanding the supply base can be difficult and time-consuming for the manufacturer. For example, it took Beckman Coulter months of searching and testing before Dovatron was discovered and deemed capable of producing the specialty circuit boards that Beckman Coulter needed (see Footnote 1). Furthermore, this process may not reveal full information about the suppliers. Beckman Coulter was shocked to learn in May 2000 of Dovatron's impending closure of the Anaheim plant (see Footnote 1). Thus, the manufacturer might like to know when it is most beneficial to have either an additional supplier (the dual-sourcing option) or better information (symmetric information about suppliers' reliabilities), or both. We find that better reliability information and the dual-sourcing option are substitutes when the manufacturer's value for the item being procured is low. However, information and the dual-sourcing option become complements when the manufacturer's value for the item being procured is high, at which point having two suppliers whose reliabilities are known makes the dual-sourcing option more valuable for the manufacturer.

In §3.8 we examine the possibility that the suppliers' disruption probabilities are correlated, for instance, the suppliers share vulnerabilities to the same underlying risk factors such as earthquakes or floods. We find that as the two suppliers' disruptions become more correlated, the manufacturer finds diversification less desirable and, hence, relies more on sole-sourcing and leveraging supplier competition. Due to increased competition, the suppliers have smaller incentives to misrepresent their reliabilities, and thus asymmetric information about suppliers' reliabilities is less of a concern for the manufacturer. In §3.9 we provide concluding remarks. All proofs are in the Appendix.

3.2. Literature Review

The work in this chapter contributes to the important and fast growing research and applications area of supply disruptions management (see review papers by Kleindorfer and Saad, 2005; Tang, 2006a). We study multi-sourcing as the risk-mitigation tool. This tool is commonly used in operations, and examples of recent articles that consider it are Babich et al. (2005); Tomlin (2006); Tomlin and Wang (2005); Dada et al. (2007); Federgruen and Yang (2007). These papers focus on the risk-reduction benefits of multi-sourcing due to diversification. However, as we highlight in this chapter, multi-sourcing has additional strategic benefits, because it encourages competition among suppliers. Babich (2006) and Babich et al. (2007) also found that, similar to our results, the manufacturer must strike the balance between diversification and competition.

Unlike the majority of papers on supply risk (including the ones mentioned in the paragraph above), we model the practical situation where the suppliers are better informed about the likelihoods of supply disruptions than the manufacturer is. In this setting, the manufacturer makes diversification decisions not only for risk management but also to control suppliers' incentives, which leads to new insights (e.g., as discussed in the Introduction). Note that our work in this chapter is different from those in procurement and economics literatures, where asymmetric information is about suppliers' costs (e.g., Dasgupta and Spulber, 1989; Corbett, 2001; Beil and Wein, 2003; Elmaghraby, 2004; Kostamis et al., 2009; Wan and Beil, 2008). As discussed in Chapter 2, asymmetric information about disruptions affects not only procurement cost but also the manufacturer's risk profile. Our work is not unique in studying asymmetric information about supply risks. Examples of other papers that do the same are Tomlin (2008); Gurnani and Shi (2006); Lim (1997); Baiman et al. (2000). The latter three, unlike our work, do not use multi-sourcing. Tomlin (2008) studies multi-sourcing, but relies on Bayesian updating over time as a mechanism for the manufacturer to learn the supplier's reliability, whereas we invoke optimal incentive-compatible contracts instead.

The work closest to this chapter is Chapter 2. In that model, the manufacturer sources from one supplier and uses backup production options to manage supply disruption risk. The supplier's reliability (the likelihood of disruption) is its private information. The manufacturer designs a menu of incentive contracts to reveal the supplier's private information. This chapter studies a wholly different risk-management tool: dual-sourcing. Our findings broaden the understanding of how asymmetric information about suppliers' reliabilities interacts with the manufacturer's risk management policies.

Another related paper is Chaturvedi and Martínez-de-Albéniz (2008). They assume that the supplier's reliability and cost are its private information and study a procurement auction with multi-sourcing. Similar to us, they find that under asymmetric information the manufacturer diversifies less. However, there are several important differences between the two papers including the following. We focus explicitly on valuing the manufacturer's dual-sourcing option as a risk-management tool and relating this value to asymmetric information about supply risk. Our penalty in the contract between the manufacturer and a supplier is variable, depending on the size of the shortfall in the delivery from the supplier. We find that as the suppliers become less reliable the manufacturer could actually stop diversifying under asymmetric information about suppliers' reliabilities, which we believe will not happen in their model. In addition, we study the case in which the suppliers' disruptions are correlated.

3.3. Model

We model a stylized supply chain with a manufacturer and two suppliers. The suppliers' production processes are subject to random disruptions. When a disruption occurs, the production process yields zero output and the supplier delivers nothing. For instance, fire could destroy inventory and halt production, or contamination could force a pharmaceutical firm to scrap vaccines. There are two types of suppliers in the market: high reliability (H) and low reliability (L). The two supplier types differ from each other in their likelihoods of disruptions and their costs of production, with low-reliability suppliers being more prone to production disruptions. Let $t_n \in \{H, L\}$ denote the type of supplier $n = 1, 2$. The commonly known probability of a supplier being of high-type is α^H, and the probability of a supplier being of low-type is α^L, where $\alpha^H + \alpha^L = 1$. We assume that the two suppliers' types are independent of one another.[5] To capture the manufacturer's lack of visibility into the suppliers' reliabilities and costs, we assume that a supplier's reliability type is its private information, unknown to the manufacturer and the other supplier.[6]

In keeping with our assumption that a disruption results in non-delivery, we represent supplier-n's proportional random yield as a Bernoulli random variable, and

[5] See §3.9 for discussion of dependent types.

[6] Our results can be extended to the case where the suppliers perfectly know the type of each other.

denote it by $\rho_n^{t_n}$:

$$\rho_n^{t_n} \stackrel{\text{def}}{=} \begin{cases} 1 & \text{with probability } \theta^{t_n} \\ 0 & \text{with probability } 1-\theta^{t_n}, \end{cases} \tag{3.1}$$

where $\theta^H = h$ and $\theta^L = l$, $h > l$. For the time being, we assume that the two suppliers' production disruption processes are independent of each other, that is, $\rho_1^{t_1}$ and $\rho_2^{t_2}$ are independent (§3.8 relaxes this assumption). The probability θ^{t_n} is a measure of supplier-n's reliability. Notice that a supplier's reliability depends only on its type.

A production attempt costs a type-t supplier ($t \in \{H, L\}$) c^t per unit regardless of whether it is successful or not. Although we allow c^H and c^L to be different, the high-type is assumed to be more cost-efficient than the low-type, that is, the expected cost of successfully producing one unit is smaller for high-type suppliers: $c^L/l > c^H/h$.[7]

The manufacturer incurs a setup cost for ordering from a supplier, denoted by K, in addition to the cost of purchasing parts. The setup cost can be the cost of transferring technology to the supplier, or administrative costs incurred to manage the procurement process. We assume the parts from the two suppliers are perfect substitutes, for example, the suppliers produce the part to the manufacturer's specifications or the part is standardized.

The manufacturer uses the parts to produce a product and sells it to meet demand. To focus on the effects of supply risk, we assume that the manufacturer faces a demand, D, that is known at the time the manufacturer places its orders. When supplier deliveries do not cover the entire demand D, the manufacturer loses r per unit shortfall. The value r represents the manufacturer's revenue per item, or alternatively its per item recourse cost to secure a backup supply.[8]

[7] Note that, for one unit of input going into production, the expected output of a type-t supplier is θ^t. Hence, were repeated production attempts allowed, the expected cost of successfully producing one unit would be c^t/θ^t.

[8] For instance, after its supplier Dovatron's production was shut down, Beckman Coulter created their own in-house specialty circuit board production line, which cost them 2.1 million dollars to construct (see Footnote 1).

To govern its relationship with the two suppliers, the manufacturer uses a pair of contracts, one for each supplier. Each contract consists of a transfer payment, X, an order quantity q, and a non-delivery unit penalty, p. The penalty serves to hold the supplier liable in case of disruption.

Intuitively, the manufacturer would like the transfer payments, order quantities and penalties to depend on the suppliers' true reliabilities. However, the manufacturer does not know the suppliers' true reliabilities, and instead—as is standard in the economics literature—we assume that the manufacturer offers several contract options (a contract "menu") from which the suppliers choose. To find the manufacturer's optimal contract menu, we apply the Revelation Principle (Myerson, 1979) and focus on the class of incentive-compatible direct-revelation menus. Under such a contract menu, both suppliers will truthfully report their reliability types to the manufacturer. For simplicity in the analysis, we assume that the suppliers cannot collude.[9]

The contract menu is a modeling construct that captures the general practice of tailoring contracts to specific suppliers in a procurement process. In particular, the contract menu captures two salient features of a typical contracting process. First, the contract for a supplier (e.g., the size of non-delivery penalty) is tailored according to the reliability risk perceived by the manufacturer. Thus, a high- and a low-type suppliers can end up with different contracts. Second, the contract for one supplier depends on the reliability of the other supplier, both of whom compete for business from the manufacturer: intuitively, a supplier's likelihood of receiving an order decreases as the other supplier becomes more reliable. Therefore, the contract for one supplier must be a function of the reliability types of both suppliers.

Thus, the contract menu in this model consists of four pairs of contracts, each

[9]For instance, the suppliers might not even know who they are competing against. Jap (2003) surveys implementations of reverse auctions for procurement and notices that most bidding events are anonymous.

pair corresponding to one of four combinations of supplier types:

$$\left\{[X_n(t_n, t_{\overline{n}}), q_n(t_n, t_{\overline{n}}), p_n(t_n, t_{\overline{n}})], n = 1, 2\right\} \text{ for } t_1, t_2 \in \{H, L\},$$

where $\overline{n}$ indicates the supplier other than supplier n (e.g., if $n = 2$, then $\overline{n}$ indicates supplier 1). To ease the notation, we use the shorthand notation $(X_n, q_n, p_n)(t_n, t_{\overline{n}})$ to denote the contract.

We consider a single-period problem in which the manufacturer has only one contracting opportunity. The timing of events is shown in Figure 3.1. The problem can be divided into two stages: contracting and execution. At the beginning of the contracting stage, nature selects the types of the two suppliers and reveals each supplier's type to that supplier only. Next, the manufacturer offers a menu of contracts to the suppliers. The suppliers make their participation decisions and then report their types to the manufacturer. Based on their reports, the manufacturer chooses a pair of contracts from the contract menu and assigns them to the respective suppliers. This concludes the contracting stage. In the execution stage, the suppliers receive their transfer payments from the manufacturer, run production, make delivery, and pay a penalty, if necessary.

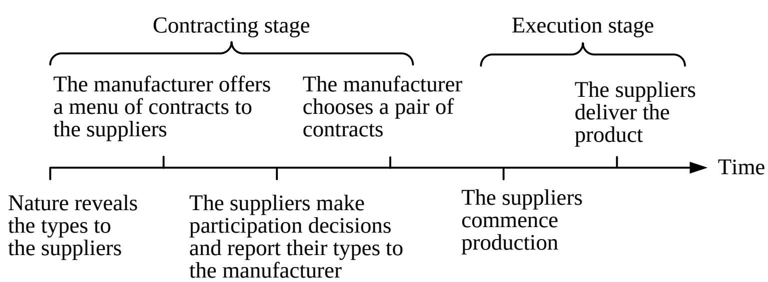


Figure 3.1: Timing of events.

We solve the problem by working backward from the execution stage. The next subsection presents the analysis of the supplier's execution stage decisions.

3.3.1 Supplier's Production Decisions

To simplify the notation in this subsection, we suppress subscript n for the suppliers. In the execution stage, given a contract (X, q, p) from the manufacturer, a supplier of type $t \in \{H, L\}$ chooses the size of its production run, z, to maximize its expected profit. Subsequently, if the production output, $\rho^t z$, is less than the order quantity q, the supplier pays a penalty p per unit of shortfall $(q - \rho^t z)^+$. (The $^+$ operation is defined such that $x^+ = x$ if $x > 0$ and $x^+ = 0$ if $x \leq 0$.) The following is supplier n's optimization problem:[10]

$$\pi^t(X, q, p) = \max_{z \geq 0} \Big\{ X - c^t\, z - pE(q - \rho^t\, z)^+ \Big\}. \tag{3.2}$$

When choosing the size of production run, z, the supplier trades off the cost of production, $c^t z$, against the expected non-delivery penalty, $pE(q - \rho^t\, z)^+$. Notice that the choice of z is independent of the transfer payment X, and, hence, the optimal z depends on q and p only (although X affects the supplier's participation decision). Let $z^t(q, p)$ denote the optimal size of the production run, given contract (X, q, p). The lemma below presents the supplier's optimal production run size and optimal expected profit. As the lemma shows, the supplier will produce the entire order quantity as long as its expected cost of successfully producing one unit, c^t/θ^t, is lower than the penalty, p.

Lemma 4. *For a given contract (X, q, p), the supplier's optimal production size, $z^t(q, p)$, and expected profit, $\pi^t(X, q, p)$, are:*

Case	$\boldsymbol{z^t(q, p)}$	$\boldsymbol{\pi^t(X, q, p)}$
(1) $p < c^t/\theta^t$	0	$X - p\, q$
(2) $p \geq c^t/\theta^t$	q	$X - c^t\, q - (1 - \theta^t) p\, q$

In case (1) of Lemma 4, where the penalty is even lower than the expected cost of successfully producing one unit, the supplier makes no production attempt. As we

[10] This is a special case of the supplier's problem (2) in Chapter 2.

will see later, this situation never arises under the manufacturer's optimal contract menu.

Lemma 4 shows that the supplier's expected profit is increasing in its reliability, θ^t. (In this chapter, we use increasing and decreasing in the weak sense.) Thus, a high-type supplier earns a larger expected profit than a low-type supplier if both suppliers are offered the same contract. We define a high-type supplier's reliability advantage over a low-type supplier to be the difference between their optimal expected profits under the same contract.

Definition 3. *Under contract (X, q, p), the supplier's reliability advantage for being of high-type as opposed to low-type is* $\Gamma(q,p) \stackrel{\text{def}}{=} \pi^H(X,q,p) - \pi^L(X,q,p)$.

Notice that Γ is not a function of the transfer payment, X, because it cancels out in the calculation. Applying the expression for the supplier's optimal profit in Lemma 4 to the definition yields:

$$\Gamma(q,p) = \begin{cases} 0 & p < c^H/h \\ (h\,p - c^H)q & c^L/l > p \geq c^H/h \\ [(h-l)\,p - (c^H - c^L)]q & p \geq c^L/l\,. \end{cases} \tag{3.3}$$

Using equation (3.3), $\Gamma(q,p)$ can be shown to be positive for all $q \geq 0$ and $p \geq 0$, increasing in p, q, and h, and decreasing in l. These properties of $\Gamma(q,p)$ will be instrumental in developing insights about the effects of asymmetric information on the manufacturer's procurement actions.

3.3.2 Manufacturer's Contract Design Problem

We now explore the manufacturer's decisions in the contracting stage. Recall that we model the manufacturer's decisions as a mechanism design problem, and, by the Revelation Principle, we focus on incentive-compatible direct-revelation contract menus.

Recall that t_n and $t_{\overline{n}}$ are the reliability types of supplier n and supplier $\overline{n}$. At the beginning of the contracting stage, the manufacturer, who does not know the suppliers' types, designs and offers a contract menu to maximize its expected profit. Let $s_n, s_{\overline{n}} \in \{H, L\}$ denote the types reported by supplier n and the other supplier upon observing the contract menu offered by the manufacturer. (Notice that if $s_n \neq t_n$, then the supplier is misrepresenting itself.) Based on the reported types, supplier n receives a contract $(X_n, q_n, p_n)(s_n, s_{\overline{n}})$, runs production of optimal size $z_n^{t_n}[(q_n, p_n)(s_n, s_{\overline{n}})]$ and earns a profit of $\pi_n^{t_n}[(X_n, q_n, p_n)(s_n, s_{\overline{n}})]$ (see Lemma 4). At the time supplier n is reporting its type, it does not know the type of the other supplier and hence supplier-n's expected profit is $\Pi_n^{t_n}(s_n) \overset{\text{def}}{=} E_{t_{\overline{n}}}\Big\{\pi_n^{t_n}[(X_n, q_n, p_n)(s_n, t_{\overline{n}})]\Big\}$, where the expectation is taken over supplier-$\overline{n}$'s type.

The manufacturer designs its contract menu to optimize its expected profit while inducing the suppliers to report their true reliability types. The manufacturer's contract design problem is the following optimization problem:

$$
\begin{aligned}
\max_{\substack{(X_n, q_n, p_n)(t_n, t_{\overline{n}})\\ n=1,2;\, t_1, t_2 \in \{H,L\}}} \quad & \Bigg\{ \sum_{t_1, t_2 \in \{H,L\}} \alpha^{t_1}\alpha^{t_2} \Bigg[rE\min\Big\{D,\ \rho_1^{t_1}\, z_1^{t_1}[(q_1,p_1)(t_1,t_2)] + \rho_2^{t_2}\, z_2^{t_2}[(q_2,p_2)(t_2,t_1)]\Big\} \\
& - X_1(t_1,t_2) + p_1(t_1,t_2)\, E\Big[q_1(t_1,t_2) - \rho_1^{t_1}\, z_1^{t_1}[(q_1,p_1)(t_1,t_2)]\Big]^+ - K\,\mathbf{1}_{\{q_1(t_1,t_2)>0\}} && \text{(3.4a)} \\
& - X_2(t_2,t_1) + p_2(t_2,t_1)\, E\Big[q_2(t_2,t_1) - \rho_2^{t_2}\, z_2^{t_2}[(q_2,p_2)(t_2,t_1)]\Big]^+ - K\,\mathbf{1}_{\{q_2(t_2,t_1)>0\}} \Bigg] \Bigg\},
\end{aligned}
$$

$$
\begin{aligned}
&\text{Subject to} && \text{For } n = 1,2 \\
&\text{(I.C.)} && \Pi_n^H(H) \geq \Pi_n^H(L), \quad \Pi_n^L(L) \geq \Pi_n^L(H) && \text{(3.4b)} \\
&\text{(I.R.)} && \Pi_n^H(H) \geq 0, \quad \Pi_n^L(L) \geq 0 && \text{(3.4c)} \\
& && q_n(t_n, t_{\overline{n}}) \geq 0,\ p_n(t_n, t_{\overline{n}}) \geq 0,\ \text{for } t_1, t_2 \in \{H, L\}.
\end{aligned}
$$

The manufacturer's objective function (3.4a) is the manufacturer's expected revenue minus the transfer payments to the two suppliers minus the setup costs of ordering from the suppliers plus the expected penalties received, weighted by the probabilities of drawing different supplier types.

Constraints (I.C.) are *incentive compatibility* constraints for high-type and low-type supplier-n, respectively. The left-hand-side of each of these constraints is supplier-n's expected profit when it truthfully reports its type, given that supplier-$\overline{n}$'s type is unknown. The right-hand-side is supplier-n's expected profit when it misrepresents itself. The constraints ensure that supplier n finds it optimal to report its true type. Constraints (I.R.) are the *individual rationality* constraints for high-type and low-type supplier-n. These constraints ensure that supplier-n's expected profit is greater than its reservation profit, which is normalized to zero. This assumption is common in the mechanism design field, and is adopted in both the economics (e.g., Myerson, 1981; Che, 1993) and operations management (e.g., Lim, 1997; Corbett et al., 2004) literatures.

For problem (3.4), we have assumed that neither supplier perfectly knows the other supplier's reliability type, leading to a Bayesian mechanism. For general mechanism design problems in which the payoff functions of the principal and the agents are quasilinear in the transfer payments (as in our model), the optimal dominant-strategy mechanism is also an optimal Bayesian mechanism (Mookherjee and Reichelstein, 1992). That is, the set of optimal Bayesian mechanisms subsumes the set of optimal dominant-strategy mechanisms. We later show that in our model we can choose a Bayesian-mechanism optimal contract menu such that it is also an optimal dominant-strategy mechanism. Consequently, the optimal Bayesian mechanism outcome could be implemented regardless of the suppliers' beliefs about each other, and the mechanism remains optimal even if the suppliers perfectly know each other's reliability type.

3.4. Optimal Contracts under Symmetric Information

To provide a benchmark we first solve a variant of problem (3.4) in which suppliers' reliabilities are common knowledge. We refer to this variant as the symmetric information model and use it to explore the effect of asymmetric information. The *incentive compatibility* constraints (3.4b) are no longer required. The *individual ra-*

tionality constraints (3.4c) become

$$\pi_n^H[(X_n, q_n, p_n)(H, t_{\overline{n}})] \geq 0 \text{ and } \pi_n^L[(X_n, q_n, p_n)(L, t_{\overline{n}})] \geq 0, \text{ for } n \in \{1,2\},\ t_{\overline{n}} = H, L.$$

Given two suppliers with types $t_1, t_2 \in \{H, L\}$, we refer to the more reliable supplier as the *primary* supplier, and the less reliable one as the *secondary* supplier. If both suppliers are of the same reliability type, we use the convention of designating supplier 1 as the primary supplier. Hereafter, we use subscripts m and $\overline{m}$ to indicate the primary and the secondary suppliers. The following proposition states the manufacturer's optimal procurement actions, illustrated in Figure 3.2.

Proposition 6. *Under symmetric information, given the reliability types of the primary and secondary suppliers, t_m and $t_{\overline{m}}$, there exist two thresholds, $\tilde{r}^{t_m}$ and $\tilde{r}^{t_m,t_{\overline{m}}}$ (given in Table 3.1), such that the manufacturer does not order from either supplier if $r \leq \tilde{r}^{t_m}$, orders only from the primary supplier if $\tilde{r}^{t_m} < r \leq \tilde{r}^{t_m,t_{\overline{m}}}$, and orders from both suppliers if $r > \tilde{r}^{t_m,t_{\overline{m}}}$. The manufacturer's optimal contract menu, $\{(\tilde{X}_n^*, \tilde{q}_n^*, \tilde{p}_n^*)(t_n, t_{\overline{n}}), n = 1,2\}$, $t_1, t_2 \in \{H, L\}$, is provided in Table 3.2.*

The suppliers earn zero profit, $\pi_n^H[(\tilde{X}_n^*, \tilde{q}_n^*, \tilde{p}_n^*)(H, t_{\overline{n}})] = \pi_n^L[(\tilde{X}_n^*, \tilde{q}_n^*, \tilde{p}_n^*)(L, t_{\overline{n}})] = 0$, for $t_{\overline{n}} \in \{H, L\}$, $n = 1, 2$. The manufacturer's expected profit is

$$\begin{aligned}
&\left(\alpha^H\right)^2 \left(\left[(h\,r - c^H)D - K\right]^+ + \left\{\left[(1-h)h\,r - c^H\right] D - K\right\}^+\right) \\
&+2\left(\alpha^H \alpha^L\right)\left(\left[(h\,r - c^H)D - K\right]^+ + \left\{\left[(1-h)l\,r - c^L\right] D - K\right\}^+\right) \\
&+\left(\alpha^L\right)^2 \left(\left[(l\,r - c^L)D - K\right]^+ + \left\{\left[(1-l)l\,r - c^L\right] D - K\right\}^+\right).
\end{aligned} \tag{3.5}$$

Our optimal contract analysis did not restrict the size of the non-delivery penalty. However, punitive penalties which exceed the damages the buyer expects to incur from supplier non-delivery are generally not enforceable in US courts (Corbin, 2007). It is therefore important to note that the optimal contract does not require punitive penalties. Notice from Table 3.2 that Proposition 6 allows various values for

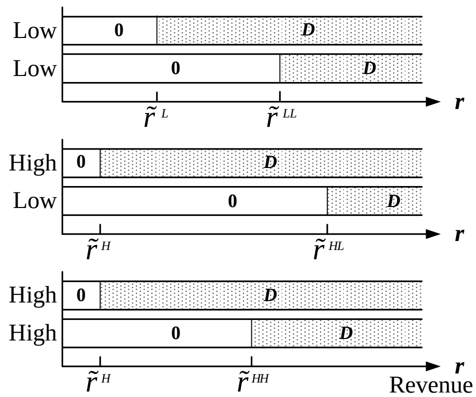


Figure 3.2: The manufacturer's optimal procurement actions under symmetric information in relation to the revenue, r. The label 0 marks the regions where a supplier receives no order, and the label D marks the regions where a supplier receives an order of size D. The manufacturer orders only from the primary supplier if the revenue, r, is small, and diversifies if r is large.

Primary	**Secondary**	$\tilde{r}^{t_m}$	$\tilde{r}^{t_m, t_{\overline{m}}}$
High-type	High-type	$\tilde{r}^H = \frac{c^H}{h} + \frac{K}{h\,D}$	$\tilde{r}^{HH} = \frac{c^H}{h(1-h)} + \frac{K}{h(1-h)\,D}$
High-type	Low-type	$\tilde{r}^H = \frac{c^H}{h} + \frac{K}{h\,D}$	$\tilde{r}^{HL} = \frac{c^L}{l(1-h)} + \frac{K}{l(1-h)\,D}$
Low-type	Low-type	$\tilde{r}^L = \frac{c^L}{l} + \frac{K}{l\,D}$	$\tilde{r}^{LL} = \frac{c^L}{l(1-l)} + \frac{K}{l(1-l)\,D}$

Table 3.1: Expressions for thresholds $\tilde{r}^{t_m}$ and $\tilde{r}^{t_m, t_{\overline{m}}}$ separating revenue into intervals within which the manufacturer does not order from either supplier, orders from only the primary supplier, or orders from both suppliers, under symmetric information.

the optimal penalties and associated transfer payments. One can check that the smallest optimal penalty $\tilde{p}_n^*$ equals its corresponding optimal transfer payment $\tilde{X}_n^*$, in which case the penalty clause boils down to recovering the payment already made to the supplier. Consequently, the manufacturer could implement the optimal contract simply by specifying a transfer payment contingent on successful delivery. This setup circumvents penalties altogether and thus obviates the need to consider penalty enforceability.

We now continue the discussion of Proposition 6. Given two suppliers of known types, once the unit revenue, r, becomes sufficiently large, the manufacturer will diversify, that is, it will order from both suppliers. Observe from Figure 3.2 that having two suppliers with different types makes it less appealing for the manufacturer to diversify, i.e., $\tilde{r}^{HL} > \tilde{r}^{HH}$ and $\tilde{r}^{HL} > \tilde{r}^{LL}$. Intuitively, if one supplier is of high-type and the other of low-type, the secondary supplier is less reliable compared to the case where both suppliers are of high-type. Similarly, if one supplier is of high-type and the

Revenue	Supplier	$\tilde{X}_n^*$	$\tilde{q}_n^*$	$\tilde{p}_n^*$
Two high-type suppliers				
$r \leq \tilde{r}^H$	Both	- No contract -		
$\tilde{r}^H < r \leq \tilde{r}^{HH}$	Supplier 1	$[c^H + (1-h)\tilde{p}_1^*]D$	D	any $\tilde{p}_1^* \in [\frac{c^H}{h}, r)$
	Supplier 2	- No contract -		
$r > \tilde{r}^{HH}$	Supplier 1	$[c^H + (1-h)\tilde{p}_1^*]D$	D	any $\tilde{p}_1^* \in [\frac{c^H}{h}, r)$
	Supplier 2	$[c^H + (1-h)\tilde{p}_2^*]D$	D	any $\tilde{p}_2^* \in [\frac{c^H}{h}, r)$
High-type supplier-m and low-type supplier-$\overline{m}$				
$r \leq \tilde{r}^H$	Both	- No contract -		
$\tilde{r}^H < r \leq \tilde{r}^{HL}$	Supplier m	$[c^H + (1-h)\tilde{p}_m^*]D$	D	any $\tilde{p}_m^* \in [\frac{c^H}{h}, r)$
	Supplier $\overline{m}$	- No contract -		
$r > \tilde{r}^{HL}$	Supplier m	$[c^H + (1-h)\tilde{p}_m^*]D$	D	any $\tilde{p}_m^* \in [\frac{c^H}{h}, r)$
	Supplier $\overline{m}$	$[c^L + (1-l)\tilde{p}_{\overline{m}}^*]D$	D	any $\tilde{p}_{\overline{m}}^* \in [\frac{c^L}{l}, r)$
Two low-type suppliers				
$r \leq \tilde{r}^L$	Both	- No contract -		
$\tilde{r}^L < r \leq \tilde{r}^{LL}$	Supplier 1	$[c^L + (1-l)\tilde{p}_1^*]D$	D	any $\tilde{p}_1^* \in [\frac{c^L}{l}, r)$
	Supplier 2	- No contract -		
$r > \tilde{r}^{LL}$	Supplier 1	$[c^L + (1-l)\tilde{p}_1^*]D$	D	any $\tilde{p}_1^* \in [\frac{c^L}{l}, r)$
	Supplier 2	$[c^L + (1-l)\tilde{p}_2^*]D$	D	any $\tilde{p}_2^* \in [\frac{c^L}{l}, r)$

Table 3.2: The optimal contract menu under symmetric information. $\tilde{r}^{t_m}$ and $\tilde{r}^{t_m, t_{\overline{m}}}$ are defined in Table 3.1.

other of low-type, the primary supplier is more reliable compared to the case where both suppliers are of low-type. Either way, the additional value from the secondary supplier is smaller when the suppliers have different types.

Per Proposition 6, under symmetric information the manufacturer extracts all channel profit. Therefore, the channel's profit is also maximized at the manufacturer's optimal contract menu. We let $\pi_C^{t_1,t_2}[(q_1, p_1), (q_2, p_2)]$ be the channel's profit under a pair of contracts $\{(X_1, q_1, p_1), (X_2, q_2, p_2)\}$, when the two suppliers are of types t_1 and t_2. Note that $\pi_C^{t_1,t_2}$ is independent of the transfer payments X_1 and X_2, because they are payments within the channel. The optimal channel profit equals $\pi_C^{t_1,t_2}[(\tilde{q}_1^*, \tilde{p}_1^*)(t_1, t_2), (\tilde{q}_2^*, \tilde{p}_2^*)(t_2, t_1)]$. The channel loses a profit when $\{(q_1, p_1), (q_2, p_2)\}$ are different from the channel-optimal contract terms in Proposition 6. We define the channel loss as:

Definition 4. *The channel loss under a pair of contracts* $\{(X_1, q_1, p_1), (X_2, q_2, p_2)\}$, *when the two suppliers' types are* t_1 *and* t_2, *is*

$$\Delta^{t_1,t_2}[(q_1, p_1), (q_2, p_2)] \stackrel{\text{def}}{=} \pi_C^{t_1,t_2}[(\tilde{q}_1^*, \tilde{p}_1^*)(t_1, t_2), (\tilde{q}_2^*, \tilde{p}_2^*)(t_2, t_1)] - \pi_C^{t_1,t_2}[(q_1, p_1), (q_2, p_2)].$$

3.5. Optimal Contracts under Asymmetric Information

In this section we explore the manufacturer's contract design problem (3.4) under asymmetric information. We first explain the tradeoff underlying the manufacturer's contracting decisions in the face of privately informed suppliers. Proposition 7 presents the optimal contract menu. We then compare the optimal contract menus under symmetric and asymmetric information to identify the effect of asymmetric information.

The manufacturer's tradeoff. Incentive problems arise when the suppliers have private information. Recall that the optimal contract menu under symmetric information, denoted by $(\tilde{X}_n^*, \tilde{q}_n^*, \tilde{p}_n^*)(t_n, t_{\overline{n}})$, $n = 1, 2,\ t_1, t_2 \in \{H, L\}$, is designed so that the manufacturer extracts the entire channel profit and leaves zero profit to the suppliers. Under asymmetric information, if the manufacturer offered the same contract menu, then a high-type supplier would have an incentive to misrepresent itself. For example, if supplier n is a high-type supplier, it would claim to be a low-type supplier and receive the contract $(\tilde{X}_n^*, \tilde{q}_n^*, \tilde{p}_n^*)(L, t_{\overline{n}})$. This contract, which yields zero profit to a low-type supplier, would bring high-type supplier-n a strictly positive profit equal to its reliability advantage, denoted by $\Gamma_n[(\tilde{q}_n^*, \tilde{p}_n^*)(L, t_{\overline{n}})]$ (see Definition 3). Therefore, under asymmetric information, if the manufacturer offered contract menu $(\tilde{X}_n^*, \tilde{q}_n^*, \tilde{p}_n^*)(t_n, t_{\overline{n}})$, $n = 1, 2,\ t_1, t_2 \in \{H, L\}$, it would have to make an *incentive payment* to high-type supplier-n in the amount of $\Gamma_n[(\tilde{q}_n^*, \tilde{p}_n^*)(L, t_{\overline{n}})]$. Alternatively, the manufacturer may offer a different contract menu to reduce this incentive payment, which nonetheless may not optimize the channel profit. The resulting channel loss (see Definition 4) will then be borne by the manufacturer. Hence, in designing the contract menu, the manufacturer must strike a balance between the incentive payment to a high-type supplier and the channel loss.

The optimal contract menu. The next proposition describes the optimal contract that achieves this goal. Using the analytical results in Proposition 7, we illustrate the manufacturer's optimal procurement actions on the right panel of Figure 3.3. We continue to use the convention that when both suppliers are the same type, supplier 1 is designated as the primary supplier.

Proposition 7. *Under asymmetric information, given the reliability types of the primary and secondary suppliers, t_m and $t_{\overline{m}}$, there exist two thresholds, r^{t_m} and $r^{t_m,t_{\overline{m}}}$ (given in Table 3.3), such that the manufacturer does not order from either supplier if $r \le r^{t_m}$, orders only from the primary supplier if $r^{t_m} < r \le r^{t_m,t_{\overline{m}}}$, and orders from both suppliers if $r > r^{t_m,t_{\overline{m}}}$. The manufacturer's optimal contract menu, $\{(X_n^*, q_n^*, p_n^*)(t_n, t_{\overline{n}}),\ n = 1,2\}$, $t_1, t_2 \in \{H, L\}$, is presented in Table 3.4. Without loss of optimality, we choose the optimal transfer payments $X_n^*(t_n, t_{\overline{n}})$ such that the optimal contract menu is also a dominant-strategy mechanism.*

High- and low-type supplier-n's profits are $\pi_n^H[(X_n^*, q_n^*, p_n^*)(H, t_{\overline{n}})] = h\left(\frac{c^L}{l} - \frac{c^H}{h}\right) q_n^*(L, t_{\overline{n}})$, and $\pi_n^L[(X_n^*, q_n^*, p_n^*)(L, t_{\overline{n}})] = 0$; the manufacturer's expected profit (before knowing supplier types) is

$$\begin{aligned}
&(\alpha^H)^2\Big(\big[(h\,r - c^H)D - K\big]^+ + \big\{\big[h(1-h)r - c^H\big]\,D - K\big\}^+\Big)\\
&+2\left(\alpha^H\alpha^L\right)\left(\big[(h\,r - c^H)D - K\big]^+ + \left\{\big[l(1-h)r - c^L\big]\,D - K - \frac{\alpha^H}{\alpha^L}\,h\left(\frac{c^L}{l} - \frac{c^H}{h}\right)D\right\}^+\right)\\
&+(\alpha^L)^2\left(\left[(l\,r - c^L)D - K - \frac{\alpha^H}{\alpha^L}\,h\left(\frac{c^L}{l} - \frac{c^H}{h}\right)D\right]^+ + \left\{\big[l(1-l)r - c^L\big]D - K - \frac{\alpha^H}{\alpha^L}\,h\left(\frac{c^L}{l} - \frac{c^H}{h}\right)D\right\}^+\right).
\end{aligned} \tag{3.6}$$

Similar to our observation following Proposition 6, the manufacturer could implement the optimal contract under asymmetric information simply by specifying a transfer payment contingent on successful delivery.

Primary	**Secondary**	$\boldsymbol{r^{t_m}}$	$\boldsymbol{r^{t_m,t_{\overline{m}}}}$
High-type	High-type	$r^H = \tilde{r}^H$	$r^{HH} = \tilde{r}^{HH}$
High-type	Low-type	$r^H = \tilde{r}^H$	$r^{HL} = \tilde{r}^{HL} + \frac{\alpha^H}{\alpha^L}\frac{h}{l(1-h)}\left(\frac{c^L}{l} - \frac{c^H}{h}\right)$
Low-type	Low-type	$r^L = \tilde{r}^L + \frac{\alpha^H}{\alpha^L}\frac{h}{l}\left(\frac{c^L}{l} - \frac{c^H}{h}\right)$	$r^{LL} = \tilde{r}^{LL} + \frac{\alpha^H}{\alpha^L}\frac{h}{l(1-l)}\left(\frac{c^L}{l} - \frac{c^H}{h}\right)$

Table 3.3: Expressions for thresholds r^{t_m} and $r^{t_m,t_{\overline{m}}}$ separating revenue into intervals within which the manufacturer does not order from either supplier, orders from only the primary supplier, or orders from both suppliers, under asymmetric information.

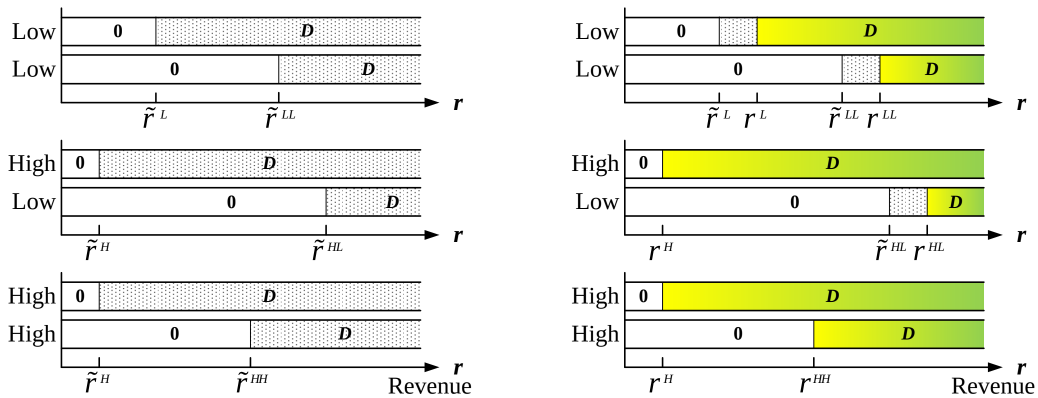


Figure 3.3: The manufacturer's optimal procurement actions in relation to the revenue, r, under symmetric information (the left panel) and asymmetric information (shaded with solid color on the right panel). The difference between the manufacturer's procurement actions under symmetric and asymmetric information is shown on the right panel. Under asymmetric information, the manufacturer forgoes ordering from the low-type supplier when r falls in the intervals corresponding to the dotted bars.

Effect of asymmetric information on ordering decisions. Compared to the symmetric information case, as the right panel of Figure 3.3 shows, the thresholds for ordering from the low-type supplier, be it a primary or secondary supplier, are higher under asymmetric information. In particular, the manufacturer stops diversifying when $\max\{r^L, \tilde{r}^{LL}\} \leq r < r^{LL}$ and both suppliers are of low-type, or $\tilde{r}^{HL} \leq r < r^{HL}$ and the two suppliers are of different types. Under symmetric information, the manufacturer sole-sources when the anticipated revenue brought by the secondary supplier does not outweigh the additional ordering costs. However, under asymmetric information there is an additional benefit to sole-source, which pushes the manufacturer

Revenue	**Supplier**	X_n^*	q_n^*	p_n^*
Two high-type suppliers				
$r \leq r^H$	Both	- No contract -		
$r^H < r \leq r^{HH}$	Supplier 1	$[c^H + (1-h)p_1^*]D$	D	any $p_1^* \in [\frac{c^H}{h}, r)$
	Supplier 2	- No contract -		
$r^{HH} < r \leq r^{HL}$	$n = 1, 2$	$[c^H + (1-h)p_n^*]D$	D	any $p_n^* \in [\frac{c^H}{h}, r)$
$r > r^{HL}$	$n = 1, 2$	$[c^H + (1-h)p_n^*]D + h(\frac{c^L}{l} - \frac{c^H}{h})D$	D	any $p_n^* \in [\frac{c^L}{l}, r)$
High-type supplier-1 and low-type supplier-2				
$r \leq r^H$	Both	- No contract -		
$r^H < r \leq r^L$	Supplier 1	$[c^H + (1-h)p_1^*]D$	D	any $p_1^* \in [\frac{c^H}{h}, r)$
	Supplier 2	- No contract -		
$r^L < r \leq r^{HL}$	Supplier 1	$[c^H + (1-h)p_1^*]D + h(\frac{c^L}{l} - \frac{c^H}{h})D$	D	any $p_1^* \in [\frac{c^L}{l}, r)$
	Supplier 2	- No contract -		
$r > r^{HL}$	Supplier 1	$[c^H + (1-h)p_1^*]D + h(\frac{c^L}{l} - \frac{c^H}{h})D$	D	any $p_1^* \in [\frac{c^L}{l}, r)$
	Supplier 2	$\frac{c^L}{l}D$	D	$p_2^* = \frac{c^L}{l}$
Low-type supplier-1 and high-type supplier-2				
$r \leq r^H$	Both	- No contract -		
$r^H < r \leq r^{LL}$	Supplier 1	- No contract -		
	Supplier 2	$[c^H + (1-h)p_2^*]D$	D	any $p_2^* \in [\frac{c^H}{h}, r)$
$r^{LL} < r \leq r^{HL}$	Supplier 1	- No contract -		
	Supplier 2	$[c^H + (1-h)p_2^*]D + h(\frac{c^L}{l} - \frac{c^H}{h})D$	D	any $p_2^* \in [\frac{c^L}{l}, r)$
$r > r^{HL}$	Supplier 1	$\frac{c^L}{l}D$	D	$p_1^* = \frac{c^L}{l}$
	Supplier 2	$[c^H + (1-h)p_2^*]D + h(\frac{c^L}{l} - \frac{c^H}{h})D$	D	any $p_2^* \in [\frac{c^L}{l}, r)$
Two low-type suppliers				
$r \leq r^L$	Both	- No contract -		
$r^L < r \leq r^{LL}$	Supplier 1	$\frac{c^L}{l}D$	D	$p_1^* = \frac{c^L}{l}$
	Supplier 2	- No contract -		
$r > r^{LL}$	$n = 1, 2$	$\frac{c^L}{l}D$	D	$p_n^* = \frac{c^L}{l}$

Table 3.4: The optimal contract menu under asymmetric information. r^{t_m} and $r^{t_m, t_{\overline{m}}}$ are defined in Table 3.3.

to diversify less. If the manufacturer will not order from a secondary supplier of low-type, then a high-type supplier knows that pretending to be of low-type might backfire – it could lose the order. Thus, when the manufacturer rolls back diversification, the suppliers find themselves in more intense competition, reducing their incentives to misrepresent themselves.

As a consequence of forgoing ordering from a low-type supplier, the manufacturer receives less supply under asymmetric information. Thus, we have the following result:

Corollary 9. *The total quantity received by the manufacturer from the two suppliers under symmetric information first-order stochastically dominates that received under asymmetric information.*

Sensitivity to supply-base reliability. A worsening of reliability in the supply base may have different effects on the use of diversification under symmetric and asymmetric information. One may intuitively expect that whenever the supply base becomes less reliable, the manufacturer will find it more attractive to diversify. Indeed, with symmetric information under a mild restriction on supplier reliabilities, $h+l>1$, the manufacturer may start diversifying when the supply base becomes less reliable, but will never stop diversifying. However, under asymmetric information, the opposite may be true: a worsening of reliability may cause the manufacturer to stop diversifying under asymmetric information. These observations are formalized in the following corollary.

Corollary 10. *Suppose the non-disruption probabilities are such that $h+l>1$. Consider the optimal contract pair offered to one high- and one low-type suppliers. Under asymmetric information, there exist h, l and unit revenue r such that the manufacturer diversifies, but if both h and l decrease by some $\epsilon \in (0,l)$ the manufacturer will stop diversifying. Under symmetric information, the manufacturer would never stop diversifying in response to a reliability decrease.*

The explanation of this result lies in high-type suppliers' incentives to misrepresent themselves. When both supplier types are sufficiently unreliable (as made precise in the proof of the above corollary), a further reduction in their reliabilities leads to an increase in a high-type supplier's reliability advantage, which in turn translates into a larger incentive payment from the manufacturer. Even though a worsening of the supply base reliability increases the chance that a low-type supplier's delivery

Revenue, r	**Informational Rent**	
	$\gamma_1(r)$, for supplier 1	**$\gamma_2(r)$, for supplier 2**
$r \leq r^L$	0	0
$r^L < r \leq r^{LL}$	$\alpha^L h \left(\frac{c^L}{l} - \frac{c^H}{h} \right) D$	
$r^{LL} < r \leq r^{HL}$		$\alpha^L h \left(\frac{c^L}{l} - \frac{c^H}{h} \right) D$
$r > r^{HL}$	$h \left(\frac{c^L}{l} - \frac{c^H}{h} \right) D$	$h \left(\frac{c^L}{l} - \frac{c^H}{h} \right) D$

Table 3.5: Informational rents earned by high-type supplier-n, $\gamma_n(r)$, $n = 1, 2$.

would be critical for meeting demand, the manufacturer can find it attractive to stop diversifying in order to circumvent a ballooning incentive payment for the high-type supplier.

Sensitivity to the production cost gap, $c^L - c^H$. To explore the effect of the cost gap between the two supplier types, we fix c^L and increase c^H. As one would expect, under symmetric or asymmetric information the manufacturer orders less from the high-type supplier as c^H increases ($\tilde{r}^H$, $\tilde{r}^{HH}$, r^H, and r^{HH} increase, see tables 3.1 and 3.3). However, interestingly, under asymmetric information the manufacturer finds diversifying with the low-type supplier more attractive (r^{HL} and r^{LL} decrease, see table 3.3) as c^H increases. This is because, as the high type's production cost increases, the gap between effective costs of the supplier types ($c^L/l - c^H/h$) decreases and there is less need to control the high-type's incentives to misrepresent its true type.

Informational rents and channel loss. We use Proposition 7 to compute the suppliers' incentive payments and the channel loss under the optimal contract menu. These results will be crucial in analyzing the value of information. Following standard information economics terminology, we refer to high-type supplier-n's expected incentive payment under the optimal contract menu as its informational rent, denoted by $\gamma_n(r)$, where the expectation is over supplier-$\overline{n}$'s type: $\gamma_n(r) \stackrel{\text{def}}{=} E_{t_{\overline{n}}}\Big\{\Gamma[(q_n^*, p_n^*)(L, t_{\overline{n}})]\Big\}$.

The optimal penalty $p_n^*(L, t_{\overline{n}})$ and optimal order quantity $q_n^*(L, t_{\overline{n}})$ are given by

Proposition 7. Table 3.5 presents the closed-form expressions for $\gamma_n(r)$, $n = 1, 2$, revealing that a high-type supplier's informational rent increases in the revenue, r. In particular, as revenue increases it becomes important for the manufacturer to avoid lost sales, encouraging the manufacturer to order from a low-type supplier and thereby allowing a high-type supplier to exploit its reliability advantage.

Given the optimal contracts for two suppliers of types t_1 and t_2 under asymmetric information, the channel loss is denoted by δ^{t_1,t_2} and is given by $\delta^{t_1,t_2}(r) \stackrel{\text{def}}{=} \Delta^{t_1,t_2}\Big[(q_1^*, p_1^*)(t_1, t_2), (q_2^*, p_2^*)(t_2, t_1)\Big]$.

Revenue, r	$\boldsymbol{\delta^{HH}(r)}$
$r > 0$	0
Revenue, r	$\boldsymbol{\delta^{HL}(r)}$ **or** $\boldsymbol{\delta^{LH}(r)}$
$\tilde{r}^{HL} < r \le r^{HL}$	$\left[(1-h)l\,r - c^L\right] D - K$
All other r	0
Revenue, r	$\boldsymbol{\delta^{LL}(r)}$
$\tilde{r}^{L} < r \le r^{L}$	$(l\,r - c^L)D - K$
$\tilde{r}^{LL} < r \le r^{LL}$	$\left[(1-l)l\,r - c^L\right] D - K$
All other r	0

Table 3.6: The channel loss under the optimal contract menu, $\delta^{t_1,t_2}(r)$.

Table 3.6 provides a closed-form expression for the channel loss, $\delta^{t_1,t_2}(r)$, $t_1, t_2 \in \{H, L\}$. Under the optimal contract menu, channel loss is strictly positive whenever asymmetric information causes the manufacturer to stop ordering from a low-type supplier from whom it would order under symmetric information. For example, given two suppliers, one of high-type and the other of low-type, if revenue r is such that $\tilde{r}_{HL} < r \le r_{HL}$, then introducing asymmetric information causes the manufacturer to stop ordering from the low-type supplier, resulting in a profit loss of $\left[(1-h)l\,r - c^L\right] D - K$, equal to channel loss $\delta^{HL}(r)$.

3.6. Value of Information

Section 3.5 shows that asymmetric information about suppliers' reliabilities changes the manufacturer's procurement actions and causes losses in the manufacturer's and the channel's profits. These losses can be avoided by acquiring information, which could be costly and, thus, needs to be justified by the benefits of having such information. In this section, we study the value of information for the suppliers, channel and manufacturer, where the value of information for an entity is defined to be the difference between its expected profits in symmetric and asymmetric information models.[11]

For a high-type supplier, the value of information is the negative of its informational rent (Table 3.5). For the channel, the value of information equals channel loss (Table 3.6) weighted by the probability of drawing suppliers of types $t_1, t_2 \in \{H, L\}$. From the manufacturer's perspective, information about suppliers' reliabilities creates value by eliminating both informational rent and channel loss. Hence, the manufacturer's value of information equals the sum of the informational rents paid to the two suppliers (each weighted by the probability that the supplier is of high-type) and the expected channel loss: $\alpha^H\left[\gamma_1(r) + \gamma_2(r)\right] + \left[2\left(\alpha^H\alpha^L\right)\delta^{HL}(r) + \left(\alpha^L\right)^2\delta^{LL}(r)\right]$.

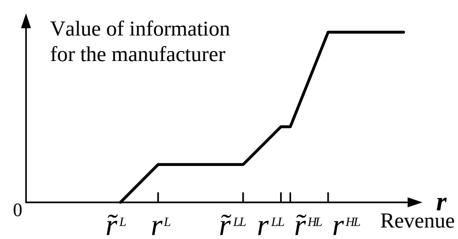


Figure 3.4: The values of information for the manufacturer increases in the revenue, r.

Figure 3.4 plots the manufacturer's value of information versus r, revealing that as the revenue increases, the manufacturer's value of information increases, alternating between regions where it is strictly increasing and regions where it is flat. For example, when $\tilde{r}^L < r \leq r^L$, given two low-type suppliers, the manufacturer would order from

[11]Recall from Proposition 7 that in the asymmetric information model, even if a supplier perfectly knows the other supplier's reliability type, it would receive the same contract and thus earn the same profit. Therefore, in this model there is no value for the suppliers only to acquire information about the reliability type of the other supplier.

one of them under symmetric information, but would strategically not order at all under asymmetric information. Hence, the manufacturer incurs channel loss, which becomes all the more costly as r continues to increase. This explains the increase in the value of information as r increases from $\tilde{r}^L$ to r^L. Once r is slightly above r^L, the channel loss becomes so onerous that the manufacturer starts ordering from one of the two low-type suppliers even under asymmetric information. While this strategic decision allows the manufacturer to avoid channel loss, it risks incurring informational rent if a high-type supplier is drawn. The information rent does not change with r, so the value of information levels off. This behavior repeats itself as r increases further. Overall, as revenue increases, the manufacturer becomes more willing to order to avert lost sales, allowing more opportunities for the high-type supplier(s) to exploit their private information and thus enhancing the value of information.

Sensitivity of the manufacturer's value of information to reliability gap, $\boldsymbol{h-l}$. Intuitively, one may expect that the manufacturer's value of information increases if the reliability gap between the two supplier-types expands, because high-type suppliers would have stronger incentives to misrepresent their reliabilities. In fact, in the case where there is only one supplier in the supply base, the manufacturer's value of information increases as the reliability gap increases (see Corollary 6 in Chapter 2). However, we find that in the dual-sourcing model the value of information may decrease, depending on the size of revenue, r.

Corollary 11. *Suppose that the low-type's reliability, l, is fixed. If $\max\{\tilde{r}^{HL}, c^L/l^2\} < r \leq r^{HL}$, then the manufacturer's value of information is decreasing in h.*

Note that when $l > \frac{1}{2}$, we have $\tilde{r}^{HL} > c^L/l^2$. Therefore, when $l > \frac{1}{2}$, for all $\tilde{r}^{HL} < r \leq r^{HL}$ the value of information is decreasing in h. To see the intuition behind Corollary 11, note that when $\tilde{r}^{HL} < r \leq r^{HL}$, asymmetric information causes the manufacturer to strategically forgo diversification when facing one high- and one low-type supplier. Doing so puts the manufacturer in peril of regretting its decision to not contract with a secondary supplier, but intuitively this risk diminishes as the high-type supplier (the primary supplier) becomes more reliable.

Corollary 11 implies that, even as the reliability gap between the high and low reliability supplier-types shrinks, meaning there is seemingly less gleaned by learning the supplier's true type, information is actually more valuable. Thus, more similarity between supplier reliability types (having "less to learn" about the suppliers' reliabilities) should not be seen as a substitute for information.

Sensitivity to the production cost gap, $c^L - c^H$. As before, we fix c^L and increase c^H. We find that as the effective cost advantage of the high type over the low type, $(c^L/l - c^H/h)$, decreases, the high type has less incentive to misrepresent its true type. Consequently, the value of information for the manufacturer decreases.

3.7. Effect of Dual-Sourcing Option

In this section, we analyze the manufacturer's benefit of acquiring the dual-sourcing option. We find that the dual-sourcing option increases the manufacturer's expected profit while reducing the informational rent of a supplier. We further show that the benefit of the dual-sourcing option for the manufacturer could be enhanced or diminished by improved information about the suppliers. In Appendix 3.10, we examine a benchmark model with a single supplier in the supply base, while retaining all other assumptions of our main model (§3.3). To differentiate from the sole-sourcing case in the dual-sourcing model, we hereafter refer to this model as the *single-sourcing* model.

3.7.1 Effect of the Dual-Sourcing Option on the Informational Rent

We now examine how the manufacturer's dual-sourcing option affects a high-type supplier's informational rent. Without loss of generality, we assume that the supplier in question is the one that is favored in case of a tie in the dual-sourcing model (i.e., supplier 1). We compare the informational rent extracted by high-type supplier-1 when it is the only supplier against the rent when it is one of two suppliers that the manufacturer can order from. The result is presented in Table 3.7.

Revenue, r	**Reduction in informational rent**
$r^L < r \leq r^{HL}$	$\alpha^H h \left(\frac{c^L}{l} - \frac{c^H}{h} \right) D$
$r \leq r^L$ or $r > r^{HL}$	0

Table 3.7: Reduction in informational rent extracted by high-type supplier-1 if the manufacturer switches from single-sourcing to dual-sourcing.

From Table 3.7, the dual-sourcing option reduces the high-type supplier's informational rent, if and only if the revenue, r, is such that $r^L < r \leq r^{HL}$. In region $r > r^{HL}$, the revenue is large enough that even when there are two suppliers both of them will receive an order regardless of their reliability types. Hence, when a high-type supplier is one of two suppliers, it has just as much incentive to misrepresent itself as it does when it is the only supplier. This explains why the dual-sourcing option does not change the high-type supplier's profits when $r > r^{HL}$.

In region $r^L < r \leq r^{HL}$, under the single-sourcing model, the manufacturer will order from a supplier regardless of its reliability type. Therefore, a high-type supplier will earn informational rent, because it can always pretend to be of low-type and still receive an order. In contrast, under the dual-sourcing model, a low-type supplier will not receive an order if the other supplier is of high-type. Given the manufacturer's reluctance to order from a low-type supplier, the high-type suppliers now know that pretending to be of low-type comes with the risk of not receiving an order. Thus, by not ordering from a low-type supplier, the manufacturer in effect creates competitive pressure that limits the high-type suppliers' incentive to misrepresent themselves. This competition manifests itself in the reduction of supplier 1's informational rent, shown in Table 3.7.

Finally, when $r \leq r^L$, the revenue is low enough that a low-type supplier does not receive an order with or without the dual-sourcing option. Hence, in this region, the high-type supplier has no incentive to misrepresent itself and cannot earn informational rent, regardless of whether or not the dual-sourcing option exists.

3.7.2 Value of the Dual-Sourcing Option for the Manufacturer

We now compute the manufacturer's values of the dual-sourcing option in the symmetric and asymmetric information models, and then compare them to examine the effect of asymmetric information on the benefit of having a dual-sourcing option. We define the value of the dual-sourcing option for the manufacturer as the difference between its expected profits in the dual-sourcing and single-sourcing models, given by (3.5) and (3.9) for the symmetric information model, and (3.6) and (3.10) for the asymmetric information model.

Symmetric information. Consider the scenario where in the single-sourcing model the only supplier is of low-type and in the dual-sourcing model the additional supplier is of high-type. In this scenario, the manufacturer enjoys one of two kinds of benefits by moving from the single-sourcing model to the dual-sourcing model. First, if revenue is high and the manufacturer orders from both suppliers in the dual-sourcing model, then the manufacturer benefits from diversification, reducing the probability of lost sales. Second, if revenue is low and the manufacturer chooses to order from only one supplier in the dual-sourcing model, the manufacturer enjoys the benefit of having access to the more efficient, high-type supplier. In the other scenarios, where either the single supplier is of high-type or both suppliers in the dual-sourcing model are of low-type, the dual-sourcing option does not yield benefits of having access to a more reliable supplier. Nonetheless, the dual-sourcing option continues to generate diversification benefits when the revenue is large enough.

Asymmetric information. The value of the dual-sourcing option under asymmetric information is similar to that under symmetric information. One important difference, however, is that the manufacturer yields informational rent(s) to the high-type supplier(s), and the dual-sourcing option may increase or decrease the total informational rent to be paid by the manufacturer. On one hand, the dual-sourcing option has the potential to reduce the informational rent paid to a supplier. As discussed in §3.7.1, this happens when a manufacturer with the dual-sourcing option chooses not to order from a low-type supplier, thus putting a competitive pressure on high-type suppliers. On the other hand, in cases where the dual-sourcing option enables the manufacturer to order from two high-type suppliers, the manufacturer may have to pay informational rents to both suppliers, reducing the appeal of the dual-sourcing option. Thus, it is not necessarily obvious whether the dual-sourcing option is more or less valuable under asymmetric information compared to under symmetric information. We next explore this comparison.

Information and the value of the dual-sourcing option for the manufacturer. Proposition 8 below formalizes the comparison between the values of the dual-sourcing option under symmetric and asymmetric information, which are plotted in Figure 3.5.

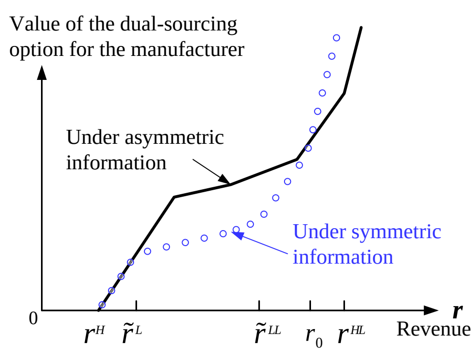


Figure 3.5: The values of the dual-sourcing option for the manufacturer under symmetric and asymmetric information. The value of the dual-sourcing option under asymmetric information is greater than under symmetric information for $\tilde{r}^L < r < r_0$, but is smaller for $r > r_0$.

Proposition 8. *Information and the dual-sourcing option are substitutes when the revenue is small and are complements when the revenue is large. Specifically, there exists a value r_0, $r^{HL} > r_0 > \tilde{r}^{LL}$, such that, for $r > r_0$, the manufacturer's value of the dual-sourcing option is larger under symmetric information than under asymmetric information; the converse is true for $\tilde{r}^L < r < r_0$.*

Intuitively, one may expect that the manufacturer would always benefit more from the dual-sourcing option under symmetric information because the manufacturer's ability to identify the suppliers' types may help it take better advantage of the option. Proposition 8 shows that information reduces the value of the dual-sourcing option when revenue, r, is small (i.e., $\tilde{r}^L < r < r_0$), but increases the value of the dual-sourcing option when revenue, r, is large (i.e., $r > r_0$).

This observation is a manifestation of the manufacturer's tradeoff between the benefit of supplier competition and the benefit of diversification. When the revenue is small, the competition effect dominates and hence the manufacturer prefers not to order from a secondary supplier. This reduces the informational rent extracted by a high-type supplier. Because this benefit is absent under symmetric information, the dual-sourcing option is more valuable under asymmetric information. When the revenue is large, the benefit of diversification becomes larger than the benefit of competition, and hence the manufacturer finds it useful to diversify. The resulting inflation of informational rents makes the dual-sourcing option less valuable under asymmetric information.

3.8. Codependent Supplier Production Disruptions

Thus far we assumed that the two suppliers' production disruption processes are independent. In reality, they could be correlated due to common infrastructure, geographic proximity, similar production technologies, overlapping supply bases and other factors. In this section we extend our model and analysis to capture codependence between the two suppliers' disruption processes.

3.8.1 Model and Optimal Contract Menu

We capture codependence between the two suppliers' disruption processes by allowing the Bernoulli yield random variables of the two suppliers to be statistically dependent. If the two suppliers are of reliability types, $t_1, t_2 \in \{H, L\}$, we may represent codependence between their disruption processes via a joint probability matrix:

$$\Omega^{t_1,t_2} \stackrel{\text{def}}{=} \begin{bmatrix} \omega^{t_1,t_2}(1,1) & \omega^{t_1,t_2}(1,0) \\ \\ \omega^{t_1,t_2}(0,1) & \omega^{t_1,t_2}(0,0) \end{bmatrix}, \tag{3.7}$$

where $\omega^{t_1,t_2}(x_1, x_2) = P\{\rho_1^{t_1} = x_1, \rho_2^{t_2} = x_2\}$, $x_1, x_2 \in \{0, 1\}$, is the joint probability that the yield rates of the two suppliers' production runs are x_1 and x_2, respectively. Matrix Ω^{t_1,t_2} can be uniquely characterized by one of its four elements and the two suppliers' marginal probabilities of successful production, $P\{\rho_1^{t_1} = 1\} = \theta^{t_1}$ and $P\{\rho_2^{t_2} = 1\} = \theta^{t_2}$, because $\theta^{t_1} = \omega^{t_1,t_2}(1,1) + \omega^{t_1,t_2}(1,0)$ and $\theta^{t_2} = \omega^{t_1,t_2}(0,1) + \omega^{t_1,t_2}(1,1)$.[12] We choose the two suppliers' joint success probability, $\omega^{t_1,t_2}(1,1)$, to be the indicator of the level of codependence between the two suppliers' disruption processes. The larger $\omega^{t_1,t_2}(1,1)$, the greater the codependence.

The manufacturer's contract design problem under asymmetric information is given by problem (3.4), where the manufacturer's expected sales, $E \min\Big\{D,\ \rho_1^{t_1} z_1^{t_1} + \rho_2^{t_2} z_2^{t_2}\Big\}$ in (3.4a), is now an expectation over Ω^{t_1,t_2}, the joint probability distribution of $\rho_1^{t_1}$ and $\rho_2^{t_2}$. To obtain an analytical solution, we assume that $\omega^{HL}(1,1)/l > \omega^{HH}(1,1)/h$. This assumption is equivalent to the following restriction on the conditional probability of high-type supplier-1 producing successfully, given that supplier 2 produced successfully:

$$P\{\rho_1^H = 1 | \rho_2^L = 1\} > P\{\rho_1^H = 1 | \rho_2^H = 1\}. \tag{3.8}$$

In words, high-type supplier-1's probability of successful production conditional on supplier 2 producing successfully is decreasing in supplier-2's reliability. For example, consider a situation where the two suppliers are located in the same region and

[12] In the exhaustive set of joint probability matrices, $\{\Omega^{HH}, \Omega^{HL}, \Omega^{LH}, \Omega^{LL}\}$, matrix Ω^{LH} is the transpose of Ω^{HL}, because we assumed that the two suppliers are symmetric if they are of the same type.

share an unreliable infrastructure and where a supplier's reliability increases in its experience of working with this infrastructure. Production success of an inexperienced supplier-2 provides a stronger signal than success of an experienced supplier-2 regarding the chance that the other supplier (supplier 1) will succeed as well.

Proposition 9. *Given that the two suppliers' disruption processes are codependent and condition* (3.8) *holds, the manufacturer's optimal contract menu and the suppliers' profits under symmetric and asymmetric information are as given in Propositions 6 and 7, respectively, with the thresholds* $\tilde{r}^{t_m,t_{\overline{m}}}$ *and* $r^{t_m,t_{\overline{m}}}$ *redefined per Table 3.8. The manufacturer's expected profits under symmetric and asymmetric information are obtained by replacing* $(1-h)h$, $(1-h)l$ *and* $(1-l)l$ *in* (3.5) *and* (3.6) *with* $h-\omega^{HH}(1,1)$, $l-\omega^{HL}(1,1)$ *and* $l-\omega^{LL}(1,1)$*, respectively.*

$\tilde{r}^{t_m,t_{\overline{m}}}$	$r^{t_m,t_{\overline{m}}}$
$\tilde{r}^{HH} = \frac{c^H}{h-\omega^{HH}(1,1)} + \frac{K}{[h-\omega^{HH}(1,1)]D}$	$r^{HH} = \tilde{r}^{HH}$
$\tilde{r}^{HL} = \frac{c^L}{l-\omega^{HL}(1,1)} + \frac{K}{[l-\omega^{HL}(1,1)]D}$	$r^{HL} = \tilde{r}^{HL} + \frac{\alpha^H}{\alpha^L}\frac{h}{l-\omega^{HL}(1,1)}\left(\frac{c^L}{l} - \frac{c^H}{h}\right)D$
$\tilde{r}^{LL} = \frac{c^L}{l-\omega^{LL}(1,1)} + \frac{K}{[l-\omega^{LL}(1,1)]D}$	$r^{LL} = \tilde{r}^{LL} + \frac{\alpha^H}{\alpha^L}\frac{h}{l-\omega^{LL}(1,1)}\left(\frac{c^L}{l} - \frac{c^H}{h}\right)D$

Table 3.8: Expressions for thresholds $\tilde{r}^{t_m,t_{\overline{m}}}$ and $r^{t_m,t_{\overline{m}}}$ when the suppliers' disruptions are codependent.

To obtain the optimal contract menu and the profits of the suppliers and the manufacturer, we can simply rewrite the joint probabilities $(1-h)h$, $(1-h)l$ and $(1-l)l$ in the thresholds of revenue and profits in the previous sections as $h-\omega^{HH}(1,1)$, $l-\omega^{HL}(1,1)$ and $l-\omega^{LL}(1,1)$, respectively.

3.8.2 Sensitivity Analysis

We analyze how the manufacturer's ordering decisions, the supply chain firms' profits, and the value of information for the manufacturer change as the codependence between the two suppliers' disruption processes increases. To model an increase in codependence, we increase at least one of the three joint success probabilities, $\omega^{HH}(1,1)$, $\omega^{HL}(1,1)$ and $\omega^{LL}(1,1)$, by a small amount ϵ, while keeping the others fixed. We further restrict the increment ϵ to be such that the resulting level of codependence does not violate inequality (3.8).

The manufacturer's diversification decision. From Proposition 9, the thresholds for the manufacturer to diversify in both symmetric and asymmetric information models, $\tilde{r}^{HH}$, $\tilde{r}^{HL}$ and $\tilde{r}^{LL}$; r^{HH}, r^{HL} and r^{LL}, increase as codependence increases. In other words, greater supplier codependence makes diversification statistically less valuable and pushes the manufacturer towards sole-sourcing, in both symmetric and asymmetric information models.

The supply chain firms' profits under asymmetric information. As the joint success probabilities, $\omega^{HH}(1,1)$, $\omega^{HL}(1,1)$ or $\omega^{LL}(1,1)$, increase, both the manufacturer's expected profit (3.6) and the high-type suppliers' informational rents (provided in Table 3.5, with r^{LL} and r^{HL} redefined as in Proposition 9) decrease in the asymmetric information model. To explain this observation, we note that greater codependence makes diversification less valuable for the manufacturer. This reduces the manufacturer's profit in both symmetric and asymmetric information models. Under asymmetric information, however, greater codependence also causes an increase in supplier competition, leading to a reduction in the informational rents extracted by the high-type suppliers. This compensates for the reduction in the benefit of diversification for the manufacturer, making the manufacturer's profit under asymmetric information less sensitive to an increase in codependence than under symmetric information.

Manufacturer's value of information. We replace joint probabilities $(1-h)h$, $(1-h)l$ and $(1-l)l$ in the expression for the manufacturer's value of information with $h-\omega^{HH}(1,1)$, $l-\omega^{HL}(1,1)$ and $l-\omega^{LL}(1,1)$. As codependence increases, the manufacturer's value of information decreases. Thus, as the two suppliers' disruptions become more correlated, the manufacturer becomes less concerned with asymmetric information despite the fact that higher codependence between supplier disruptions makes the supply base less reliable overall. To see why, recall that greater codependence makes diversification less desirable, leading to increased supplier competition. This in turn reduces the suppliers' incentives to misrepresent their reliability, and hence reduces the value of information for the manufacturer. The managerial implication is that strategic actions to reduce codependence between supplier disruptions (e.g., sourcing from different geographic regions) should not be seen as a substitute for obtaining better information about suppliers' reliabilities.

3.9. Concluding Remarks

Supply disruptions lead to significant losses in shareholders' value (Hendricks and Singhal, 2003). A common operational tool for controlling supply disruption risks is placing orders with several suppliers (diversification), so that if one of the suppliers experiences a problem, others might still deliver parts to the manufacturer. However, working with several suppliers is administratively expensive, and managers must carefully weigh the benefits of diversification against its costs. This tradeoff depends on a number of factors such as whether suppliers are located in the same geographical area (and are exposed to the same causes of disruptions) and how much the manufacturer would lose if a disruption did occur. Furthermore, this chapter shows that another important factor is whether suppliers are better informed than the manufacturer about the disruption likelihood.

First, we observe that a dual-sourcing option (the option of the manufacturer to order from one or two suppliers) has several benefits, with the risk-reduction due to diversification being just one of them. The other important benefit comes from competition. Consistent with the extant economics and operations literatures, we find that suppliers use their private information about their reliabilities to extract informational rents from the manufacturer. If the manufacturer orders from both suppliers (i.e., diversifies) then it pays high rents to both suppliers, which leads to very high effective diversification costs. On the other hand, if the manufacturer commits to ordering from only one of the two suppliers, the competition between suppliers keeps these rents down. Thus, we find that asymmetric information about suppliers' reliabilities pushes the manufacturer away from diversification and towards sole-sourcing. As a consequence, the additional cost that asymmetric information imposes on diversification may cause the manufacturer to cease diversifying even as the supply base reliability erodes, which would never happen under symmetric information.

Second, diversification is still used by the manufacturer under asymmetric information about suppliers' reliabilities, but only if the manufacturer's costs in case of a disruption are very high. Because diversification results in high informational rents, manufacturers that choose to diversify have a strong incentive to learn about suppliers' reliabilities, for example, by investing in long-term relationships with suppliers, sending representatives to supplier factories, etc. In contrast, when costs of disruptions are low and consequently the manufacturer orders from only one supplier, competition between suppliers is very effective in curtailing informational rents and the manufacturer would not gain much by knowing everything suppliers know. Thus, in such cases, arm's-length relationships between the manufacturer and the suppliers are more tenable. Moreover, we find that information may become more valuable even as a high-type supplier's reliability becomes closer to that of a low-type, because in such a case supply diversification becomes more important. Thus, surprisingly, more similarity between supplier reliability types (having "less to learn" about the suppliers' true reliabilities) should not be seen as a substitute for information.

Third, having less information about supplier reliability does not necessarily decrease the value of a dual-sourcing option for the manufacturer. If disruptions costs are low, this option is more valuable for a manufacturer who is not as knowledgeable as the suppliers, because it enables such a manufacturer to leverage competition to drive down suppliers' informational rents.

Fourth, introducing codependence between supplier disruptions does not alter any of the above insights, but adds new findings. Although greater supplier codependence reduces the manufacturer's profit, it also heightens supplier competition by making suppliers more similar. Consequently, the decrease in the manufacturer's profit due to greater supplier codependence is less severe under asymmetric information (where competition is more vital) than under symmetric information. In fact, greater codependence between supplier disruptions reduces the suppliers' incentives to misrepresent their reliabilities and reduces the value of information for the manufacturer. Hence, strategic actions to reduce supplier codependence (such as choosing suppliers from different regions) should not be seen as a substitute for learning suppliers' reliabilities.

To spotlight the main features of our model we omitted both salvage value and disposal costs for the manufacturer. It is straightforward to see that incorporating a salvage value would make diversification more attractive. Because, as we already discussed, the value of information about suppliers' reliabilities increases in the manufacturer's propensity to diversify, a larger salvage value translates into a larger value of information. Analogously, because disposal costs discourage diversification, information about reliabilities becomes less valuable in the presence of disposal costs.

We believe that if we extended our analysis to include multi-sourcing, the effects of competition, the benefits of selecting the best available supplier(s), and additional costs of diversification due to informational rents would continue to shape the solution of the manufacturer's problem. In fact, our insights suggest that with more suppliers these effects will intensify and the manufacturer will rely more on competition and less on diversification. However, there will be many more combinations of suppliers that are candidates for receiving an order, increasing the complexity of the analysis.

In our model each supplier can be one of two possible types, and the manufacturer's demand is known at the time it places its order. While we suspect that having more than two supplier types or modeling random demand would leave the spirit of our insights unchanged, we believe that the analysis would become substantially more complex. In particular, the monotonicity condition, which enables the incentive compatibility conditions to be verified, might be violated, making the derivation of the optimal contract very cumbersome.

In our model, the high-type supplier was assumed to have a lower expected cost of successfully producing one unit, $\frac{c^H}{h} < \frac{c^L}{l}$. There could be settings where the cost relationship is reversed, namely the low-type supplier has a lower cost of successfully producing one good unit. If $\frac{c^L}{l} \leq \frac{c^H}{h} < \frac{1-l}{1-h}\frac{c^L}{l}$, the monotonicity condition again might be violated, making the derivation of the optimal contract difficult. However, if $\frac{c^H}{h} \geq \frac{1-l}{1-h}\frac{c^L}{l}$, our analysis carries through by reversing the labels "high" and "low". This makes $l > h$, but interprets the "high" type supplier as again being the supplier with the lower expected cost of successfully producing one unit.

Finally, we assumed that the supplier types are independent. Applying the results from Fudenberg and Tirole (1991, page 292), if the suppliers' types in our model were correlated, the manufacturer could implement the same contract as if the supplier types were public information. Additionally, as in Maskin and Tirole (1990) (also see discussion in Chapter 2), we could allow the demand or unit revenue to be the manufacturer's private information, but the manufacturer would not do any better than if the demand and unit revenue information were public.

In future work, it could be interesting to consider the effects of supplier collusion on the contract design and the value of the dual-sourcing option. Colluding suppliers could agree to misreport their types to the manufacturer, receive higher payments, and then split the resulting benefits. Therefore, we expect that supplier competition will be weakened in the presence of supplier collusion, pushing the manufacturer towards diversification. At the same time, informational rents could be significantly higher if the manufacturer diversifies, pushing the manufacturer away from diversification.

Therefore, it is difficult to say, a priori, if collusion will encourage or discourage diversification.

This chapter establishes a number of trends between diversification and information about supplier reliability. Future research could also study a risk-averse manufacturer, making objective function (3.4a) an argument of a non-linear utility function. Intuitively, one might expect risk aversion to encourage diversification, which, as the results of this chapter suggest, would make information about suppliers' reliability more valuable.

3.10. Appendix: Single-Sourcing Model (Benchmark)

Lemma 5 below summarizes the manufacturer's ordering decisions, the manufacturer's profit, and the supplier's profit at the optimal contract menu under symmetric and asymmetric information. Thresholds $\tilde{r}^H$, $\tilde{r}^L$, r^H and r^L are defined in Propositions 6 and 7.

Lemma 5. *In the symmetric information model with a single supplier, at the optimal contract menu, the manufacturer will order from the high-type supplier if and only if $r > \tilde{r}^H$, and will order from the low-type supplier if and only if $r > \tilde{r}^L$. The expected profits of both the high-type and the low-type suppliers are zero. The expected profit of the manufacturer is*

$$\alpha^H \left[(h\,r - c^H)D - K\right]^+ + \alpha^L \left[(l\,r - c^L)D - K\right]^+ . \tag{3.9}$$

In the asymmetric information model with a single supplier, at the optimal contract menu, the manufacturer will order from the high-type supplier if and only if $r > r^H$, and will order from the low-type supplier if and only if $r > r^L$. The expected profit of the low-type supplier is zero. The expected profit of the high-type supplier equals informational rent, $h\left(c^L/l - c^H/h\right)D$, for $r > r^L$, and equals zero for $r \le r^L$. The expected profit of the manufacturer is

$$\alpha^H \left[(h\,r - c^H)D - K\right]^+ + \alpha^L \left[(l\,r - c^L)D - K - \frac{\alpha^H}{\alpha^L} h \left(\frac{c^L}{l} - \frac{c^H}{h}\right) D\right]^+ . \tag{3.10}$$

Proof. Omitted. Compared to the dual-sourcing model, the manufacturer's optimization problem in the single-supplier model changes in a straightforward way. Proofs of the results for the single-supplier model are similar to that for Proposition 7. ■

3.11. Appendix: Proofs of Statements

Proof of Lemma 4. The supplier's objective function (3.2) is piecewise linear. We focus on the corner-point solutions: $z = 0$ or q. The result follows. ■

Proof of Proposition 6. Omitted. The case with symmetric information is a special case of that with asymmetric information; see proof of Proposition 7. ■

Proof of Proposition 7. From the supplier's optimal profit (3.2), the manufacturer's transfer payment to supplier n net of the expected penalty received equals supplier-n's optimal profit plus its cost of production. Under contract $(X_n, q_n, p_n)(t_n, t_{\overline{n}})$, this equality has the following form:

$$\begin{aligned} &X_n(t_n, t_{\overline{n}}) - p_n(t_n, t_{\overline{n}})E\Big\{q_n(t_n, t_{\overline{n}}) - \rho_n^{t_n} z_n^{t_n}[(q_n, p_n)(t_n, t_{\overline{n}})]\Big\}^+ \\ &= \pi_n^{t_n}[(X_n, q_n, p_n)(t_n, t_{\overline{n}})] + c^{t_n} z_n^{t_n}[(q_n, p_n)(t_n, t_{\overline{n}})]. \end{aligned} \tag{3.11}$$

Rolling equation (3.11) into (3.4a), the manufacturer's maximization problem becomes:

$$\begin{aligned} \max \Bigg\{ &\sum_{t_1, t_2 \in \{H,L\}} \alpha^{t_1}\alpha^{t_2}\Bigg[\, rE\min\Big\{D,\ \rho_1^{t_1} z_1^{t_1}[(q_1,p_1)(t_1,t_2)] + \rho_2^{t_2} z_2^{t_2}[(q_2,p_2)(t_2,t_1)]\Big\} \\ &- \Big\{c^{t_1} z_1^{t_1}[(q_1,p_1)(t_1,t_2)] + K\,\mathbf{1}_{\{q_1(t_1,t_2)>0\}}\Big\} - \Big\{c^{t_2} z_2^{t_2}[(q_2,p_2)(t_2,t_1)] + K\,\mathbf{1}_{\{q_2(t_2,t_1)>0\}}\Big\}\Bigg] \\ &- \sum_{t_1=H,L}\Big\{\alpha^{t_1}\Pi_1^{t_1}(t_1)\Big\} - \sum_{t_2=H,L}\Big\{\alpha^{t_2}\Pi_2^{t_2}(t_2)\Big\}\Bigg\} \end{aligned} \tag{3.12a}$$

Subject to For $n = 1, 2$

$$\Pi_n^H(H) \geq \Pi_n^H(L) \tag{3.12b}$$

$$\Pi_n^L(L) \geq \Pi_n^L(H), \tag{3.12c}$$

$$\Pi_n^H(H) \geq 0, \tag{3.12d}$$

$$\Pi_n^L(L) \geq 0, \tag{3.12e}$$

$$q_n(t_n, t_{\overline{n}}) \geq 0,\ p_n(t_n, t_{\overline{n}}) \geq 0,\ \text{for } t_1, t_2 \in \{H, L\}, \tag{3.12f}$$

where $\Pi_n^{t_n}(s) \overset{\text{def}}{=} E_{t_{\overline{n}}}\Big\{\pi_n^{t_n}[(X_n, q_n, p_n)(s, t_{\overline{n}})]\Big\}$ is supplier-n's expected profit when it reports itself as of type-s, $s \in \{H, L\}$, where the expectation is taken over supplier-$\overline{n}$'s type.

Here is our plan to solve problem (3.12). First, we reduce the *incentive compatibility* and *individual rationality* constraints (3.12b–3.12f) to an equivalent set of constraints, among which there are *monotonicity* constraints for the two suppliers. Then, we temporarily relax the *monotonicity* constraints. We show that the optimal solution to the relaxation satisfies the monotonicity constraints and, thus, is optimal for the original problem.

To reduce problem (3.12), we first rearrange the *incentive compatibility* constraints (3.12b) and (3.12c) and the *individual rationality* constraints (3.12d) and (3.12e) for supplier $n = 1, 2$. Applying the definition of a high supplier-type's reliability advantage (Definition 3) under the contract for low-type supplier-n, $(X_n, q_n, p_n)(L, t_{\overline{n}})$, we represent high-type supplier-n's expected profit, when reporting itself as of low-type, as

$$\Pi_n^H(L) = \Pi_n^L(L) + E_{t_{\overline{n}}}\Big\{\Gamma_n[(q_n, p_n)(L, t_{\overline{n}})]\Big\}.$$

Similarly, applying Definition 3 with the contract for high-type supplier-n, $(X_n, q_n, p_n)(H, t_{\overline{n}})$, we represent low-type supplier-n's expected profit, when reporting itself as of high-type, as

$$\Pi_n^L(H) = \Pi_n^H(H) - E_{t_{\overline{n}}}\Big\{\Gamma_n[(q_n, p_n)(H, t_{\overline{n}})]\Big\}.$$

We substitute these two equalities into the right-hand-side of the *incentive compatibility* constraints, (3.12b) and (3.12c), obtaining

$$\Pi_n^H(H) \geq \Pi_n^L(L) + E_{t_{\overline{n}}}\Big\{\Gamma_n[(q_n, p_n)(L, t_{\overline{n}})]\Big\}, \tag{3.13a}$$

$$\Pi_n^L(L) \geq \Pi_n^H(H) - E_{t_{\overline{n}}}\Big\{\Gamma_n[(q_n, p_n)(H, t_{\overline{n}})]\Big\}. \tag{3.13b}$$

Furthermore, inequalities (3.13a), $\Gamma_n[(q_n, p_n)(L, t_{\overline{n}})] \geq 0$ (see the discussion following

(3.3)) and $\Pi_n^L(L) \geq 0$ (constraint (3.12e), *individual rationality* for the low-type) together imply $\Pi_n^H(H) \geq 0$. That is, the *individual rationality* constraint for high-type supplier-n (3.12d) is redundant.

Using the new *incentive compatibility* constraint (3.13) and *individual rationality* constraint (3.12e), we then choose $X_n(t_n, t_{\overline{n}})$ optimally for any given $(q_n, p_n)(t_n, t_{\overline{n}})$. The objective function (3.12a) suggests that the objective is maximized when $X_n(t_n, H)$ and $X_n(t_n, L)$ are chosen such that the expected profit of supplier n of type-t_n, $\Pi_n^{t_n}(t_n)$, is minimized. Thus, at the optimal solution, the *individual rationality* constraint (3.12e) reduces to

$$\Pi_n^L(L) = 0. \tag{3.14}$$

Similarly, at the optimal solution the *incentive compatibility* constraint (3.13a) reduces to

$$\Pi_n^H(H) = E_{t_{\overline{n}}}\Big\{\Gamma_n[(q_n, p_n)(L, t_{\overline{n}})]\Big\}. \tag{3.15}$$

We substitute (3.14) and (3.15) in the *incentive compatibility* constraints (3.13), obtaining

$$(\textit{Monotonicity}) \quad E_{t_{\overline{n}}}\Big\{\Gamma_n[(q_n, p_n)(H, t_{\overline{n}})]\Big\} \geq E_{t_{\overline{n}}}\Big\{\Gamma_n[(q_n, p_n)(L, t_{\overline{n}})]\Big\},\ n = 1, 2 \tag{3.16}$$

which is commonly called the *monotonicity* constraint in the information economics literature.

So far, we have reduced the original *incentive compatibility* and *individual rationality* constraints (3.12b–3.12e) to constraints (3.14–3.16). We roll (3.14) and (3.15) into the objective function (3.12a), obtaining

$$\max \left\{ \sum_{t_1,t_2\in\{H,L\}} \alpha^{t_1}\alpha^{t_2} \left[rE\min\Big\{D,\ \rho_1^{t_1} z_1^{t_1}[(q_1,p_1)(t_1,t_2)] + \rho_2^{t_2} z_2^{t_2}[(q_2,p_2)(t_2,t_1)]\Big\} \right.\right.$$
$$\left. - \Big\{c^{t_1} z_1^{t_1}[(q_1,p_1)(t_1,t_2)] + K\,\mathbf{1}_{\{q_1(t_1,t_2)>0\}}\Big\} - \Big\{c^{t_2} z_2^{t_2}[(q_2,p_2)(t_2,t_1)] + K\,\mathbf{1}_{\{q_2(t_2,t_1)>0\}}\Big\}\right] \tag{3.17}$$
$$\left. - \alpha^H E_{t_2}\Big\{\Gamma_1[(q_1,p_1)(L,t_2)]\Big\} - \alpha^H E_{t_1}\Big\{\Gamma_2[(q_2,p_2)(L,t_1)]\Big\}\right\}.$$

We expand the summation over t_1 and t_2 and the expectations over t_1 and t_2 in the objective function (3.17). The manufacturer's contract design problem (3.4) is reduced to

$$\begin{aligned}
\max_{\substack{(q_n,p_n)(t_n,t_{\overline{n}})\\ n=1,2;\,t_1,t_2\in\{H,L\}}} \Bigg\{ & \left(\alpha^H\right)^2 \Bigg[rE\min\Big\{D,\ \rho_1^H z_1^H[(q_1,p_1)(H,H)] + \rho_2^H z_2^H[(q_2,p_2)(H,H)]\Big\} \\
&\quad - \Big\{c^H z_1^H[(q_1,p_1)(H,H)] + K\,\mathbf{1}_{\{q_1(H,H)>0\}}\Big\} \\
&\quad - \Big\{c^H z_2^H[(q_2,p_2)(H,H)] + K\,\mathbf{1}_{\{q_2(H,H)>0\}}\Big\}\Bigg] \\
+ \left(\alpha^H\alpha^L\right) & \Bigg[rE\min\Big\{D,\ \rho_1^H z_1^H[(q_1,p_1)(H,L)] + \rho_2^L z_2^L[(q_2,p_2)(L,H)]\Big\} \\
&\quad - \Big\{c^H z_1^H[(q_1,p_1)(H,L)] + K\,\mathbf{1}_{\{q_1(H,L)>0\}}\Big\} \\
&\quad - \Big\{c^L z_2^L[(q_2,p_2)(L,H)] + K\,\mathbf{1}_{\{q_2(L,H)>0\}}\Big\}\Bigg] \\
+ \left(\alpha^L\alpha^H\right) & \Bigg[rE\min\Big\{D,\ \rho_1^L z_1^L[(q_1,p_1)(L,H)] + \rho_2^H z_2^H[(q_2,p_2)(H,L)]\Big\} \\
&\quad - \Big\{c^L z_1^L[(q_1,p_1)(L,H)] + K\,\mathbf{1}_{\{q_1(L,H)>0\}}\Big\} \\
&\quad - \Big\{c^H z_2^H[(q_2,p_2)(H,L)] + K\,\mathbf{1}_{\{q_2(H,L)>0\}}\Big\}\Bigg] \\
+ \left(\alpha^L\right)^2 & \Bigg[rE\min\Big\{D,\ \rho_1^L z_1^L[(q_1,p_1)(L,L)] + \rho_2^L z_2^L[(q_2,p_2)(L,L)]\Big\} \\
&\quad - \Big\{c^L z_1^L[(q_1,p_1)(L,L)] + K\,\mathbf{1}_{\{q_1(L,L)>0\}}\Big\} \\
&\quad - \Big\{c^L z_2^L[(q_2,p_2)(L,L)] + K\,\mathbf{1}_{\{q_2(L,L)>0\}}\Big\}\Bigg] \\
- \left(\alpha^H\right)^2 & \Gamma_1[(q_1,p_1)(L,H)] - \alpha^H\alpha^L\Gamma_1[(q_1,p_1)(L,L)] \\
- \left(\alpha^H\right)^2 & \Gamma_2[(q_2,p_2)(L,H)] - \alpha^H\alpha^L\Gamma_2[(q_2,p_2)(L,L)]\Bigg\}
\end{aligned} \tag{3.18}$$

$$\begin{aligned}
&\text{Subject to} && \text{for } n = 1,2 \text{ and } t_1, t_2 \in \{H, L\},\\
&(\textit{Monotonicity}) && E\Big\{\Gamma_n[(q_n,p_n)(H,t_{\overline{n}})]\Big\} \geq E\Big\{\Gamma_n[(q_n,p_n)(L,t_{\overline{n}})]\Big\},\\
& && q_n(t_n,t_{\overline{n}}) \geq 0,\ p_n(t_n,t_{\overline{n}}) \geq 0.
\end{aligned}$$

This concludes our first major step of reducing problem (3.12).

Now, we carry on with the second major step: to solve the equivalent problem (3.18) to find the optimal $(q_n, p_n)(t_n, t_{\overline{n}})$. We first temporarily drop the *monotonicity* constraint (3.16) and solve problem (3.18) with only nonnegativity constraints. We move $\Gamma_n[(q_n, p_n)(L, t_{\overline{n}})]$ in (3.18) to be with other terms that depend on $(q_n, p_n)(L, t_{\overline{n}})$. This allows us to rearrange problem (3.18) as a weighted sum of four maximization problems:

$$\begin{aligned}
&\left(\alpha^H\right)^2 \max_{\substack{(q_1,p_1)(H,H)\geq 0\\(q_2,p_2)(H,H)\geq 0}} \Big\{ rE\min\Big\{D,\ \rho_1^H z_1^H[(q_1,p_1)(H,H)] + \rho_2^H z_2^H[(q_2,p_2)(H,H)]\Big\} && \text{(3.19a)}\\
&\qquad - \Big\{c^H z_1^H[(q_1,p_1)(H,H)] + K\,\mathbf{1}_{\{q_1(H,H)>0\}}\Big\} - \Big\{c^H z_2^H[(q_2,p_2)(H,H)] + K\,\mathbf{1}_{\{q_2(H,H)>0\}}\Big\}\Big\}\\
&+ \left(\alpha^H\alpha^L\right) \max_{\substack{(q_1,p_1)(H,L)\geq 0\\(q_2,p_2)(L,H)\geq 0}} \Big\{ rE\min\Big\{D,\ \rho_1^H z_1^H[(q_1,p_1)(H,L)] + \rho_2^L z_2^L[(q_2,p_2)(L,H)]\Big\}\\
&\qquad - \Big\{c^H z_1^H[(q_1,p_1)(H,L)] + K\,\mathbf{1}_{\{q_1(H,L)>0\}}\Big\} && \text{(3.19b)}\\
&\qquad - \Big\{c^L z_2^L[(q_2,p_2)(L,H)] + K\,\mathbf{1}_{\{q_2(L,H)>0\}} + \frac{\alpha^H}{\alpha^L}\Gamma_2[(q_2,p_2)(L,H)]\Big\}\Big\}\\
&+ \left(\alpha^L\alpha^H\right) \max_{\substack{(q_1,p_1)(L,H)\geq 0\\(q_2,p_2)(H,L)\geq 0}} \Big\{ rE\min\Big\{D,\ \rho_1^L z_1^L[(q_1,p_1)(L,H)] + \rho_2^H z_2^H[(q_2,p_2)(H,L)]\Big\} && \text{(3.19c)}\\
&\qquad - \Big\{c^L z_1^L[(q_1,p_1)(L,H)] + K\,\mathbf{1}_{\{q_1(L,H)>0\}} + \frac{\alpha^H}{\alpha^L}\Gamma_1[(q_1,p_1)(L,H)]\Big\}\\
&\qquad - \Big\{c^H z_2^H[(q_2,p_2)(H,L)] + K\,\mathbf{1}_{\{q_2(H,L)>0\}}\Big\}\Big\}\\
&+ \left(\alpha^L\right)^2 \max_{\substack{(q_1,p_1)(L,L)\geq 0\\(q_2,p_2)(L,L)\geq 0}} \Big\{ rE\min\Big\{D,\ \rho_1^L z_1^L[(q_1,p_1)(L,L)] + \rho_2^L z_2^L[(q_2,p_2)(L,L)]\Big\} && \text{(3.19d)}\\
&\qquad - \Big\{c^L z_1^L[(q_1,p_1)(L,L)] + K\,\mathbf{1}_{\{q_1(L,L)>0\}} + \frac{\alpha^H}{\alpha^L}\Gamma_1[(q_1,p_1)(L,L)]\Big\}\\
&\qquad - \Big\{c^L z_2^L[(q_2,p_2)(L,L)] + K\,\mathbf{1}_{\{q_2(L,L)>0\}} + \frac{\alpha^H}{\alpha^L}\Gamma_2[(q_2,p_2)(L,L)]\Big\}\Big\}
\end{aligned}$$

We solve each of the four maximization problems in (3.19). One can show that setting $z_n^{t_n}[(q_n, p_n)(t_n, t_{\overline{n}})] = q_n(t_n, t_{\overline{n}})$ and $p_n(t_n, t_{\overline{n}}) \geq c^{t_n}/\theta^{t_n}$ is without loss of optimality. Next, notice from equation (3.3) that $\Gamma_n[(X_n, q_n, p_n)(L, t_{\overline{n}})]$ is increasing in $p_n(L, t_{\overline{n}})$. Hence, it is optimal to set $p_n(L, t_{\overline{n}})$ to be its minimum c^L/l, which gives $\Gamma_n[(X_n, q_n, p_n)(L, t_{\overline{n}})] = h\,(\frac{c^L}{l} - \frac{c^H}{h})\, q_n(L, t_{\overline{n}})$.

For each of the four maximization problems in (3.19) we find the optimal order quantities $q_1(t_1, t_2)$ and $q_2(t_2, t_1)$. Because for each of these four maximization problems the objective function is piecewise linear in the order quantities, without loss of optimality, we focus on the corner-point solutions only: $(q_1(t_1, t_2), q_2(t_2, t_1)) \in \big\{(0,0), (D,0), (0,D), (D,D)\big\}$. Comparing the objective function value at these four corner points reveals the optimal order quantities. We present the optimal solution to (3.19) in the following table, where we make use of the following thresholds:

$$r^{t_m} \stackrel{\text{def}}{=} \inf\left\{r : (\theta^{t_m} r - c^{t_m})D - K - \frac{\alpha^H}{\alpha^L} h \left(\frac{c^L}{l} - \frac{c^H}{h}\right) D \mathbf{1}_{\{t_m = L\}} > 0\right\} \tag{3.20a}$$

$$r^{t_m, t_{\overline{m}}} \stackrel{\text{def}}{=} \inf\left\{r : \left[\theta^{t_{\overline{m}}}(1 - \theta^{t_m}) r - c^{t_{\overline{m}}}\right] D - K - \frac{\alpha^H}{\alpha^L} h \left(\frac{c^L}{l} - \frac{c^H}{h}\right) D \mathbf{1}_{\{t_{\overline{m}} = L\}} > 0\right\} \tag{3.20b}$$

Problem (3.19a), $t_1 = t_2 = H$			
When $r \leq r^H$:			
$q_1(H,H) = 0$	$q_2(H,H) = 0$	$p_1(H,H) \geq 0$	$p_2(H,H) \geq 0$
When $r^H < r \leq r^{HH}$:			
$q_1(H,H) = D$	$q_2(H,H) = 0$	$p_1(H,H) \geq \frac{c^H}{h}$	$p_2(H,H) \geq 0$
When $r > r^{HH}$:			
$q_1(H,H) = D$	$q_2(H,H) = D$	$p_1(H,H) \geq \frac{c^H}{h}$	$p_2(H,H) \geq \frac{c^H}{h}$

Problem (3.19b), $t_1 = H$ and $t_2 = L$			
When $r \leq r^H$:			
$q_1(H,L) = 0$	$q_2(L,H) = 0$	$p_1(H,L) \geq 0$	$p_2(L,H) \geq 0$
When $r^H < r \leq r^{HL}$:			
$q_1(H,L) = D$	$q_2(L,H) = 0$	$p_1(H,L) \geq \frac{c^H}{h}$	$p_2(L,H) \geq 0$
When $r > r^{HL}$:			
$q_1(H,L) = D$	$q_2(L,H) = D$	$p_1(H,L) \geq \frac{c^H}{h}$	$p_2(L,H) = \frac{c^L}{l}$

Problem (3.19c), $t_1 = L$ and $t_2 = H$
The solution is identical to the solution for problem (3.19b), except that the indices of the two suppliers are swapped.

Problem (3.19d), $t_1 = L$ and $t_2 = L$			
When $r \leq r^L$:			
$q_1(L,L) = 0$	$q_2(L,L) = 0$	$p_1(L,L) \geq 0$	$p_2(L,L) \geq 0$
When $r^L < r \leq r^{LL}$:			
$q_1(L,L) = D$	$q_2(L,L) = 0$	$p_1(L,L) = \frac{c^L}{l}$	$p_2(L,L) \geq 0$
When $r > r^{LL}$:			
$q_1(L,L) = D$	$q_2(L,L) = D$	$p_1(L,L) = \frac{c^L}{l}$	$p_2(L,L) = \frac{c^L}{l}$

In Lemma 6, we show that the optimal solution to the relaxation problem (3.19) in the above table satisfies the *monotonicity* constraint (3.16) for supplier 1 and supplier 2, as long as we restrict $p_n(H, t_{\overline{n}}) \geq \frac{c^L}{l}$ whenever $q_n(L, t_{\overline{n}}) = D$ at the optimal solution. Thus, with the additional restriction on $p_n(H, t_{\overline{n}})$, the optimal solution to the relaxation is also optimal for the original problem (3.12).

We now compute the optimal transfer payments using (3.11), (3.14) and (3.15). Without loss of optimality, for $t_{\overline{n}} \in \{H, L\}$ we choose the optimal payments $X_n^*(t_n, t_{\overline{n}})$

to be such that

$$\pi_n^H[(X_n^*, q_n^*, p_n^*)(H, t_{\overline{n}})] = \Gamma_n[(q_n^*, p_n^*)(L, t_{\overline{n}})] \tag{3.21a}$$

$$\pi_n^L[(X_n^*, q_n^*, p_n^*)(L, t_{\overline{n}})] = 0. \tag{3.21b}$$

That is,

$$\begin{aligned} X_n^*(H, t_{\overline{n}}) =& \Gamma_n[(q_n^*, p_n^*)(L, t_{\overline{n}})] + c^{t_n} z_n^{t_n}[(q_n^*, p_n^*)(H, t_{\overline{n}})] \\ &+ p_n^*(H, t_{\overline{n}}) E\left[q_n^*(H, t_{\overline{n}}) - \rho_n^{t_n} z_n^{t_n}[(q_n^*, p_n^*)(H, t_{\overline{n}})]\right]^+, \end{aligned} \tag{3.22}$$

$$\begin{aligned} X_n(L, t_{\overline{n}}) =& c^{t_n} z_n^{t_n}[(q_n^*, p_n^*)(L, t_{\overline{n}})] \\ &+ p_n^*(L, t_{\overline{n}}) E\left[q_n^*(L, t_{\overline{n}}) - \rho_n^{t_n} z_n^{t_n}[(q_n^*, p_n^*)(L, t_{\overline{n}})]\right]^+. \end{aligned} \tag{3.23}$$

Finally, we show that the optimal contract menu (in Table 3.4) satisfies the dominant-strategy *incentive compatibility* and *individual rationality* constraints, which are for $n = 1, 2$ and $t_{\overline{n}} \in \{H, L\}$

$$\begin{aligned} \text{(IC)} \quad & \pi_n^H[(X_n^*, q_n^*, p_n^*)(H, t_{\overline{n}})] \geq \pi_n^H[(X_n^*, q_n^*, p_n^*)(L, t_{\overline{n}})], \\ & \pi_n^L[(X_n^*, q_n^*, p_n^*)(L, t_{\overline{n}})] \geq \pi_n^L[(X_n^*, q_n^*, p_n^*)(H, t_{\overline{n}})] \\ \text{(IR)} \quad & \pi_n^H[(X_n^*, q_n^*, p_n^*)(H, t_{\overline{n}})] \geq 0, \quad \pi_n^L[(X_n^*, q_n^*, p_n^*)(L, t_{\overline{n}})] \geq 0. \end{aligned}$$

By the standard procedure, we can show that these constraints are equivalent to

$$\begin{aligned} \Gamma_n[(q_n^*, p_n^*)(H, t_{\overline{n}})] \geq & \pi_n^H[(X_n^*, q_n^*, p_n^*)(H, t_{\overline{n}})] - \pi_n^L[(X_n^*, q_n^*, p_n^*)(L, t_{\overline{n}})] \\ \geq & \Gamma_n[(q_n^*, p_n^*)(L, t_{\overline{n}})] \end{aligned} \tag{3.24a}$$

$$\pi_n^L[(X_n^*, q_n^*, p_n^*)(L, t_{\overline{n}})] \geq 0 \tag{3.24b}$$

Using (3.21a) and (3.25), we can verify that the above constraints hold for the optimal contract. ■

Lemma 6. *The optimal solutions to the relaxation* (3.19) *(in the table above) satisfy the monotonicity constraints* (3.16) *for supplier* 1 *and supplier* 2*, if we restrict* $p_n(H, t_{\overline{n}}) \geq \frac{c^L}{l}$ *whenever* $q_n(L, t_{\overline{n}}) = D$*, for* $t_{\overline{n}} \in \{H, L\}$*.*

Proof. It is sufficient to show that, for $n = 1, 2$ and $t_{\overline{n}} = H, L$, with the additional restriction $p_n(H, t_{\overline{n}}) \geq \frac{c^L}{l}$, the optimal solution to (3.19) satisfies

$$\Gamma_n[(q_n, p_n)(H, t_{\overline{n}})] \geq \Gamma_n[(q_n, p_n)(L, t_{\overline{n}})]. \tag{3.25}$$

When $\Gamma_n[(q_n, p_n)(L, t_{\overline{n}})] = 0$ (i.e., $q_n(L, t_{\overline{n}}) = 0$), the inequality (3.25) holds trivially. We now focus on the case when $q_n(L, t_{\overline{n}}) = D$.

From equation (3.3), $\Gamma_n(q, p)$ is increasing in both q and p. Therefore, it suffices to show that $q_n(H, t_{\overline{n}}) \geq q_n(L, t_{\overline{n}})$ and $p_n(H, t_{\overline{n}}) \geq p_n(L, t_{\overline{n}})$ for all r. First, it can be verified that the optimal solution to (3.19) satisfies $q_n(H, t_{\overline{n}}) \geq q_n(L, t_{\overline{n}})$ for all r. Next, recall that when $q_n(L, t_{\overline{n}}) = D$, $p_n(L, t_{\overline{n}}) = \frac{c^L}{l}$ is optimal. Since the assumption in the lemma gives $p_n(H, t_{\overline{n}}) \geq \frac{c^L}{l}$ whenever $q_n(L, t_{\overline{n}}) = D$, we have $p_n(H, t_{\overline{n}}) \geq p_n(L, t_{\overline{n}})$. Inequality (3.25) follows. ■

Proof of Corollary 10. We want to show that, for h and l such that $h + l > 1$, as both h and l decrease by ϵ, in the symmetric information model $\tilde{r}^{HL}$ always decreases, but in the asymmetric information model, there exist h and l, $h + l > 1$, such that r^{HL} increases.

Let $h = l + \nu$ for some $\nu > 0$. We write $\tilde{r}^{HL}$ as a function of l: $\tilde{r}^{HL}(l) = \frac{c^L + \frac{K}{D}}{(1-l-\nu)l}$. Its first-order derivative with respective to l is strictly positive for $2\,l + \nu > 1$, that is, $h + l > 1$. Therefore, for any $h + l > 1$, as both h and l decrease by ϵ, $\tilde{r}^{HL}$ decreases.

Similarly, we write r^{HL} in the asymmetric information model as:

$$r^{HL}(l) = \frac{c^L + \frac{K}{D} + \frac{\alpha^H}{\alpha^L}\left(\frac{l+\nu}{l} c^L - c^H\right)}{(1 - l - \nu)l}.$$

Its first order derivative with respect to l equals

$$\left[r^{HL}(l)\right]' = \frac{\left(c^L + \frac{K}{D}\right) l(2l+\nu-1) - \frac{\alpha^H}{\alpha^L}\left\{c^L\left[2(l+\nu)(1-\nu-l)-l\right] + c^H l(2l+\nu-1)\right\}}{l^3(1-\nu-l)^2}.$$

For any c^H, c^L, $\frac{K}{D}$ and α^H, there exist l and $h = l+\nu$, for some $\nu > 0$, such that $h+l > 1$, $h > l$, $c^L/l > c^H/h$ and $[r^{HL}(l)]' < 0$. To see this, we let $h = 1-\xi+\xi^2$ and $l = \xi$, for some $\xi \in (0,1)$, and substitute $l = \xi$ and $\nu = h-l = 1-2\xi+\xi^2$ into $[r^{HL}(l)]'$, to obtain

$$[r^{HL}(l)]'\left[l^3(1-\nu-l)^2\right] = -\frac{\alpha^H}{\alpha^L}c^L\xi + \frac{\alpha^H}{\alpha^L}4c^L\xi^2 + \left[c^L + \frac{K}{D} - \frac{\alpha^H}{\alpha^L}(4c^L + c^H)\right]\xi^3 + \frac{\alpha^H}{\alpha^L}2c^L\xi^4 \tag{3.26}$$

As ξ approaches zero, the right-hand-side of (3.26) approaches zero from below (since the right-hand-side of (3.26) is polynomial in ξ and its leading term is negative). Therefore, one can always pick some $\xi > 0$ that will yield $[r^{HL}(l)]' < 0$. Note that h need not be extremely close to 1 and l need not be extremely small. For instance, suppose $c^H = c^L$, $K = 0$ and $\alpha^H > 2\alpha^L$. At $l = 1/2$ and $\nu = 1/8$ (i.e., $h = 5/8$), $[r^{HL}(l)]'\,[l^3(1-\nu-l)^2] = \frac{1}{16}(1-\frac{\alpha^H}{2\alpha^L}) < 0$. ■

Proof of Proposition 8. We compare the manufacturer's expected profits under symmetric information in the dual- and single-sourcing models, (3.5) and (3.9). This yields the following expression for the manufacturer's value of the dual-sourcing option under symmetric information (note that in this expression, the definitions of the thresholds $\tilde{r}^H$, $\tilde{r}^L$, $\tilde{r}^{LL}$, $\tilde{r}^{HL}$ and $\tilde{r}^{HH}$ have been used to replace the positive operators $[\ ]^+$ of (3.5) and (3.9) with indicator functions):

$$\begin{aligned}
&\left(\alpha^L\alpha^H\right)\left([(h\,r-c^H)D-K]\mathbf{1}_{\{r>\tilde{r}^H\}} - [(l\,r-c^L)D-K]\mathbf{1}_{\{r>\tilde{r}^L\}}\right)\\
&+\left(\alpha^H\right)^2\left\{\left[h(1-h)r-c^H\right]D-K\right\}\mathbf{1}_{\{r>\tilde{r}^{HH}\}}\\
&+2\left(\alpha^H\alpha^L\right)\left\{\left[l(1-h)r-c^L\right]D-K\right\}\mathbf{1}_{\{r>\tilde{r}^{HL}\}} + \left(\alpha^L\right)^2\left\{\left[l(1-l)r-c^L\right]D-K\right\}\mathbf{1}_{\{r>\tilde{r}^{LL}\}}.
\end{aligned} \tag{3.27}$$

Similarly, we compare the expected profits of the manufacturer under asymmetric information in the dual- and single-sourcing models, (3.6) and (3.10), obtaining the expression for the manufacturer's value of the dual-sourcing option under asymmetric information:

$$
\begin{aligned}
&\left(\alpha^L \alpha^H\right)\left(\Big[(h\,r - c^H)D - K\Big]\mathbf{1}_{\{r>r^H\}} - \left[(l\,r - c^L)D - K - \frac{\alpha^H}{\alpha^L}\,h\left(\frac{c^L}{l} - \frac{c^H}{h}\right)D\right]\mathbf{1}_{\{r>r^L\}}\right)\\
&+\left(\alpha^H\right)^2\Big\{\left[h(1-h)r - c^H\right]D - K\Big\}\mathbf{1}_{\{r>r^{HH}\}}\\
&+2\left(\alpha^H\alpha^L\right)\left\{\left[l(1-h)r - c^L\right]D - K - \frac{\alpha^H}{\alpha^L}\,h\left(\frac{c^L}{l} - \frac{c^H}{h}\right)D\right\}\mathbf{1}_{\{r>r^{HL}\}}\\
&+\left(\alpha^L\right)^2\left\{\left[l(1-l)r - c^L\right]D - K - \frac{\alpha^H}{\alpha^L}\,h\left(\frac{c^L}{l} - \frac{c^H}{h}\right)D\right\}\mathbf{1}_{\{r>r^{LL}\}}.
\end{aligned}
\tag{3.28}
$$

The difference between the manufacturer's value of the dual-sourcing option under asymmetric information and symmetric information, (3.28) minus (3.27), is

$$
\begin{aligned}
&\left(\alpha^L \alpha^H\right)\left(\left[(l\,r - c^L)D - K\right]\mathbf{1}_{\{r>\tilde{r}^L\}} - \left[(l\,r - c^L)D - K - \frac{\alpha^H}{\alpha^L}\,h\left(\frac{c^L}{l} - \frac{c^H}{h}\right)D\right]\mathbf{1}_{\{r>r^L\}}\right)\\
&+2\left(\alpha^H\alpha^L\right)\left(\left\{\left[l(1-h)r - c^L\right]D - K - \frac{\alpha^H}{\alpha^L}\,h\left(\frac{c^L}{l} - \frac{c^H}{h}\right)D\right\}\mathbf{1}_{\{r>r^{HL}\}}\right.\\
&\qquad\qquad\left. - \left\{\left[l(1-h)r - c^L\right]D - K\right\}\mathbf{1}_{\{r>\tilde{r}^{HL}\}}\right)\\
&+\left(\alpha^L\right)^2\left(\left\{\left[l(1-l)r - c^L\right]D - K - \frac{\alpha^H}{\alpha^L}\,h\left(\frac{c^L}{l} - \frac{c^H}{h}\right)D\right\}\mathbf{1}_{\{r>r^{LL}\}}\right.\\
&\qquad\qquad\left. - \left\{\left[l(1-l)r - c^L\right]D - K\right\}\mathbf{1}_{\{r>\tilde{r}^{LL}\}}\right).
\end{aligned}
\tag{3.29}
$$

We treat (3.29) as a function of r and show there exists a unique $r_0 \in (\tilde{r}^{LL}, r^{HL})$, at which the curve changes from non-negative to strictly negative. Because the lower bound of the interval, $\tilde{r}^{LL}$, could be either greater or smaller than r^L, we consider two cases: $\tilde{r}^{LL} \geq r^L$ and $\tilde{r}^{LL} < r^L$.

Case $\tilde{r}^{LL} \geq r^L$. We prove the result by tracing the value of (3.29) for $r > \tilde{r}^L$.

From the tables describing the thresholds $\tilde{r}^L, \ldots, \tilde{r}^{HL}$ and $r^L, \ldots, r^{HL}$ in Propositions 6 and 7, respectively, and the assumption of the case, we get $\tilde{r}^L < r^L \leq \tilde{r}^{LL} < \{r^{LL}, \tilde{r}^{HL}\} < r^{HL}$. One can check that (3.29) is equal to zero at $r = \tilde{r}^L$, strictly positive and strictly increasing in r for $r \in (\tilde{r}^L, r^L]$, constant with respect to r for $r \in (r^L, \tilde{r}^{LL}]$, decreasing in r for $r \in (\tilde{r}^{LL}, r^{HL}]$ (regardless of the ordering of r^{LL} and $\tilde{r}^{HL}$) and constant in r thereafter. Also, (3.29) is negative at $r = r^{HL}$. Thus, there must exist $r_0 \in (\tilde{r}^{LL}, r^{HL})$ such that (3.29) changes from non-negative to strictly negative at r_0.

Case $\tilde{r}^{LL} < r^L$. Again using the definitions of the thresholds and the assumption of the case, we know $\tilde{r}^L < \tilde{r}^{LL} < r^L < r^{LL} < r^{HL}$. We utilize two sub-cases, depending on $\tilde{r}^{HL}$.

Sub-case $\tilde{r}^{LL} < \tilde{r}^{HL} \leq r^L$. One can check that (3.29) is zero at $r = \tilde{r}^L$, and strictly positive and strictly increasing in r for $r \in (\tilde{r}^L, \tilde{r}^{LL}]$. As for $r \in (\tilde{r}^{LL}, r^L]$, there are three possibilities for (3.29): increasing throughout, increasing until $\tilde{r}^{HL}$ and then decreasing thereafter, or decreasing throughout. Additionally, (3.29) is decreasing in r for $r \in (r^L, r^{HL}]$ and constant in r thereafter. Therefore, there exists $r^* \in [\tilde{r}^{LL}, r^L]$ such that (3.29) is strictly positive at $r = r^*$ and decreasing for $r > r^*$. Furthermore, (3.29) is negative at $r = r^{HL}$. Thus, there must exist $r_0 > r^*$ such that (3.29) changes from non-negative to strictly negative at r_0.

Sub-case $r^L < \{r^{LL}, \tilde{r}^{HL}\} < r^{HL}$. Similarly, one can check that (3.29) is zero at $r = \tilde{r}^L$, and strictly positive and strictly increasing in r for $r \in (\tilde{r}^L, \tilde{r}^{LL}]$. As for $r \in (\tilde{r}^{LL}, r^L]$, there are two possibilities for (3.29): increasing throughout, or decreasing throughout. For $r \in (r^L, r^{HL}]$, (3.29) is decreasing (regardless of the ordering of r^{LL} and $\tilde{r}^{HL}$), and is constant for $r > r^{HL}$. Therefore, the same logic as in the previous sub-case establishes the existence of r_0. ■

Proof of Proposition 9. Omitted. Proofs of the results under codependent disruptions are similar to those for Proposition 7, and are omitted for brevity. ■

Chapter 4

Delegating Procurement under Supply Risk and Asymmetric Information

4.1. Introduction

When choosing the sourcing strategy, an important decision of the manufacturer is to decide how much control it assumes over the procurement process. The manufacturer may directly contract with suppliers. However, a supplier need not produce the entire order in house to meet the manufacturer's requirement—the supplier may outsource part or all of its production assignment. In anticipation of such action of the suppliers, the manufacturer may preemptively delegate a part of its procurement decision to a supplier. That is, the supplier may be allowed to decide whether to produce all in house or to outsource and, in the latter case, how to allocate the production assignment.

When the suppliers are unreliable, delegating the procurement decision to a supplier could potentially alter the manufacturer's supply-risk profile and its risk management strategy. To mitigate supply disruption risk, a manufacturer can use several suppliers at the same time (diversification). When the manufacturer directly contracts with suppliers, it decides on the number of suppliers to use and allocates orders among them to achieve the best cost-risk balance. When the manufacturer delegates procurement to a supplier, it transfers part of its risk management responsibility to the supplier, but also gives up some of its control over its preparation for a supply disruption.

In addition, delegating the procurement decision could potentially alter how much a manufacturer relies on its information about the suppliers. In practice, suppliers typically have private information about their costs and abilities to fulfill the requirements. As we have shown in Chapters 2 and 3, such asymmetric information could introduce additional risk to the supply chain. There are occasions where suppliers have closer relationships among themselves than that with the manufacturer. In such an occasion, the manufacturer may reduce its information gap with its suppliers by delegating procurement to a more knowledgeable supplier.

In this chapter, we study the problem of a manufacturer delegating its procurement of a part to one of its two unreliable suppliers, who have private information about their probabilities of experiencing a disruption. We explore the interaction between the manufacturer's supply risk management and its use of delegation strategy. Specifically, our research questions are:

- How does delegation affect the manufacturer's risk profile?
- Does delegation increase or decrease the manufacturer's profit?
- How does asymmetric information about supply risk affect the manufacturer's use of delegation?

This chapter is organized as follows. After a review of the related literature, we introduce the model. We then present the preliminary insights. In the conclusion, we summarize the findings and discuss our plans for further study on this topic. All proofs are relegated to the appendix of this chapter.

4.2. Literature Review

The issue of delegating contracting responsibility has been studied in the economics literature. For a review of this body of research, we refer the reader to Mookherjee (2006). In this literature, a class of models invoke the Revelation Principle (e.g., Tirole, 1986; Melumad et al., 1992, 1995; Laffont and Martimort, 1998;

Mookherjee and Tsumagari, 2004). This approach takes an incentive perspective for explaining the cost of delegation caused by the principal's loss of control over the agents. In our study, we follow this approach and model the manufacturer's contracting decision as a mechanism design problem. The two suppliers (agents) form a coalition and the manufacturer (principal) offers an incentive-compatible contract menu to the coalition. This model corresponds to the model in which the principal delegates to a middleman who has perfect information about the agents (e.g., Mookherjee and Tsumagari, 2004).

In operations management, there is a sparse literature on delegating procurement decisions. A recent paper by Kayıs et al. (2007) studies a supply chain of two tiers of suppliers, where the tier-1 supplier is the sub-assembler and the tier-2 supplier delivers a component to the tier-1 supplier. In their model, the suppliers are perfectly reliable, and the buyer has asymmetric information about the cost of the suppliers. In our model, the suppliers are unreliable and the manufacturer has asymmetric information about the suppliers' reliabilities. In their model, the two suppliers' products are complementary and hence there is no competition between the suppliers. In our model, the two suppliers produce perfectly substitutable products, and the manufacturer can use the two suppliers at the same time to reduce the risk of no delivery. Their study focuses on the benefit of using a simple contract in delegation, under which the manufacturer offers the same price-only contract across all supplier types. In contrast, we study an incentive-compatible contract menu. The use of the contract menu enables us to analyze the change caused by delegation in the suppliers' incentives and its effect on the manufacturer's sourcing strategy.

4.3. The Model

The setup of the model is similar to the two-supplier model in Chapter 3. There are two suppliers, each of which is subject to a random production disruption. There are two supplier types. The suppliers have private information about their types:

high reliability or low reliability. For this study, we set the manufacturer's setup cost of contracting with a supplier, K, to be zero.

Unlike the model in Chapter 3, here the manufacturer contracts with at most one supplier, be it supplier 1 or supplier 2. The two suppliers form a centralized coalition, and the manufacturer anticipates that the suppliers do so. The manufacturer designs an incentive-compatible contract menu to elicit the coalition's type information. Each contract consists of a transfer payment, an order quantity and a non-delivery penalty that applies to the coalition of the suppliers.

The timing of events is as follows. First, the manufacturer offers a contract menu to the supplier coalition. The coalition accepts or rejects the offer. Then, if it accepts the contract, the coalition decides the sizes of the two suppliers' respective production runs. The suppliers run production independently. Finally, the coalition collects the outputs from the suppliers and delivers to the manufacturer.

We solve this problem backwards, starting with the supplier coalition's problem.

4.3.1 The Supplier Coalition's Optimal Production Actions

Given the manufacturer's contract (X, q, p), the supplier coalition chooses the sizes of the two suppliers' production runs, z_1 and z_2, to maximize its expected profit:

$$\hat{\pi}^{t_1,t_2}(X,q,p) = X - \min_{z_1 \geq 0,\, z_2 \geq 0} \left\{ c^{t_1} z_1 + c^{t_2} z_2 + \underset{\rho_1^{t_1},\, \rho_2^{t_2}}{E} p \left(q - \rho_1^{t_1} z_1 - \rho_2^{t_2} z_2 \right)^+ \right\} \tag{4.1}$$

Lemma 7 summarizes the coalition's optimal production sizes $(\hat{z}_1^*, \hat{z}_2^*)$ and its optimal expected profit $\hat{\pi}^{t_1,t_2}(X,q,p)$:

Lemma 7. *Under the manufacturer's contract (X, q, p), the supplier coalition's optimal production sizes, $(\hat{z}_1^*, \hat{z}_2^*)$, and its optimal expected profit, $\hat{\pi}^{t_1,t_2}(X,q,p)$, are:*

(t_1, t_2)	Penalty	$(\hat{z}_1^*, \hat{z}_2^*)$	$\hat{\pi}^{t_1,t_2}(X, q, p)$
(H,H)	$p < \frac{c^H}{h}$	$(0,0)$	$X - pq$
	$\frac{c^H}{h} \leq p < \frac{c^H}{h(1-h)}$	$(q,0)$ or $(0,q)$	$X - c^H q - (1-h)pq$
	$p \geq \frac{c^H}{h(1-h)}$	(q,q)	$X - 2c^H q - (1-h)^2 pq$
(H,L) or (L,H)	$p < \frac{c^H}{h}$	$(0,0)$	$X - pq$
	$\frac{c^H}{h} \leq p < \frac{c^L}{l(1-h)}$	$(q,0)$ or $(0,q)$	$X - c^H q - (1-h)pq$
	$p \geq \frac{c^L}{l(1-h)}$	(q,q)	$X - c^H q - c^L q - (1-h)(1-l)pq$
(L,L)	$p < \frac{c^L}{l}$	$(0,0)$	$X - pq$
	$\frac{c^L}{l} \leq p < \frac{c^L}{l(1-l)}$	$(q,0)$ or $(0,q)$	$X - c^L q - (1-l)pq$
	$p \geq \frac{c^L}{l(1-l)}$	(q,q)	$X - 2c^L q - (1-l)^2 pq$

As the non-delivery penalty p increases, the coalition increases the number of suppliers that run production. Consider the case of $t_1 = H$ and $t_2 = L$, for example. When the non-delivery penalty is low, $p < \frac{c^H}{h}$, neither supplier will run production. When the penalty is medium, $\frac{c^H}{h} \leq p < \frac{c^L}{l(1-h)}$, only the high-type supplier will run production of size q. The manufacturer effectively sole-sources. When the non-delivery penalty is high, $p \geq \frac{c^L}{l(1-h)}$, both suppliers will produce, and the manufacturer's supply is effectively diversified.

A coordinating contract that implements $(\hat{z}_1^*, \hat{z}_2^*)$. One may question whether or not the optimal production sizes of the centralized system, $(\hat{z}_1^*, \hat{z}_2^*)$, are implementable. That is, whether or not there exists a coordinating contract between the two suppliers that induce them to produce quantities $(\hat{z}_1^*, \hat{z}_2^*)$. The difficulty in designing such a contract is that the size of a supplier's production run need not be verifiable to the other supplier. Hence, the contract between the two suppliers cannot be written over the supplier's production sizes, z_1 and z_2. We circumvent this issue by assuming that the suppliers can verify each other's production outcome, $\rho_1^{t_1} z_1$ and

$\rho_2^{t_2} z_2$.

We find a coordinating contract, under which the two suppliers share the total cost of the coalition and run production of sizes $(\hat{z}_1^*, \hat{z}_2^*)$.

Lemma 8. *The coalition is coordinated and the two suppliers run production of sizes* $(\hat{z}_1^*, \hat{z}_2^*)$*, if they share the coalition's costs in the following way: after both suppliers complete production, supplier 1 pays supplier 2 the amount* $\beta_1 c^{t_2} \frac{\rho_2^{t_2} z_2}{E\rho_2^{t_2}}$ *and shares a fraction of* β_1 *of the total penalty paid to the manufacturer; supplier 2 pays supplier 1 the amount* $\beta_2 c^{t_1} \frac{\rho_1^{t_1} z_1}{E\rho_1^{t_1}}$ *and shares a fraction of* β_2 *of the total penalty. The fractions,* β_1 *and* β_2*, satisfy* $0 < \beta_1 < 1$*,* $0 < \beta_2 < 1$ *and* $\beta_1 + \beta_2 = 1$.

Under this contract, supplier 1 bears a fraction of β_1 of the total expected cost of the two suppliers, and supplier 2 bears a fraction of β_2. Hence, it is Pareto efficient for them to run production of sizes $(\hat{z}_1^*, \hat{z}_2^*)$.

4.3.2 The Manufacturer's Decision under Asymmetric Information

Under asymmetric information, we invoke the revelation principle and model the manufacturer's contracting decision as a mechanism design problem. In this problem, the principal (the manufacturer) offers an incentive-compatible contract menu to a "grand agent", that is, the coalition of the two suppliers. Given that the two suppliers are identical if they are of the same reliability type, the coalition can be one of the following three compositions: two high-type suppliers, a high-type and a low-type supplier, and two low-type suppliers; with probability $(\alpha^H)^2$, $2(\alpha^H \alpha^L)$ and $(\alpha^L)^2$, respectively. The manufacturer's contract menu is made up of three contracts: $(X, q, p)(H, H)$, $(X, q, p)(H, L)$ and $(X, q, p)(L, L)$. The contract menu must be incentive compatible, such that a coalition of any type would have no incentive to misreport its type.

Compared to a mechanism design problem of a single agent with two types, our problem has three agent types, and thus involves more complicated incentive compatibility constraints. The coalition of two high-type suppliers has incentives to pretend to be a high- and a low-type supplier or be two low-type suppliers. In the economics literature, the incentive compatibility constraint that prevents the former misrepresentation is called a *local* incentive compatibility constraint, and the latter is called a *global* incentive compatibility constraint. Similarly, the coalition of two low-type suppliers also has a local and a global incentive compatibility constraint. The coalition of a high- and a low-type supplier has two local incentive compatibility constraints that prevent it from pretending to be two high-type suppliers or be two low-type suppliers.

The manufacturer's contracting decision is represented by the following optimization program:

$$\max_{(X,q,p)(\cdot,\cdot)} \quad E_{t_1,t_2}\Big\{ rE\min\Big(D, \rho_1^{t_1}\hat{z}_1^* + \rho_2^{t_2}\hat{z}_2^*\Big) - X(t_1,t_2) + p(t_1,t_2)E\Big[q(t_1,t_2) - \rho_1^{t_1}\hat{z}_1^* - \rho_2^{t_2}\hat{z}_2^*\Big]^+ \Big\}$$

Subject to

$$\begin{aligned}
&\text{(IC.HH)} && \hat{\pi}^{HH}\big[(X,q,p)(H,H)\big] \geq \hat{\pi}^{HH}\big[(X,q,p)(H,L)\big] \text{ (local IC)}\\
& && \hat{\pi}^{HH}\big[(X,q,p)(H,H)\big] \geq \hat{\pi}^{HH}\big[(X,q,p)(L,L)\big] \text{ (global IC)}\\
&\text{(IC.HL)} && \hat{\pi}^{HL}\big[(X,q,p)(H,L)\big] \geq \hat{\pi}^{HL}\big[(X,q,p)(H,H)\big] \text{ (local IC)}\\
& && \hat{\pi}^{HL}\big[(X,q,p)(H,L)\big] \geq \hat{\pi}^{HL}\big[(X,q,p)(L,L)\big] \text{ (local IC)}\\
&\text{(IC.LL)} && \hat{\pi}^{LL}\big[(X,q,p)(L,L)\big] \geq \hat{\pi}^{LL}\big[(X,q,p)(H,H)\big] \text{ (global IC)}\\
& && \hat{\pi}^{LL}\big[(X,q,p)(L,L)\big] \geq \hat{\pi}^{LL}\big[(X,q,p)(H,L)\big] \text{ (local IC)}\\
&\text{(IR)} && \hat{\pi}^{HH}\big[(X,q,p)(H,H)\big] \geq 0,\ \hat{\pi}^{HL}\big[(X,q,p)(H,L)\big] \geq 0\\
& && \hat{\pi}^{LL}\big[(X,q,p)(L,L)\big] \geq 0
\end{aligned} \tag{4.2}$$

4.4. The Manufacturer's Optimal Contract Menu

In general, it is difficult to solve a mechanism design problem with an agent of more than two discrete types. However, with two restrictions over the modeling parameters we manage to find the closed-form optimal solution. First, we assume

$1-h<(1-l)^2$. This restriction sets an upper bound over the low-type's probability of successful production: $l<1-\sqrt{1-h}$. Second, we assume $\frac{c^H}{h(1-h)}>\frac{c^L}{l(1-l)}$. Along with the assumption $\frac{c^L}{l}>\frac{c^H}{h}$, this restriction implies inequalities $1<\left(\frac{c^L}{l}/\frac{c^H}{h}\right)<\frac{1-l}{1-h}$. That is, the gap between the effective costs of producing one good unit by the low-type and the high-type is not too large. These restrictions ensure that the global and local incentive-compatibility constraints across all three coalition types are slack at the optimal solution.

We present the optimal solution in Proposition 10, where the critical revenues, $\hat{r}^H$, $\hat{r}^L$, $\hat{r}^{HH}$, $\hat{r}^{HL}$ and $\hat{r}^{LL}$ are defined to be

$$\hat{r}^H \stackrel{\text{def}}{=} \frac{c^H}{h} \tag{4.3a}$$

$$\hat{r}^L \stackrel{\text{def}}{=} \frac{c^L}{l}+\left[\left(\frac{\alpha^H}{\alpha^L}\right)^2+\frac{2\alpha^H}{\alpha^L}\right]\frac{h}{l}\left(\frac{c^L}{l}-\frac{c^H}{h}\right) \tag{4.3b}$$

$$\hat{r}^{HH} \stackrel{\text{def}}{=} \frac{c^H}{h(1-h)} \tag{4.3c}$$

$$\hat{r}^{HL} \stackrel{\text{def}}{=} \frac{c^L}{l(1-h)}+\frac{\alpha^H}{2\alpha^L}\frac{h}{l(1-h)}\left(\frac{c^L}{l}-\frac{c^H}{h}\right) \tag{4.3d}$$

$$\hat{r}^{LL} \stackrel{\text{def}}{=} \frac{c^L}{l(1-l)}+\left[\left(\frac{\alpha^H}{\alpha^L}\right)^2+\frac{2\alpha^H}{\alpha^L}\right]\frac{h-l}{1-l}\frac{c^L}{1(1-l)}. \tag{4.3e}$$

Proposition 10. *Given that $1-h<(1-l)^2$ and $\frac{c^H}{h(1-h)}>\frac{c^L}{l(1-l)}$, under asymmetric information the manufacturer's optimal order quantity, $\hat{q}^*(t_1,t_2)$, and the optimal non-delivery penalty, $\hat{p}^*(t_1,t_2)$, and the optimal production actions of the coalition, $(\hat{z}_1^*,\hat{z}_2^*)$, are presented in Table 4.1.*

We explain how the manufacturer's procurement action and the coalition's production actions change as the revenue, r, increases. Take the contract designated for a coalition of two high-type suppliers as an example. When the revenue is low, $r<\hat{r}^H$, the manufacturer does not order. When the revenue is medium, $\hat{r}^H\le r<\hat{r}^{HH}$, the manufacturer orders from the supplier coalition but sets the non-delivery penalty

(t_1, t_2)	r	$\hat{q}^*$	$\hat{p}^*$	$(\hat{z}_1^*, \hat{z}_2^*)$
(H, H)	$r \in [0, \hat{r}^H)$	No contract		
	$r \in [\hat{r}^H, \hat{r}^{HH})$	D	$\frac{c^L}{l(1-l)}$	$(D, 0)$ or $(0, D)$
	$r \in [\hat{r}^{HH}, \infty)$	D	$\frac{c^L}{l(1-h)}$	(D, D)
(H,L) or (L,H)	$r \in [0, \hat{r}^H)$	No contract		
	$r \in [\hat{r}^H, \hat{r}^{HL})$	D	$\frac{c^L}{l(1-l)}$	$(D, 0)$ or $(0, D)$
	$r \in [\hat{r}^{HL}, \infty)$	D	$\frac{c^L}{l(1-h)}$	(D, D)
(L,L)	$r \in [0, \hat{r}^L)$	No contract		
	$r \in [\hat{r}^L, \hat{r}^{LL})$	D	$\frac{c^L}{l}$	$(D, 0)$ or $(0, D)$
	$r \in [\hat{r}^{LL}, \infty)$	D	$\frac{c^L}{l(1-l)}$	(D, D)

Table 4.1: The manufacturer's optimal order quantity and penalty and the coalition's optimal production actions.

to be low, $\hat{p}^*(H, H) = \frac{c^L}{l(1-l)}$. Under such a medium penalty, only one supplier will run production, and the manufacturer is effectively sole-sourcing from the coalition. When the revenue is large, $r \geq \hat{r}^{HH}$, the manufacturer orders from the supplier coalition and sets the non-delivery penalty to be high, $\hat{p}^*(H, H) = \frac{c^L}{l(1-h)}$. Under such a large penalty, both suppliers will run production, and the manufacturer's supply is diversified.

4.5. Analysis

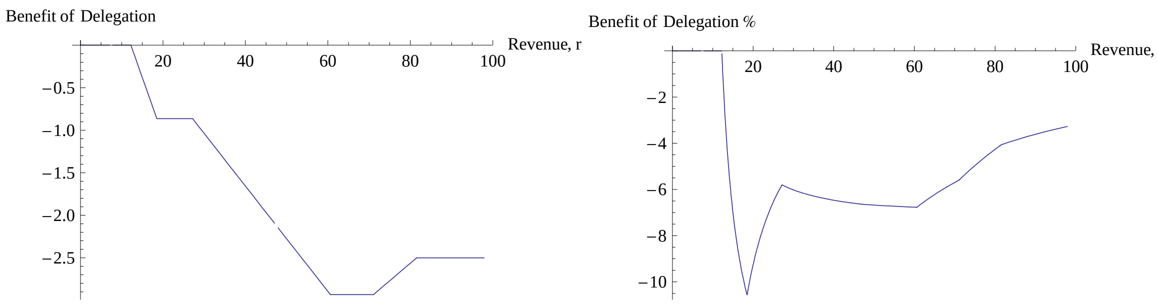
Effect of delegating procurement decision. We compare the manufacturer's optimal contract menus and the corresponding production actions of the suppliers in the direct contracting scheme (as in the two-supplier model in Chapter 3) and the delegation scheme. We find that the critical revenue for the manufacturer to diversify with a high- and a low-type supplier is lower in the delegation scheme: $\hat{r}^{HL} < r^{HL}$. The inequality implies that delegation may cause the manufacturer to start diversifying with a high- and a low-type supplier.

This is because, compared to direct contracting, under delegation two high-type suppliers have a smaller total incentive to pretend to be of a high- and a low-type supplier. Under delegation, when the manufacturer induces diversification, the two suppliers receive one contract and jointly minimize the sum of their costs. The suppliers pay one penalty to the manufacturer only if both of them are unsuccessful with their production. In contrast, under direct contracting, the suppliers receives two separate contracts and act independently. Each supplier pays a penalty if its production is unsuccessful, regardless of whether or not the other supplier is successful. Hence, delegation reduces the total penalty paid by and thus the total payment to a high- and a low-type supplier, making the contract designed for them less attractive for two high-type suppliers.

However, we find that $\hat{r}^{LL} > r^{LL}$, that is, delegation may cause the manufacturer to stop diversifying with two low-type suppliers. This is because, compared to direct contracting, under delegation the manufacturer enjoys a larger reduction in the supplier's misrepresentation incentives by forgoing diversifying with two low-type suppliers. Under direct contracting, acting independently, two high-type suppliers may pretend to be a high- and a low-type supplier, but would not commit to both reporting to be of low-type. The reason for the latter is that a supplier can gain competitive advantage by truthfully reporting to be of high-type if the other supplier reports itself as of low-type. Hence, under direct contracting the only benefit of forgoing diversify with two low-type suppliers is the reduction in the incentive of a high- and a low-type supplier. In contrast, under delegation the suppliers can coordinate their type reports, and two high-type suppliers can creditable commit to reporting to be two low-type suppliers. Hence, under delegation forgoing diversifying with two low-type suppliers has an additional benefit: it also reduces the misrepresentation incentives of two high-type suppliers.

The benefits of delegation. Using a numerical study, we compare the manufacturer's profits in the delegation scheme and in the direct contracting scheme to derive the benefit of delegation. We find that, compared to direct contracting, delegation may reduce the manufacturer's profit when the revenue r is relatively large, but may increase the manufacturer's profit when r is relatively small.

Result 1: $\alpha^H = 0.5$, $h = 0.85$, $l = 0.55$, $c^H = 6$, and $c^L = 5$



Result 2: $\alpha^H = 0.9$, $h = 0.65$, $l = 0.4$, $c^H = 5$, and $c^L = 5$

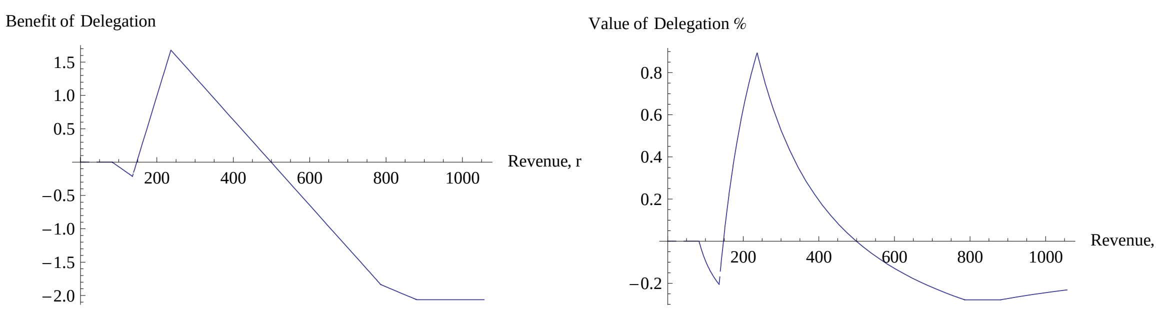


Figure 4.1: The increase in the manufacturer's profit due to delegation (the left panels) and the percentage of increase (the right panels).

Figure 4.1 shows the benefit of delegation as a function of the revenue r. The two upper panels plot the benefit of diversification with parameters $\alpha^H = 0.5$, $h = 0.85$, $l = 0.55$, $c^H = 6$, and $c^L = 5$, when the critical revenues for diversification are $\hat{r}^{HH} = 47$, $\hat{r}^{HL} = 71$ and $\hat{r}^{LL} = 60$. In this case, delegation could cause as much as 10% loss of its expected profit. In particular, when $r > \hat{r}^{LL}$, delegation could cause a significant loss (see the upper-left panel).

The plots at the top may suggest that delegation would not benefit the manufacturer. However, this is not generally true. To better illustrate the case of a positive benefit of delegation, we set the model parameters to be $\alpha^H = 0.9$, $h = 0.65$, $l = 0.4$, and $c^H = c^L = 5$ and plot the benefit of delegation on the two lower panels in Figure 4.1. In this case, the critical revenues for diversification are $\hat{r}^{HH} = 22$, $\hat{r}^{HL} = 136$ and $\hat{r}^{LL} = 880$. Roughly in interval $\hat{r}^{HL} < r \ll \hat{r}^{LL}$ delegation could increase the manufacturer's profit, although by a relatively small amount.

An explanation to the above observations is that delegation may increase or decrease the total incentive payment to the two high-type suppliers, depending on the revenue. When the revenue is high, e.g., $r > \hat{r}^{LL}$, the manufacturer diversifies under delegation even if the two suppliers are both of low-type. Under delegation, two high-type suppliers would have a strong incentive to pretend to be two low-type suppliers. Compared to the direct contracting scheme, the manufacturer must pay them an extra incentive payment in order to elicit their true types. Hence, delegation reduces the manufacturer's profit.

When the revenue is low, e.g., $r \ll \hat{r}^{LL}$, the manufacturer does not diversify with two low-type suppliers under delegation. As in the direct contracting scheme, two high-type suppliers have no incentive to pretend to be two low-type suppliers. On the other hand, delegation also reduces two high-type suppliers' incentive to report to be a high- and a low-type, because delegation reduces the costs of, and thus the cost gap between, these two types of the coalition. Hence, delegation increases the manufacturer's profit.

Effect of asymmetric information on delegation. Repeating the above analysis for the case of symmetric information, we find that, under symmetric information, delegating procurement has no effect over how the manufacturer would induce the supplier production actions and the manufacturer's expected profit. That is, delegation affects the manufacturer only when the suppliers' reliabilities are unknown to the manufacturer. This is because under symmetric information the suppliers cannot misreport their types, whether the manufacturer delegates or not.

Because the manufacturer is indifferent of delegation and direct contracting, under symmetric information the benefit of delegation is zero. Having information likely increases the benefit of delegation. Hence, we have the following corollary: information and delegation need not be substitutes. In other words, delegating procurement to a more knowledgeable supplier need not reduces the importance of information for the manufacturer.

4.6. Conclusion

In the chapter, we study the problem where the manufacturer delegates procurement when both suppliers are unreliable and have private information about their reliabilities. Compared to direct contracting (the two-supplier model in Chapter 3), delegation alters the suppliers' incentive of misrepresentation. On the one hand, delegation increases the suppliers' incentive to pretend to be two low-type suppliers. On the other hand, delegation reduces the suppliers' incentive to pretend to be a high-type and a low-type.

The change in the suppliers' incentive due to delegation manifests itself in the manufacturer's sourcing strategy. When the suppliers are a high-type and a low-type, delegation may cause the manufacturer to start inducing diversification, because delegation decreases the suppliers' incentive to pretend to be a high-type and a low-type. In this case, delegation weakens the effect of asymmetric information on the manufacturer's use of diversification observed in the two-supplier model in Chapter 3. When the suppliers are both of low-type, delegation may cause the manufacturer to stop inducing diversification, because delegation increases the suppliers' incentive to pretend to be both of low-type. In this case, delegation enhances the effect of asymmetric information.

While the suppliers' reliabilities information is always valuable, it may be expensive to obtain. As we have shown in the two-supplier model in Chapter 3, the manufacturer can reduce the importance of information by encouraging competition between the suppliers. In the model of this chapter, delegation eliminates supplier competition and, hence, allows the suppliers to earn larger informational rents. Overall, delegation may increase the importance of information for the manufacturer, and hence delegation need not be a substitute for information.

In the economics literature on delegation, an important question is whether delegation is preferred over direct contracting. In general, direct contracting is superior to delegation, under which the principal suffers from loss of control (Mookherjee, 2006). This result is obtained under asymmetric information about the agents' costs. There are a few exceptions. For example, Mookherjee and Tsumagari (2004) show that when the two suppliers produce complementary products, with an additional assumption over the distributions of the suppliers' cost types, delegation is superior to direct contracting. In contrast, we assume asymmetric information about the supplier's reliability and that the suppliers' products are substitutable. We find that the manufacturer's profit under delegation may be greater or smaller than that under direct contracting, depending on the model parameters.

For future work, we plan to extend the scope of this study. In the current model, the two suppliers can always form a coalition and the manufacturer anticipates that the suppliers do so. We plan to consider the situation where there is uncertainty in the formation process of the coalition by the suppliers. For example, a second supplier need not be available after the manufacturer contracts with the primary supplier. In the current model, the manufacturer offers one contract to the coalition. We can allow the manufacturer to have more contracting flexibility. For example, the manufacturer may contract with both suppliers, while anticipating that the suppliers will collaborate with each other. This is a direct contracting problem with colluding suppliers.

4.7. Appendix: Proofs of Statements

Proof of Lemma 7. The coalition's problem (4.1) can be rewritten as:

$$\hat{\pi}^{t_1,t_2}(X,q,p) = X - p\,q + \max_{z_1\geq 0,\, z_2\geq 0} \left\{ pE\min\left(q,\ \rho_1^{t_1} z_1 + \rho_2^{t_2} z_2\right)^+ - c^{t_1} z_1 - c^{t_2} z_2 \right\}. \quad (4.4)$$

The maximization program in the right-hand-side of the above equation is a piecewise linear, concave objective function of z_1 and z_2, with four corner-points: $(z_1, z_2) = (0,0)$, $(q,0)$, $(0,q)$ or (q,q). Without loss of optimality, we focus on these corner-points. The optimal corner-point is the one that obtains the largest objective value. ■

Proof of Lemma 8. We consider a production game of two suppliers. In this game, the two suppliers simultaneously choose their production sizes z_1 and z_2. We show that $(z_1, z_2) = (\hat{z}_1^*, \hat{z}_2^*)$ is a Nash equilibrium for the game.

Under the cost sharing contract proposed in this lemma, supplier 1 choose its production size z_1 to minimizes its total cost:

$$\min_{z_1\geq 0} \mathop{E}_{\rho_1^{t_1},\rho_2^{t_2}} \left\{ c^{t_1} z_1 + \beta_1 c^{t_2} \frac{\rho_2^{t_2} z_2}{E\rho_2^{t_2}} - \beta_2 c^{t_1} \frac{\rho_1^{t_1} z_1}{E\rho_1^{t_1}} + \beta_1 p (q - \rho_1^{t_1} z_1 - \rho_2^{t_2} z_2)^+ \right\}.$$

Applying the outer expectation to each term within the curly brackets, and using $\beta_1 + \beta_2 = 1$, we rewrite supplier 1's minimization problem as

$$\beta_1 \min_{z_1\geq 0} \left\{ c^{t_1} z_1 + c^{t_2} z_2 + p \mathop{E}_{\rho_1^{t_1},\rho_2^{t_2}} (q - \rho_1^{t_1} z_1 - \rho_2^{t_2} z_2)^+ \right\}.$$

Similarly, supplier 2's minimization problem is

$$\beta_2 \min_{z_2\geq 0} \left\{ c^{t_1} z_1 + c^{t_2} z_2 + p \mathop{E}_{\rho_2^{t_2},\rho_1^{t_1}} (q - \rho_1^{t_1} z_1 - \rho_2^{t_2} z_2)^+ \right\}.$$

Note that the objective function of each of the two suppliers is a fraction of the coalition's expected total cost.

Now, we show that $(z_1, z_2) = (\hat{z}_1^*, \hat{z}_2^*)$ is a Nash equilibrium. Let $z_2 = \hat{z}_2^*$. Then, $z_1 = \hat{z}_1^*$ must be supplier 1's best response, because $(z_1, z_2) = (\hat{z}_1^*, \hat{z}_2^*)$ minimizes the coalition's expected total cost and hence minimizes supplier 1's expected cost. Similarly, $z_2 = \hat{z}_2^*$ is supplier 2's best response to supplier 1's action of $z_1 = \hat{z}_1^*$. ■

Lemma 9. *For a given contract (X, q, p) by the manufacturer, we define the local reliability advantage of the coalition of two high-type suppliers, denoted as $\Gamma^{HH}_{HL}(q,p)$, to be the difference between its expected profit over the expected profit of the coalition with one high- and one low-type suppliers: $\Gamma^{HH}_{HL}(q,p) \overset{def}{=} \hat{\pi}^{HH}(q,p) - \hat{\pi}^{HL}(q,p)$. Similarly, we define the local cost advantage of the coalition of a high- and a low-type supplier to be $\Gamma^{HL}_{LL}(q,p) \overset{def}{=} \hat{\pi}^{HL}(q,p) - \hat{\pi}^{LL}(q,p)$. The expressions of $\Gamma^{HH}_{HL}(q,p)$ and $\Gamma^{HL}_{LL}(q,p)$ are*

Penalty	$\boldsymbol{\Gamma^{HH}_{HL}(q,p)}$
$p < \frac{c^H}{h(1-h)}$	0
$\frac{c^H}{h(1-h)} \le p < \frac{c^L}{l(1-h)}$	$[h(1-h)p - c^H]q$
$r \ge \frac{c^L}{l(1-h)}$	$[(h-l)(1-h)p - (c^H - c^L)]q$
Penalty	$\boldsymbol{\Gamma^{HL}_{LL}(q,p)}$
$p < \frac{c^H}{h}$	0
$\frac{c^H}{h} \le p < \frac{c^L}{l}$	$(hp - c^H)q$
$\frac{c^L}{l} \le r < \frac{c^L}{l(1-l)}$	$[(h-l)p - (c^H - c^L)]q$
$\frac{c^L}{l(1-l)} \le r < \frac{c^L}{l(1-h)}$	$[(h-l)p - (c^H - c^L)]q - [l(1-l)p - c^L]q$
$p \ge \frac{c^L}{l(1-h)}$	$[(h-l)(1-l)p - (c^H - c^L)]q$

$\Gamma^{HH}_{HL}(q,p)$ and $\Gamma^{HL}_{LL}(q,p)$ are non-negative and monotonic increasing in q. $\Gamma^{HL}_{LL}(q,p)$ is monotonic increasing in p. When $1-h < (1-l)^2$, $\Gamma^{HH}_{HL}(q,p)$ is monotonic increasing in p.

Proof. One can derive the expressions of $\Gamma^{\frac{HH}{HL}}(q,p)$ and $\Gamma^{\frac{HL}{LL}}(q,p)$ using the expressions of the coalition's optimal profit in Lemma 7. The non-negativity and monotonicity of $\Gamma^{\frac{HH}{HL}}(q,p)$ and $\Gamma^{\frac{HL}{LL}}(q,p)$ can be verified using the obtained expressions. ■

Proof of Lemma 10. First of all, we temporarily neglect the two global incentive compatibility constraints of the high-high and low-low coalition types. We will later show that at the optimal solution, these constraints are slack.

We begin by applying (4.1) to the objective function of problem (4.2), obtaining

$$\max \underset{t_1,t_2}{E} \left\{ r\, E \min\left(D, \rho_1^{t_1} \hat{z}_1^* + \rho_2^{t_2} \hat{z}_2^*\right) - \hat{\pi}^{t_1,t_2}[(X,q,p)(t_1,t_2)] - c^{t_1} \hat{z}_1^* - c^{t_2} \hat{z}_2^* \right\}. \quad (4.5)$$

We apply the definitions of the local reliability advantages of high-high and high-low coalition types, $\Gamma^{\frac{HH}{HL}}(q,p)$ and $\Gamma^{\frac{HL}{LL}}(q,p)$ (see Lemma 9), and establish the following relationships among the profits of different coalition types:

$$\begin{aligned}
\hat{\pi}^{HH}\big[(X,q,p)(H,L)\big] &= \hat{\pi}^{HL}\big[(X,q,p)(H,L)\big] + \Gamma^{\frac{HH}{HL}}\big[(q,p)(H,L)\big],\\
\hat{\pi}^{HL}\big[(X,q,p)(L,L)\big] &= \hat{\pi}^{LL}\big[(X,q,p)(L,L)\big] + \Gamma^{\frac{HL}{LL}}\big[(q,p)(L,L)\big],\\
\hat{\pi}^{HL}\big[(X,q,p)(H,H)\big] &= \hat{\pi}^{HH}\big[(X,q,p)(H,H)\big] - \Gamma^{\frac{HH}{HL}}\big[(q,p)(H,H)\big],\\
\hat{\pi}^{LL}\big[(X,q,p)(H,L)\big] &= \hat{\pi}^{HL}\big[(X,q,p)(H,L)\big] - \Gamma^{\frac{HL}{LL}}\big[(q,p)(H,L)\big].
\end{aligned}$$

We apply the above equations to the four local incentive compatibility constraints in (4.2), transforming them into

$$\hat{\pi}^{HH}\big[(X,q,p)(H,H)\big] \geq \hat{\pi}^{HL}\big[(X,q,p)(H,L)\big] + \Gamma^{\frac{HH}{HL}}\big[(q,p)(H,L)\big], \quad (4.6a)$$

$$\hat{\pi}^{HL}\big[(X,q,p)(H,L)\big] \geq \hat{\pi}^{HH}\big[(X,q,p)(H,H)\big] - \Gamma^{\frac{HH}{HL}}\big[(q,p)(H,H)\big], \quad (4.6b)$$

$$\hat{\pi}^{HL}\big[(X,q,p)(H,L)\big] \geq \hat{\pi}^{LL}\big[(X,q,p)(L,L)\big] + \Gamma^{\frac{HL}{LL}}\big[(q,p)(L,L)\big], \quad (4.6c)$$

$$\hat{\pi}^{LL}\big[(X,q,p)(L,L)\big] \geq \hat{\pi}^{HL}\big[(X,q,p)(H,L)\big] - \Gamma^{\frac{HL}{LL}}\big[(q,p)(H,L)\big]. \quad (4.6d)$$

Following the standard procedure of solving a mechanism design problem, we identify that the following individual rationality and local incentive compatibility constraints are binding at the optimal solution:

$$\hat{\pi}^{LL}[(X,q,p)(L,L)] = 0 \tag{4.7a}$$

$$\hat{\pi}^{HL}[(X,q,p)(H,L)] = \Gamma^{\frac{HL}{LL}}[(q,p)(L,L)] \tag{4.7b}$$

$$\hat{\pi}^{HH}[(X,q,p)(H,H)] = \Gamma^{\frac{HH}{HL}}[(q,p)(H,L)] + \Gamma^{\frac{HL}{LL}}[(q,p)(L,L)]. \tag{4.7c}$$

Applying (4.5) and (4.7) to problem (4.2), we reduce it to be (with the two global incentive compatibility constraints being neglected):

$$\begin{aligned}
&(\alpha^H)^2 \max_{(q,p)(H,H)} \left\{ rE\min(D, \rho_1^H \hat{z}_1^* + \rho_2^H \hat{z}_2^*) - c^H(\hat{z}_1^* + \hat{z}_2^*) \right\} \\
&+2(\alpha^H\alpha^L) \max_{(q,p)(H,L)} \left\{ rE\min(D, \rho_1^H \hat{z}_1^* + \rho_2^L \hat{z}_2^*) - c^H\hat{z}_1^* - c^L\hat{z}_2^*) - \frac{\alpha^H}{2\alpha^L}\Gamma^{\frac{HH}{HL}}\Big[(q,p)(H,L)\Big] \right\} \\
&(\alpha^L)^2 \max_{(q,p)(L,L)} \Big\{ rE\min(D, \rho_1^L \hat{z}_1^* + \rho_2^L \hat{z}_2^*) - c^L(\hat{z}_1^* + \hat{z}_2^*) \\
&\qquad\qquad - \Big[\left(\alpha^H/\alpha^L\right)^2 + 2\alpha^H/\alpha^L\Big]\Gamma^{\frac{HL}{LL}}\Big[(q,p)(L,L)\Big] \Big\}
\end{aligned}$$

Subject to local monotonicity constraints:

$$\Gamma^{\frac{HH}{HL}}[(q,p)(H,H)] \geq \Gamma^{\frac{HH}{HL}}[(q,p)(H,L)] \tag{4.8a}$$

$$\Gamma^{\frac{HL}{LL}}[(q,p)(H,L)] \geq \Gamma^{\frac{HL}{LL}}[(q,p)(L,L)]. \tag{4.8b}$$

One can check that the solution proposed in this proposition, $(\hat{q}^*, \hat{p}^*)(t_1,t_2)$, maximizes the above problem while the two local monotonicity constraints are relaxed.

Now, we show that $(\hat{q}^*, \hat{p}^*)(t_1,t_2)$ is optimal to problem (4.2), by showing that $(\hat{q}^*, \hat{p}^*)(t_1,t_2)$ satisfies the local monotonicity constraints (4.8) and the two global incentive compatibility constraints in (4.2), which were intentionally neglected in the very beginning of the proof.

$(\hat{q}^*, \hat{p}^*)(t_1,t_2)$ satisfies the local monotonicity constraints (4.8). This is because, under restriction $1-h < (1-l)^2$, $\Gamma^{\frac{HH}{HL}}(q,p)$ and $\Gamma^{\frac{HL}{LL}}(q,p)$ are both monotonic increasing in q and p (see Lemma 9). We have $\hat{p}^*(H,H) \geq \hat{p}^*(H,L) \geq \hat{p}^*(L,L)$ and $\hat{p}^*(H,H) \geq \hat{p}^*(H,L) \geq \hat{p}^*(L,L)$.

$(\hat{q}^*, \hat{p}^*)(t_1,t_2)$ also satisfies the two global incentive compatibility constraints:

$$\hat{\pi}^{HH}\big[(X,q,p)(H,H)\big] \geq \hat{\pi}^{HH}\big[(X,q,p)(L,L)\big]$$
$$\hat{\pi}^{LL}\big[(X,q,p)(L,L)\big] \geq \hat{\pi}^{LL}\big[(X,q,p)(H,H)\big].$$

Note from the definitions of the local reliability advantages, $\Gamma^{\frac{HH}{HL}}(q,p)$ and $\Gamma^{\frac{HL}{LL}}(q,p)$, that

$$\pi^{HH}\big[(X,q,p)(L,L)\big] = \pi^{LL}\big[(X,q,p)(L,L)\big] + \Gamma^{\frac{HH}{HL}}[(q,p)(L,L)] + \Gamma^{\frac{HL}{LL}}[(q,p)(L,L)]$$
$$\pi^{LL}\big[(X,q,p)(H,H)\big] = \pi^{HH}\big[(X,q,p)(H,H)\big] - \Gamma^{\frac{HH}{HL}}[(q,p)(H,H)] - \Gamma^{\frac{HL}{LL}}[(q,p)(H,H)].$$

We apply these two equations together with (4.7a) and (4.7c) to the two global incentive compatibility constraints, obtaining

$$\begin{aligned}\Gamma^{\frac{HH}{HL}}[(q,p)(H,H)] + \Gamma^{\frac{HL}{LL}}[(q,p)(H,H)]& \\ \geq \Gamma^{\frac{HH}{HL}}[(q,p)(H,L)] + \Gamma^{\frac{HL}{LL}}[(q,p)(L,L)]& \\ \geq \Gamma^{\frac{HH}{HL}}[(q,p)(L,L)] + \Gamma^{\frac{HL}{LL}}[(q,p)(L,L)]& \quad (4.9)\end{aligned}$$

The above inequalities hold for the optimal solution $(\hat{q}^*, \hat{p}^*)(t_1,t_2)$ because $\hat{p}^*(H,H) \geq \hat{p}^*(H,L) \geq \hat{p}^*(L,L)$ and $\hat{p}^*(H,H) \geq \hat{p}^*(H,L) \geq \hat{p}^*(L,L)$; and $\Gamma^{\frac{HH}{HL}}(q,p)$ and $\Gamma^{\frac{HL}{LL}}(q,p)$ are monotonic increasing in q and p. ■

Chapter 5

Conclusion

This dissertation studies a manufacturer's supply-risk management under asymmetric information about the supplier's probability of disruption. In the first model (Chapter 2), the manufacturer (buyer) purchases a part from a supplier that is subject to a random production disruption. The supplier's reliability (the probability of disruption) is its private information. The supplier or the manufacturer can use backup production in the event of disruption. The manufacturer sets a non-delivery penalty term (or, equivalently, a payment-on-delivery term) to ensure that the supplier has an incentive to deliver. In the second model (Chapter 3), the manufacturer faces two suppliers who are subject to random disruptions, the probabilities of which are the suppliers' private information. To increase the chance of delivery the manufacturer can diversify, that is, contract with both suppliers simultaneously. In the third model (Chapter 4), while there are two suppliers in the supply base, the manufacturer contracts with only one of them, and the two suppliers form a coalition to meet the manufacturer's requirement.

In these studies, we model the manufacturer's contracting decision under asymmetric information as a mechanism design problem. The manufacturer offers a menu of take-it-or-leave-it contracts to the supplier(s). The supplier(s) selects the contract(s) it most prefers. The manufacturer designs the contract menu so that a supplier's choice of contract reveals its true reliability type to the manufacturer.

To the best of my knowledge, these studies are among the first in the supply-risk management literature to explore asymmetric information about supply risk. We now summarize the main results.

Effect of asymmetric information on supply-risk management tools. In supply-risk management context, an important question is how asymmetric information about the supplier's reliability affects the manufacturer's use of supply-risk management tools.

We find that when the supplier's reliability is its private information, the manufacturer is less likely to use the backup production option of the supplier, but more likely to rely on its own (more costly) backup option. Why does asymmetric information about supply risk cause the manufacturer to utilize supplier backup production less? If the supplier is asked to use its backup production in the event of a disruption, the cost differential between a more reliable supplier type and a less reliable type grows, since the latter is more likely to suffer a disruption and, hence, more likely to incur the cost of using backup production. This widening of the cost gap increases the more reliable supplier type's incentive to misrepresent itself. Thus, the manufacturer may choose to forego the backup production option of the less reliable supplier type to reduce the more reliable type's misrepresentation incentive.

Similarly, because asymmetric information effectively makes it more costly to do business with suppliers, diversification becomes more costly and, hence, the manufacturer utilizes diversification less. However, even as the supply base reliability worsens, the manufacturer may stop diversifying under asymmetric information, at the cost of facing a greater risk of not receiving a delivery. Interestingly, this would not occur if the suppliers' reliabilities were known by the manufacture.

Value of information about supplier reliability. Learning about the supplier(s) is always valuable for the manufacturer. Interestingly, an increase in the reliability of the supply base may make it even more valuable to learn about the supplier(s)' reliability. Therefore, a higher reliability of the supplier(s) need not be a substitute for better information.

For example, consider the one-supplier model, and suppose that the reliabilities of both supplier types increase. As we have shown, when the supplier's type is unknown, the manufacturer may be forced to forgo using the low-reliability type of the supplier, in order to avoid paying an incentive payment. As a result, the manufacturer forgoes the chance of receiving a delivery from the low-type and making a profit. After an increase in the reliabilities of both types, the manufacturer forgoes a larger chance of receiving the delivery from the low-type, leading to a greater loss of profit. In other words, as the reliabilities of both types increase, not knowing the supplier's type leads to a larger loss of profit under asymmetric information. Hence, the value of learning the supplier's type becomes even larger.

Value of risk management tools under asymmetric information. We have found that asymmetric information effectively makes it more expensive to use the risk management tools, namely, backup production option and dual-sourcing option. However, this does not mean that such tools are no longer as valuable as under symmetric information.

With the one-supplier model, we find that the value of the supplier's backup production option for the manufacturer is not necessarily larger when it perfectly knows the supplier's reliability. In particular, adding a cheap backup production option diminishes the supplier's benefit of misrepresenting its reliability (since reliability becomes less of a concern). This incentive reduction provides an extra benefit which does not exist when information is symmetric.

Furthermore, under asymmetric information, as the supply base reliability increases, the backup production option could become more valuable for the manufacturer. An increase in the reliability of the supplier may lead to a smaller cost gap between the more reliable and the less reliable supplier types, when using backup production option. The more reliable type now has a smaller incentive to misrepresent itself as less reliable, making backup production effectively less costly. As a result, the manufacturer makes more use of backup production, even though disruptions are less likely than before.

With the two-supplier model, we find that having a dual-sourcing option (i.e., having two potential suppliers) is very valuable for the manufacturer even if it does not use this option to diversify its supply. Merely having two suppliers allows the manufacturer to play one supplier against the other to receive better pricing, a competition benefit which is absent when the manufacturer has perfect information about its suppliers.

Competition and diversification under asymmetric information. In our two-supplier model, supplier competition arises when the manufacturer commits to sole-sourcing. The presence of the other supplier affects a supplier's profit in a way that is akin to the suppliers bidding against each other for the manufacturer's business. In the presence of the other supplier, a high-reliability supplier would risk not winning the order if it pretends to have low reliability, given that the other supplier could be of a high reliability. This reduces the high-reliability supplier's incentive to pretend to be of low reliability. Hence, compared with the single supplier model, competition between suppliers in a two-supplier model causes the suppliers to earn smaller profits.

Competition and diversification can work against each other, and the manufacturer's preference over supplier competition and diversification depends on the degree of codependence between the causes of the suppliers' disruptions. We find that the manufacturer prefers low correlation between the the suppliers' disruption processes, when the benefit of diversification is large. In our model, because the manufacturer is the Stackleberg leader, who designs the allocation mechanism, the suppliers have no pricing power beyond making "participate/do not participate" decision. Hence, higher correlation across the suppliers' disruption processes does not increase the manufacturer's benefit from competition between the suppliers, but reduces its benefit from diversification, if it is used. Therefore, the manufacturer prefers less correlation across the suppliers' disruptions, in order to make diversification more valuable.

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