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Capacity Planning with Financial and Operational Hedging in Low-Cost Countries

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The authors of this paper outline a capacity planning problem in which a risk-averse firm reserves capacities with potential suppliers that are located in multiple low-cost countries. While demand is uncertain, the firm also faces multi-country foreign currency exposures. This study develops a mean-variance model that maximizes the firm's optimal utility and derives optimal utility and optimal decisions in capacity and financial hedging size. The authors show that when demand and exchange rate risks are perfectly correlated, a risk-averse firm, by using financial hedging, will achieve the same optimal utility as a risk-neutral firm. In this paper as well, a special case is examined regarding two suppliers in China and Vietnam. The results show that if a single supplier is contracted, financial hedging most benefits the highly risk-averse firm when the demand and exchange rate are highly negatively related. When only one hedge is used, financial hedging dominates operational hedging only when the firm is very risk averse and the correlation between the two exchange rates have become positive. With both theoretical and numerical results, this paper concludes that the two hedges are strategic tools and interact each other to maximize the optimal utility.

Key words: operational hedging, financial hedging, risk management, capacity planning

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1. Introduction

Outsourcing production to an offshore supplier can generate cost savings for North American companies. In the last decade, many companies in North America have moved substantial portions of their operations overseas in order to lower costs and improve profitability. However, although offshore outsourcing can provide significant cost reduction opportunities, it also exposes companies to various risks. Among these risks, foreign exchange risk is consistently considered to be the top concern of supply chain executives. In a study entitled The Economist Team (2009), the research team surveyed 500 global company executives responsible for risk management. The exchange rate uncertainty was ranked as the second most important risk factor next to demand uncertainty due to the economic recession in 2009. In addition, the executives ranked foreign exchange risk as their number one concern for the subsequent twelve months. For example, China has become the world's manufacturing factory in the last decade, but for a long time, the CNY exchange rate against the US dollar had been largely fixed. In 2010, the high volatility of the U.S. dollar and the possible appreciation of the Chinese Yuan (CNY) posed significant risks to many multi-national companies (MNCs) involved in offshore outsourcing and global trade. In a single year from 2010 to 2011, the CNY further appreciated 4.72% against the US dollar. Foreign exchange risk arises whenever manufacturers incur production costs in one country but are paid in the currency of a different country.

While some large companies tend to use financial hedging tools to mitigate the exchange rate risk, many companies have adopted operational hedging strategies by diversifying operations in more than one low-cost country such as Vietnam and India. By doing so, companies gain operational flexibility in their supply chains and are able to dynamically allocate capacity. When deployed effectively, such flexibility can help reduce the impact of shifts in currency values on costs, revenues, and the risk of not meeting demand. Considering the trend of outsourcing in low-cost countries, in this paper, we examine how operational hedging and financial hedging can help sustain cost advantages in low-cost countries, and the role that each hedge plays in mitigating demand and exchange rate risk. We intend to examine the benefits of sourcing from multiple low-cost countries by developing a two-stage general model in which a risk-averse firm makes contracts to reserve capacities with n suppliers located in n countries to meet uncertain demands in n countries. The risks of exchange rates and demand are the main concern of this study. We realize that there are other risks such as quality risk driven by information asymmetry, poor communication and lack of supplier capability, productivity uncertainty due to less productive facilities in low cost countries, and delivery risk due to suppliers misunderstanding of the deadline or overstatement of their capacity. While the general model developed in this paper can incorporate various risks, to obtain meaningful results, we focus on the uncertain exchange rates that directly affect the total expected cost because incorporating all the risks mentioned above may lead to a much more complex model and intractability in deriving analytical results. As Li and Kouvelis (1999) pointed out, lower cost ranks the highest among all the reasons that drives manufacturers to outsource.

Since it is difficult to evaluate the roles that operational and financial hedges each play in the general model, we then study a special case in which a company considers to contract one or two low-cost countries, that is, China and Vietnam.

In operations management literature, researchers focus on operational hedging models to relocate manufacturing bases, optimize supply chain networks and increase productivity in global operations. A typical example of operational hedging is geographic diversification of operational capacity. Van Mieghem (2008) points out that while it is important to have global sourcing, sufficient excess capacity in each location will provide a high level of operational flexibility that allows manufacturers to switch production among global sources as demand and exchange rates become more volatile. Although operational hedging is an approach commonly used to offset risks in demand and exchange rates, it is sometimes costly and irreversible because of expenses related to the resources. On the other hand, the benefits of financial hedging have not been explored thoroughly in the field of operations management. This is due to the fact that, traditionally, the exchange rate risks in most MNCs were managed by finance departments distinct from operations departments. As a result, the firms risk management was uncoordinated. This situation began to change with the introduction of the concept of Enterprise Risk Management (ERM) that integrates financial, operational, and other business risks within one framework. ERM provides a holistic view of risk that generalizes and perceives portfolio risk not simply as the sum of the individual risk elements. For example, Coldhard Steel Company, a US family-owned firm, faces operational risk because its employees are members of the local labor union. That labor relationship represents potential operational risk, and the firm is also exposed to foreign exchange risk due to significant sales in Latin America and Europe. Using ERM, Coldhard Steel formed a risk management committee headed by a chief financial officer with representatives from operations, human resources and marketing. The committee adopted a Value at Risk (VaR) approach to address portfolio risk (see Lam (2003)).

Our research makes the following contributions: (i) We develop a general model in which a risk-averse firm faces multi-country foreign currency exposures and demand uncertainties and derive the first-order conditions for the optimal utilities, capacities and financial hedging sizes. (ii) For the general model, we show that when the exchange rates and demands are perfectly correlated, the optimal capacities and utilities between a risk-averse and a risk-neutral firm are identical. This finding in the general model extends the results in Gaur and Seshadri (2005) and Ding et al. (2007a). The first-order conditions also demonstrate that optimal financial hedging is constructed on the basis of the expected operational profit, the firms risk attitude and the market risk premium. (iii) For the two-supplier case, we evaluate the effect of financial hedging when the operational hedging is or is not used and conclude the two hedges plays different roles. (iv) For the special case, we also show that financial hedging can partially substitute operational flexibility but play a role of complement to the total capacity when both hedges are present. This leads us to our final contribution: (v) by contracting suppliers in different low-cost countries, the operational hedging provides the firm a competitive edge by reducing production costs while the financial hedging helps the firm mitigate the adverse effects associated with fluctuations in the firms expected profit. Our findings enrich the research on outsourcing, capacity planning and the interface of operations and finance by providing managerial insights regarding how to use hedges to mitigate operational and financial risks.

The remainder of the paper is organized as follows: In the next section, we provide a brief review of the relevant literature. Section 3 introduces a general model and derives analytical results for the general case. Section 4 considers a special case that addresses the choice between suppliers in China and Vietnam. Both analytical and numerical results are provided. Section 5 summarizes the research and discusses future research directions. For the sake of concise writing, some of the proofs with technical details are presented in the companion appendix.

2. Literature Review

Few studies address the importance of linking operational hedging with financial hedging in an offshore setting. There are two streams of existing literature that are relevant to our research. The first stream studies operational hedging through inventory and capacity decisions in a global supply chain environment. The second stream focuses on the latest research trend that incorporates financial hedging into operational problems.

The value of operational hedging is first examined by Huchzermeier and Cohen (1996) who provide a dynamic programming framework to value the real option to shift production between countries due to currency fluctuations. When the switch-over costs are significant, due to economic and political factors such as exchange rates, inflation, taxes and tariffs, the optimal production allocation policy among the countries becomes a barrier policy that specifies the upper and lower barriers based on these factors (Dixit and Pindyck (1994), Dasu and Li (1997)). Kouvelis and Gutierrez (1997) investigate a "global newsvendor" problem in which a producer of "styled goods" sells goods to two markets (a primary or domestic market and a secondary market). They explicitly consider the effect of exchange rate uncertainty in production allocation decisions. In their attempt to optimally solve a Harvard Business School case entiled Applichem (HBS 9685051, 1986), which deals with the closure of some overseas plants due to cost inefficiency and expensive exchange rates, Lowe et al. (2002) propose a global production network to hedge exchange rate fluctuations. Allon and Van Mieghem (2010) consider a firm that has access to a responsive near-shore supplier (e.g., Mexico) and a low-cost, off-shore supplier (e.g., China). The firm determines sourcing and inventory policies to satisfy random demand over time.

While the above literature optimizes production quantity among geographically dispersed plants for risk-neutral decision makers, other research studies production without and with sourcing problems with risk-averse attitudes. Eeckhoudt et al. (1995) show that optimal capacity levels decrease with risk aversion for any concave utility function when a single source is considered. Agrawal and Seshadri (2000) investigate pricing and order quantity decisions in a single-period inventory model in which the retailer is risk-averse. Van Mieghem (2007) proposes the concept of a risk-averse newsvendor network that extends the classical model from a single facility to multi-location facilities. Chen et al. (2009) analyze a risk-averse newsvendor by using Conditional Value-at-Risk (CVaR) as the decision criterion. Li and Wang (2010) examine the impact of operational hedging by considering the trade-offs between an expensive domestic supplier and a low-cost country supplier. Their results show that under uncertain exchange rate and demand risks, both suppliers might be contracted in order to gain operational flexibility; however, as the risk-averse attitude increases, the total amount of capacity would be reduced.

Research on the relationship between operational hedging and financial hedging began with empirical studies. Based on a sample of US non-financial firms during the period 1996–1998, Allayannis et al. (2001) find that operational hedging is not an effective substitute for financial risk management. However, the more geographically dispersed a firm is, the more likely it is to use financial hedging. Pantzalis et al. (2001a) examine the impact of operational hedging on their exchange rate exposure based on the data of 220 US MNCs. They show that operational hedging is a significant determinant of exchange rate risk. Similarly, using a sample of 208 US MNCs drawn from the period $1994 - 1998$, Carter et al. (2001) conclude that MNCs with dispersed operating networks have lower levels of currency exposure. Carter et al. (2003) investigate the influence of both financial and operational hedging on foreign exchange rate exposure by the MNCs and find that both can effectively reduce foreign-currency exposure (exchange rate risks). Gleason et al. (2005) demonstrate that operational hedging and financial hedging are complements based on a sample of US high technology firms. Kim et al. (2006) show that operationally hedged firms use less financial hedging than their non-operationally hedged competitors. Chod et al. (2010) show that product flexibility (flexible capacity for producing two different products) and financial hedging tend to be complements (substitutes) when demands are positively (negatively) correlated.

On the theoretical side, Milgrom and Roberts (1995) adopt supermodular concepts to define complementarity between two elements. For example, they conclude that flexible capacity and the breadth of the product line are complements. Chowdhry and Howe (1999) find that if the total capacity level in two countries is fixed, operational hedging is necessary only when uncertainties are present in both exchange rate and demand. Gaur and Seshadri (2005) analyze how to mitigate inventory risks by using stock market instruments for the purpose of designing an optimal financial hedging contract to minimize the variance of profits. Caldentey and Haugh (2006) solve a corporate hedging problem under an incomplete market pricing approach that is mostly seen in the finance field. Ding et al. (2007b) consider a risk-averse firm that produces a product in-house and has to decide whether to sell the product in either a domestic or foreign market, given the fluctuations in demand and the exchange rate in the foreign country. The financial hedging portfolio consists of a linear combination of call and put options. Zhu and Kapuscinski (2006) consider a similar problem with a domestic and a foreign country. Although they model the problem as multi-stage, no inventory is allowed over stages, and capacity decisions are made only in the first period. Their results show that operational hedging dominates financial hedging. Chod et al. (2010) examine a risk-averse firm that produces two products and faces two risks: mismatch between demand and capacity, and profit uncertainty. The firm can use operational flexibility to mitigate the demand risk and financial hedging to cope with profit risk. Based on an exponential utility function, they find that the relationship between the two types of hedging depends on the correlation between the demands of these two products.

Our research differs from the previous literature on financial hedging in several respects. First, our basic model considers multiple foreign currency exposures, whereas earlier papers like Gaur and Seshadri (2005) and Ding et al. (2007b) focus on a single financial risk such as product price or one foreign country currency. Second, in addition to studying the impact of correlation between operational and financial risks on decision-making, as in early literature, we also examine whether the risk-averse attitude has adverse impact on the optimal solutions. While previous literature did not study the specific roles of the two hedges, our results show that the two hedges may play the role of strategic complements. As Lee and Lee (2007) point out: "Our knowledge and experience of operating and managing a supply chain that involves emerging economies, however, is still very limited." Hence, we believe the findings of our research will provide some guidelines and managerial insight into the current offshore trend in emerging economies.

3. General Model under Financial and Operational Risk Settings

In this section, we develop a general model to study how a risk-averse MNC uses operational and financial hedging to mitigate operational and financial risks by contracting n-supplier in n low-cost countries. The objective of the general model is to maximize a mean-variance (MV) utility function over a predefined strategic planning horizon. The analytical results from the general model are able to answer the following questions: (i) How much should the optimal financial hedges be contracted when n-country suppliers are involved? (ii) What would be the optimal utility and optimal capacity decisions with or without financial hedging? And, (iii) Would optimal utilities differ between risk-neutral and risk-averse firms when demand is perfectly correlated with exchange rates and market risk premium is zero?

3.1. Model and Properties

The following notation is used in our model (a superscript T on the up-right corner of a vector or a matrix denotes a vector (matrix) transpose):

- $\mathbf{K} = [K_1, K_2, ..., K_n]^T \in R^n$, where $K_i, i \in [1, \ldots, n]$, $\mathbf{K}$ is a vector that represents operational hedging decisions.
- $\mathbf{x} = [x_1, x_2, ..., x_n]^T \in R^n$ is an n-dimensional random variable vector. $\mathbf{x}$ denotes financial risk factors with each element representing one country's risk.
- $\mathbf{y} = [y_1, y_2, ..., y_n]^T \in R^n$ is an n-dimensional random variable vector. $\mathbf{y}$ denotes operational risk factors with each element representing one country's risk.
- $\pi_f(\cdot)$ is the total payoff function over time $[0, T]$ from financial hedging contracts. $\pi_o(\cdot)$ is the total profit function over time $[0, T]$ from operational activities; and $\pi_{of}(\cdot)$ is the total profit function over time $[0, T]$, which is the sum of operational and financial hedging profits.
- $U_o(\cdot)$ and $U_{of}(\cdot)$ are objective utility functions without and with financial hedging, respectively.

On the financial side, we denote financial risks by a random variable vector $\mathbf{x}$, where each x_i represents financial risk factors such as exchange rate risks, commodity (raw materials) price fluctuations, or stock market indices. On the operational side, we denote a random variable vector $\mathbf{y}$ as operational risks where each y_i may represent one type of risk such as demand and inventory risks. The strategic planning horizon spans between time $[0, T]$. We denote the firm's operational profit by $\pi_o = \pi_o(\mathbf{K}; \mathbf{x}, \mathbf{y})$ to reflect its dependency on financial and operational risk factors. It can be interpreted as the total profits (revenue minus costs) that are earned from operating activities over time $[0, T]$. To mitigate operating profit variability, the firm has another option, that is, to enter financial markets. Because the firm's operating profit, $\pi_o(\mathbf{K}; \mathbf{x}, \mathbf{y})$, depends partially on financial market variable vector $\mathbf{x}$, it is viable to use the financial market to partly hedge operating risks. Let $\pi_f = \pi_f(\mathbf{x})$ be the total payoff from financial hedging contracts. This comes from the transaction of financial forwards, futures, options, or certain exotic financial products.

The financial markets do not depend on the firms operational decision $\mathbf{K}$ or its related operational risks $\mathbf{y}$. In other words, we expect that the financial market is big enough to be immune from the operating policy of an individual firm. Thus, the firm's aggregate profit consists of two parts, one from operations or production activity and the other from transactions in the financial markets. We also assume that the financial markets are complete, which means the markets are arbitrage-free and every contingent claim is attainable (see Bingham and Kiesel (2004) or Shreve (2004) for further discussion). In the static hedging setting, we can denote $\pi_{f,0}$ and $\pi_{f,T}$ as the discounted payoffs from the financial markets at time 0 and T. Without loss of generality, we assume zero risk-free interest rate, but we could also adjust the parameters in $\pi_{f,T}$ by a constant, e^{-rT}, to reflect the time value. Then, the total payoff from the financial markets, π_f, can be expressed as the sum of the payoffs from time 0 to T,

$$\pi_f = \pi_{f,0} + \pi_{f,T} \text{ with } \pi_{f,0} = -\mathbb{E}\left[\xi\left(\pi_{f,T}\right)\right],$$

which leads to the following equation:

$$\mathbb{E}^N\left[\pi_f\right] = \mathbb{E}\left[\xi\pi_f\right] = \mathbb{E}\left[\xi\left(\pi_{f,0} + \pi_{f,T}\right)\right] = \pi_{f,0} + \mathbb{E}\left[\xi\pi_{f,T}\right] = 0 \tag{1}$$

where $\mathbb{E}^N[\cdot]$ is the expectation operator under risk-neutral measure N and ξ is called state price density (Duffie (2001)). (See the companion appendix for detailed explanation of ξ). We must remark that ξ is *always* ~~adaptable~~ **measurable** to $\mathbf{x}$ because ξ corresponds to the Radon-Nikodym derivative between physical measure and risk-neutral measure in the financial market. ξ can be expressed as

$$\xi = \frac{dN}{dP} = \exp\left(-\lambda W_T - \frac{1}{2}\lambda^2 T\right) \text{ with } \lambda = \frac{\mu_{\mathbf{x}} + r_f - r_d}{\sigma_{\mathbf{x}}},$$

where W_T is a standard Wiener process at time T, r_f and r_d are risk-free interest rates in the foreign and domestic countries, and $\mu_{\mathbf{x}}$ and $\sigma_{\mathbf{x}}$ are the drift rate and volatility of the exchange rate.

Thus, our model can be expressed as the following:

$$
\begin{aligned}
\max_{\mathbf{K},\pi_f} U_{of}\left(\mathbf{K},\pi_f\right) &= \mathbb{E}\left[\pi_{of}\left(\mathbf{K};\mathbf{x},\mathbf{y}\right)\right] - \frac{\gamma}{2} Var\left[\pi_{of}\left(\mathbf{K};\mathbf{x},\mathbf{y}\right)\right], \\
s.t.\ \ \pi_{of}\left(\mathbf{K};\mathbf{x},\mathbf{y}\right) &= \pi_o\left(\mathbf{K};\mathbf{x},\mathbf{y}\right) + \pi_f\left(\mathbf{x}\right), \\
\mathbb{E}\left[\xi\pi_f\left(\mathbf{x}\right)\right] &= 0,
\end{aligned} \tag{2}
$$

where $\pi_f\left(\mathbf{x}\right) = \pi_f$ is the payoff from the financial hedging contracts over two stages and a function of exchange rate that does not require demand information.

In the above model, the objective is a Mean-Variance (MV) utility, $U_{of}(\mathbf{K},\pi_f)$, that includes the total expected profit and its variance augmented by the risk-averse parameter γ. This is a two-stage model. In the first stage, the firm, facing uncertain exchange rates, $\mathbf{x}$, and demand, $\mathbf{y}$, makes capacity decisions of $\mathbf{K}$ along with financial hedging decisions. When the uncertainties are realized in the second stage, the firm makes its production and shipping decisions accordingly. $\pi_o(\mathbf{K};\mathbf{x},\mathbf{y})$ is the profit from the production and $\pi_f(\mathbf{x})$ is the payoff from the financial hedging. The first constraint states that with financial hedging, total profit, $\pi_{of}(\mathbf{K};\mathbf{x},\mathbf{y})$, equals the profit from the production plus the payoff from financial hedging contracts. Since Model (2) is the *planning* model of MNCs, both $\pi_o(\mathbf{K};\mathbf{x},\mathbf{y})$ and $\pi_{of}(\mathbf{K};\mathbf{x},\mathbf{y})$ are *projected* profits without and with financial hedging, respectively. According to Croushore (1993), the corporate profits are so volatile because of the business cycle, changes in the value of dollar against other currencies, inflation rate, and changes in tax laws. Thus, the projected profits are inevitably associated with variations which are

$$
\pi_o(\mathbf{K};\mathbf{x},\mathbf{y}) - \mathbb{E}[\pi_o(\mathbf{K};\mathbf{x},\mathbf{y})] \text{ and } \pi_{of}(\mathbf{K};\mathbf{x},\mathbf{y}) - \mathbb{E}[\pi_{of}(\mathbf{K};\mathbf{x},\mathbf{y})]
$$

respectively. A satisfactory projection is to ensure the above variations are not predictable in advance because if they were, it would be possible to create a better projection. This fact means that, by a variety of statistical methods, the projected profits would have the same magnitude of positive and negative variations. Therefore, we can assume that both $\pi_o(\mathbf{K};\mathbf{x},\mathbf{y})$ and $\pi_{of}(\mathbf{K};\mathbf{x},\mathbf{y})$ are symmetrically distributed around their mean values. If more than one suppliers are contracted, the firm is engaged in operational hedging and has the operational flexibility to switch production among multiple suppliers. The second constraint is previously introduced Equation (1) that includes the risk premium in the financial market.

Note that Model (2) suggests that the firm might be engaged in both financial hedging and speculative activities. In many articles, such as Anderson and Danthine (1981), Schwarz (2010), and Spiegel and Subrahmanyam (1992), researchers conclude that hedging and speculation motives are often mixed. The optimal solution should contain both hedging and speculative positions. However, both positions are fundamentally different on their intentions. Hedgers reduce their risk by taking an opposite position in the exchange rate market to what they are trying to hedge. The goal is to cause one effect to cancel out the opposite. Speculators, on the other hand, make bets on the market's direction in an attempt to profit from it. ~~It is fair to say that hedgers are seen as risk-averse and speculators are typically seen as risk-takers~~. Hedgers try to reduce the risks associated with uncertainty, while speculators make profit from market moves and hedging and speculating are mutually exclusive by their means of operation. For example, MNCs hedge against the exchange rate by buying and selling foreign currencies, future contracts, tangible assets that hold their value against paper currencies. A typical speculator of the exchange rate, however, is to hold currency, without owning gold or silver or other currency or asset that goes up when your holding currency goes down. Therefore, MNCs are risk-averse and they are protecting themselves from a price rise or decline with financial contracts and tangible assets. In other words, MNCs are hedgers rather than speculators. In the following Proposition, we propose an optimal financial hedging contract for model (2):

Proposition 1. *For any operational profit, $\pi_o = \pi_o(\mathbf{K}; \mathbf{x}, \mathbf{y})$, the corresponding optimal financial hedging contract is given by*

$$\pi_f^* = \mathbb{E}\left[\xi\left(\mathbb{E}\left[\pi_o|\,\mathbf{x}\right] + \frac{\xi}{\gamma}\right)\right] - \left(\mathbb{E}\left[\pi_o|\,\mathbf{x}\right] + \frac{\xi}{\gamma}\right), \tag{3}$$

and the resulting utility function becomes

$$U_{of} = \mathbb{E}\left[\xi\mathbb{E}\left[\pi_o|\,\mathbf{x}\right]\right] - \frac{\gamma}{2}\left\{Var\left[\pi_o\right] - \left(Var\left[\mathbb{E}\left[\pi_o|\,\mathbf{x}\right]\right] + Var\left[\frac{\xi}{\gamma}\right]\right)\right\} \tag{4}$$

The proof of Proposition 1 is provided in the companion appendix. In Proposition 1, the first item in the right-hand side of Equation (3), $\mathbb{E}\left[\xi\left(\mathbb{E}\left[\pi_o|\mathbf{x}\right]+\frac{\xi}{\gamma}\right)\right]$, is the total payoff that the firm obtains at time 0 by selling financial obligations (for example, a put option), while the second item, $\left(\mathbb{E}\left[\pi_o|\mathbf{x}\right]+\frac{\xi}{\gamma}\right)$, is what it owes to financial contract buyers at time T contingent on exchange rates $\mathbf{x}$. Proposition 1 states that the optimal financial contract is not only determined by operational profits, but is also affected by the financial market risk premium ξ and the firm's own risk attitude γ. **In particular, a speculative behavior would be reflected in equation** (3) **when** $\xi \neq 1$ **and consequently, the position** π_f^* **will explode when** $\gamma \to 0$**. Since MNCs are hedgers rather than speculators,** $\xi = 1$ **becomes the focus of this paper and we assume** $\xi = 1$ **from this point on**.

Note that Gaur and Seshadri (2005) and Ding et al. (2007b) also have similar findings to Proposition 1; with the former assuming the firm is firmly risk-averse and the latter assuming zero market risk premium. We know that Proposition 2 provides optimal solutions only under the condition that the objective function in Model (2) is concave or unimodal. Consider the general MV objective function without adopting financial hedging as below:

$$U_o(\mathbf{K}) = \mathbb{E}[\pi_o(\mathbf{K};\mathbf{x},\mathbf{y})] - \frac{\gamma}{2}Var[\pi_o(\mathbf{K};\mathbf{x},\mathbf{y})] \tag{5}$$

And, similarly, the MV objective with financial hedging is

$$U_{of}(\mathbf{K}) = \mathbb{E}[\pi_{of}(\mathbf{K};\mathbf{x},\mathbf{y})] - \frac{\gamma}{2}Var[\pi_{of}(\mathbf{K};\mathbf{x},\mathbf{y})] \tag{6}$$

In general, the MV objective is only piecewise concave, but not concave with respect to $\mathbf{K}$ (see Ahmed (2006)). In our research, the MV objectives (5) and (6) are indeed concave because the distributions of random variables, $\pi_o(\mathbf{K};\mathbf{x},\mathbf{y})$ and $\pi_{of}(\mathbf{K};\mathbf{x},\mathbf{y})$, are symmetrically distributed around their expected values, namely their mean values for every $\mathbf{K}$ as previously discussed. By (Ruszczynski and Shapiro 2003, Chapter 1), when random variables are symmetrically distributed, the MV objective would be concave.

We now demonstrate the differences in the optimal solutions in terms of optimal capacity levels and optimal utilities for three types of firms: (i) risk-neutral without financial hedging; (ii) risk-averse without financial hedging; and (iii) risk-averse with financial hedging in the following Proposition.

PROPOSITION 2. *(Property of Conditional Financial Information) The optimal capacity decisions for three different firms: a risk-neutral firm with operational hedging only; a risk-averse firm with operational hedging only, and a risk-averse firm with both financial and operational hedging, denoted by* $\mathbf{K}_{rn}^*$, $\mathbf{K}_o^*$, *and* $\mathbf{K}_{of}^*$, *all of which satisfy the following first-order conditions, respectively:*

$$\begin{aligned} \mathbb{E}\left[\frac{\partial \pi_o}{\partial \mathbf{K}}\right] &= 0, \\ \mathbb{E}\left[\frac{\partial \pi_o}{\partial \mathbf{K}}\right] - \gamma Cov\left(\frac{\partial \pi_o}{\partial \mathbf{K}}, \pi_o\right) &= 0, \\ \mathbb{E}\left\{\xi \mathbb{E}\left[\frac{\partial \pi_o}{\partial \mathbf{K}}\middle| \mathbf{x}\right] - \gamma Cov\left(\frac{\partial \pi_o}{\partial \mathbf{K}}, \pi_o \middle| \mathbf{x}\right)\right\} &= 0, \end{aligned} \tag{7}$$

and the optimal utility for the three different firms are, respectively,

$$\begin{aligned} U_{rn}^* &= \mathbb{E}\left[\pi_o\left(\mathbf{K}_{rn}^*\right)\right], \\ U_o^* &= \mathbb{E}\left[\pi_o\left(\mathbf{K}_o^*\right)\right] - \frac{\gamma}{2} Var\left[\pi_o\left(\mathbf{K}_o^*\right)\right], \\ U_{of}^* &= \mathbb{E}\left\{\xi \mathbb{E}\left[\pi_o\left(\mathbf{K}_{of}^*\right)\middle| \mathbf{x}\right] - \frac{\gamma}{2} Var\left[\pi_o\left(\mathbf{K}_{of}^*\right)\middle| \mathbf{x}\right]\right\} + \frac{\gamma}{2} Var\left[\frac{\xi}{\gamma}\right]. \end{aligned} \tag{8}$$

In particular, if market risk premium is zero, then for the third firm, the first-order condition and optimal utility are

$$\mathbb{E}\left\{\mathbb{E}\left[\frac{\partial \pi_o}{\partial \mathbf{K}}\middle| \mathbf{x}\right] - \gamma Cov\left(\frac{\partial \pi_o}{\partial \mathbf{K}}, \pi_o \middle| \mathbf{x}\right)\right\} = 0, \tag{9}$$

$$U_{of}^* = \mathbb{E}\left\{\mathbb{E}\left[\pi_o\left(\mathbf{K}_{of}^*\right)\middle| \mathbf{x}\right] - \frac{\gamma}{2} Var\left[\pi_o\left(\mathbf{K}_{of}^*\right)\middle| \mathbf{x}\right]\right\}, \tag{10}$$

and the optimal financial hedging contract is given by

$$\pi_f^*(\mathbf{x}) = \mathbb{E}\left[\pi_o\left(\mathbf{K}_{of}^*\right)\right] - \mathbb{E}\left[\pi_o\left(\mathbf{K}_{of}^*\right)|\mathbf{x}\right]. \tag{11}$$

Proposition 2 is derived based on the fact the above two-stage stochastic programming model is usually a complete fixed recourse problem, meaning: (i) The parameters such as capacity reservation cost in home country currency and production costs in low cost countries' currencies are fixed constants. And, (ii) the second stage problem will always be feasible under all the possible scenarios of $\mathbf{x}$ and $\mathbf{y}$. Consequently, the recourse function's first two moments are well-bounded to facilitate the mean variance risk-averse analysis. In reality, the firm may call operational and finance departments to cooperate with each other. That is, the former makes capacity decisions based on financial information provided, and the latter develops financial hedging portfolios based on the capacity decisions made by the operations department. Note that when the market risk premium in the financial market is zero, the first-order conditions (7) and (9) and the objective functions (8) and (10) are similar except that with financial hedging, the first-order condition and the objective function are conditional on the random variable of exchange rates.

In Ding et al. (2007b), the authors note that when demand and currency exchange rate are partially correlated, the interrelatedness of the operational hedging (e.g. capacity decisions) and the financial hedging is stronger, and a natural hedge of the demand risk might arise by using the appropriate financial hedging. We now extend their statement to show that when the demand and exchange rate risks are perfectly correlated (either positively or negatively), then future uncertainties can be completely hedged by using financial instruments, although, in reality, the two risks are uncorrelated or partially correlated. This is stated in the following corollary:

Corollary 1. *Under zero market risk premium, if exchange rate change* $\mathbf{x}$ *and demand* $\mathbf{y}$ *are perfectly correlated, the optimal capacity levels and the optimal utility of a risk-averse firm with financial hedging will be identical to those of a risk-neutral firm. That is,* $\mathbf{K}^*_{of} = \mathbf{K}^*_{rn}, U^*_{of} = U^*_{rn}$.

Proof. When $\mathbf{y}$ is perfectly correlated with $\mathbf{x}$,

$$Var\left[\pi_o|\mathbf{x}\right] = \mathbb{E}\left[\pi_o^2|\mathbf{x}\right] - \mathbb{E}\left[\pi_o|\mathbf{x}\right]^2 = 0.$$

Following (10), we obtain $U_{of}\left(\mathbf{K}, \pi_f\right) = \mathbb{E}\left[\pi_o\right]$. $\square$

Corollary 1 considers only the case of zero market risk premium. An example of perfect correlation is given using a linear model to combine both demand and exchange rates (e.g., $\mathbf{y} = a + b\mathbf{x}$). Corollary 1 suggests that the future net profit can be perfectly hedged by financial market instruments. Thus, the optimal utilities and optimal capacity levels are identical for both risk-averse and risk-neutral firms. Corollary 1 generalizes the finding in Gaur and Seshadri (2005) that obtained a similar finding, but the problem is limited to a single period and a single item.

In this section, we provide an n-country and an n-supplier general model and derive the optimal financial hedging contracts that are not limited by put or call options. We show that optimal utility and optimal capacity can be determined because the MV objectives are concave. Under zero market risk premium, with financial hedging, a risk-averse firm will have identical optimal objective value and capacity solutions as a risk-neutral firm when the demand and exchange rates are perfectly correlated.

4. A Special Case of Two Suppliers: Effect of Operational and Financial Hedges

As discussed in Section 1, many companies in North America have moved substantial portions of their operations to low-cost countries. While some companies contract only one low-cost country supplier and possibly use financial hedging tools to mitigate the exchange rate risk, many others diversify their operations in more than one low-cost country that may help reduce the risks of both demand and exchange rate. To examine the roles that each financial and operational hedging plays, we consider a special case of two suppliers in this section. In this special case, a company has been outsourcing a supplier in a low-cost country to satisfy the uncertain demand of a product in the domestic market but the exchange rate of the country where the supplier is located has started to appreciate, the company is considering whether to add one supplier located in another country whose exchange rate is relatively stable and favorable to the home country where the company is located. Due to the infrastructure already set up at the existing supplier site for quite a few years, the company does not want to cancel the contract with the current supplier but the company wonders when and whether it should add a supplier in another low-cost country when facing exchange rates and demand uncertainties. The objective of this special case is to examine when to contract a single supplier by employing financial hedging and when to contract both suppliers. We also like to explore the complementary roles between the two hedges. For ease of analysis and comparison, we make an assumption that the risk premium in the financial market is zero or $\xi = 1$

from this point on. This assumption is reasonable because the risk premium is typically positive and very small in the exchange-rate market (Biger and Hull (1983)). Foreign exchange markets, and markets in general, are efficient if market participants use all the information available to them in making transaction decisions. This assumption also helps us focus on the correlation between two exchange rates.

To illustrate the two supplier case, we assume a risk-averse US MNC firm that is already contracting a supplier in China and considers an option to add a supplier in Vietnam. In contrast to the appreciation of Chinese yuan, Vietnamese done (VND) has recently depreciated against the US dollar. Figures 1 and 2 show that the two exchange rates move in opposite directions against

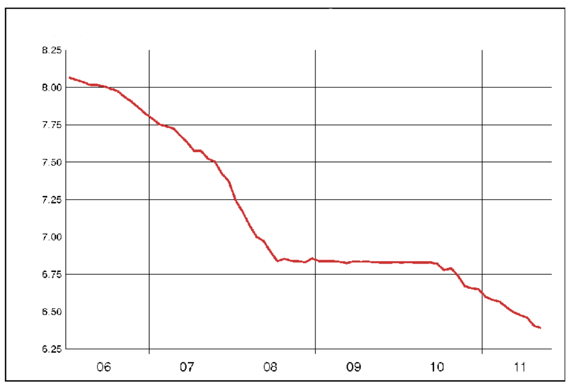


Figure 1 USD to 1 RMB Exchange Rate (Sept. 2010-Jan. 2011)

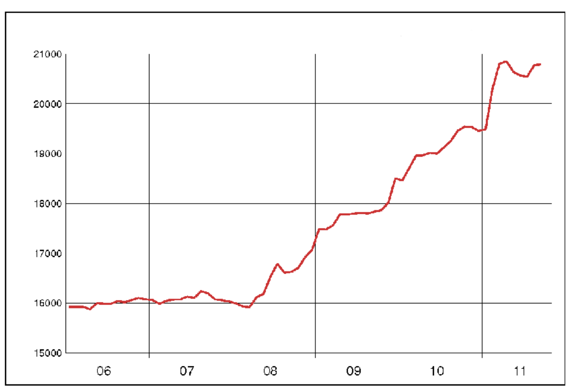


Figure 2 USD to 1 VND Exchange Rate (Oct. 2010-Jan. 2011)

the US dollar, and based on the data in the figures, we find they are actually negatively correlated by approximately 0.74. Obviously, if this trend continues, Vietnamese suppliers may gain considerable wage advantage over Chinese counterparts. However, Thanh and Dapice (2009) point out the inefficiency in infrastructure development and the lack of an efficient limited access to highway and freight rail systems in Vietnam which are the biggest problems hindering foreign producers when contracting with suppliers in Vietnam. For example, the authors state that, according to the World Bank, exporters in Vietnam pay domestic costs of US $669 to ship a 20-foot container from Vietnam, while it only costs Chinese exporters US $390. Therefore, we assume the MNC firm would not make a choice between the two suppliers in China and Vietnam and instead, the MNC firm would consider the supplier in Vietnam as an option. Naturally, this production and supplier contract problem gives rise to the following research questions:

1. What is the effect of financial hedging when a single supplier is contracted?
2. When should a risk-averse firm contract one supplier by using financial hedging and when to diversify the operations in two countries?
3. How would optimal utility and capacity change when both hedges are used? What happens to the operational flexibility? What are the roles of the two hedges?

To answer the above questions, we study four possibilities in Figure 3: (I) Contract an existing Chinese supplier with no financial hedging; (II) contract a Chinese supplier and use financial hedging; (III) contract two suppliers, in China and Vietnam, with no financial hedging; and (IV) contract two suppliers with financial hedging. Note that I is the base case, and comparing II and III provides the answer to question 1. Comparing III and IV provides the answers to questions 2 and 3. We denote US, China and Vietnam as countries 1, 2, and 3, respectively. The utility functions of the four alternatives are denoted by U_I, U_{II}, U_{III} and U_{IV} and the following figure provides the four cases:

Now we introduce new notation below:

- c_{j1} is the unit cost for production and shipping from country j $(j = 2, 3)$ in the country j's currency.

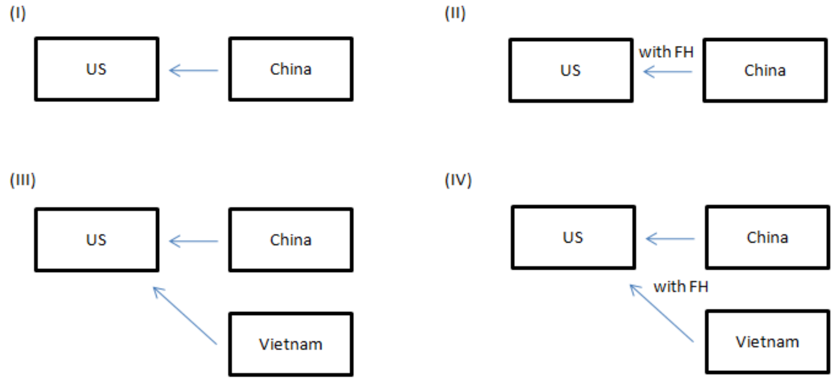


Figure 3 **Operational Hedging and Financial Hedging Strategies**

- c_k is the unit capacity reservation cost expressed in the home country currency and for simplicity, we assume c_k is identical in two suppliers' countries.
- p_1 is the unit selling price in the home country and is a constant in home country currency.
- $\rho_{\mathbf{xy}}$ is the correlation between exchange rate x and demand y in the home country.
- $s_{1j,0}$ is the exchange rate between the home currency and the currency in country j ($j = 2, 3$) at time 0.
- $s_{1j,T}$ is the exchange rate between the home currency and the currency in country j ($j = 2, 3$) at time T.

4.1. Benefits of Financial Hedging by Contracting a Single Supplier

In this subsection, we examine the impact of financial hedging on optimal solutions when only one supplier (e.g., Chinese supplier) is contracted, assuming demand rate and exchange rate are independent or correlated.

We recall that cases I and II refer to single supplier without and with financial hedging, and thus we may write the net profit for both cases at time T as below:

$$\pi_T = r_2 \min(y_1, K_2) \text{ where } r_2 = (p_1 - c_{21}x_{12})^+, \tag{12}$$

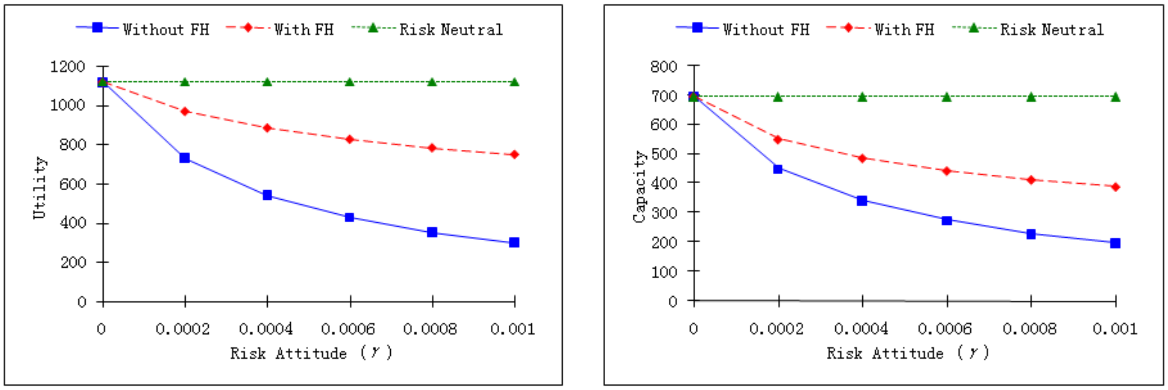
where K_2 is the capacity reserved with the Chinese supplier, and y_1 and x_{12} are the realized domestic demand and exchange rate, respectively. Note that the product is sold in a domestic market therefore p_1 is not affected by the exchange rate.

When domestic demand, y_1, and exchange rate, x_{12}, are mutually independent, the firm sells a put option with a market value at time 0 which is equal to the expected profit at time T. In Proposition 3 below, we further study the effect of risk attitude and financial hedging on optimal utility and capacity levels. Since the result is similar to Ding et al. (2007b), we provide financial contract size in the companion appendix. In the Proposition, we denote $K^*_{2,I}$, $K^*_{2,II}$, U^*_I and U^*_{II} as the optimal capacity level and utility for I and II, respectively. The variables $K^*_{2,rn}$ and U^*_{rn} are the optimal capacity and utility for the risk-neutral firm.

PROPOSITION 3. *If the demand and exchange rates are mutually independent and the corporate profits are symmetrically distributed, then: When the firm becomes more risk-averse, optimal capacity level and utility decrease, regardless of whether or not financial hedging is used. That is,* $K^*_{2,I}(\gamma)$, $K^*_{2,II}(\gamma)$, $U^*_I(\gamma)$ *and* $U^*_{II}(\gamma)$ *all decrease with* γ.

The proof is provided in the companion appendix. Proposition 3 extends the classical findings in Eeckhoudt et al. (1995) to the domain of financial hedging. That is, with or without financial hedging, as the firm becomes more risk-averse, optimal capacity level and utility decrease. Our numerical examples in Figure 4 illustrate the optimal solutions for risk-neutral and averse firms with or without financial hedging and use one horizontal line to represent the optimal capacity and utility level for the risk-neutral firm with $\gamma = 0$. Figure 4 shows that when demand and exchange rate are not correlated, in comparison to the risk-neutral firm, both utility and capacity decrease with risk attitude regardless financial hedging. However, with financial hedging, the decreases in utility and capacity are less than these of the case without financial hedging. This is a clear indication of the fact that financial hedging can reduce the foreign exchange rate exposure so that the risk-averse firm feels more protected. As a result, the firm is willing to reserve more capacity with suppliers.

Nevertheless, in Corollary 1, we prove that the optimal solutions can be identical between a risk-averse and a risk-neutral firm only when x_{12} and y_1 are perfectly correlated. Alternately, when the demand and exchange rate are correlated, it is difficult to provide a closed-form expression,

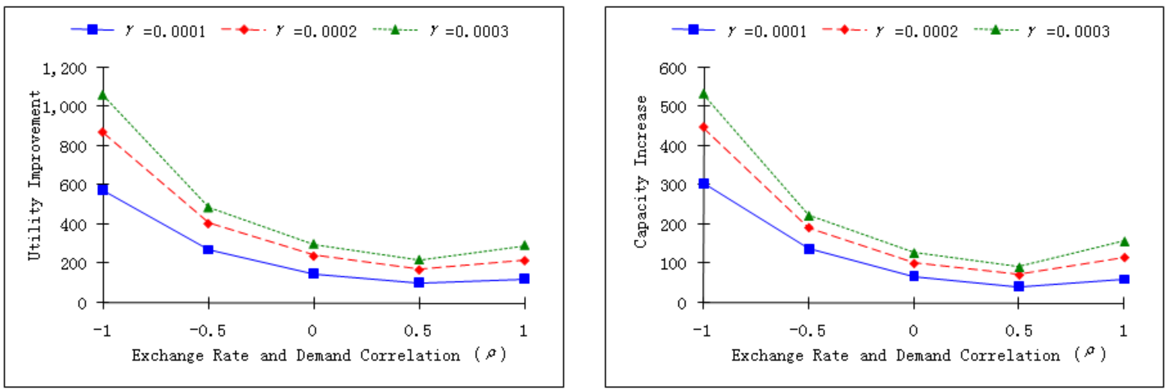


(a) Utility vs γ (b) K_2^* vs γ

Figure 4 The Dynamic of Optimal Capacity Reservation and Utility Level

and hence we present numerical results. In the numerical experiments, we assume x_{12} and y_1 follow a lognormal distribution. That is, x_{12} evolves following Geometric Brownian Motion and y_1 will be non-negative. Jointly, $x_{12,t}$ and $y_{1,t}$, $t \in [0,T]$ are multidimensional Geometric Brownian Motions with a constant instantaneous correlation of $\rho_{\mathbf{xy}}$. A total of $10,000$ pairs of the logarithms of the random demand and exchange rate changes are generated independently with $\mu_{x_{12}} = 0$, $\sigma_{x_{12}} = 1$, $\mu_{y_1} = \ln(1000)$, $\sigma_{y_1} = 1$. The values of $\rho_{\mathbf{xy}}$ are set in the range of $(-1, -0.9, ..., 1)$, and γ is set in the range of (0, 0.000001,...,0.001). Then, for each combination of $\rho_{\mathbf{xy}}$ and γ (a total of $21 \times 1001 = 21,021$ combinations), we obtain optimal solutions from equations (8) and (10), respectively, by using standard MatLab optimization procedures. The other parameters are set as follows: $p_1 = 12$, $c_{21} = 3$,$c_{K_2} = 5$.

We denote the utility improvement with financial hedging from I to II by $\Delta_{II-I}(\rho_{\mathbf{xy}}, \gamma) := U_{II}^* - U_I^*$, a function that depends on the correlation $\rho_{\mathbf{xy}}$ and risk attitude γ. We denote the corresponding capacity increase (decrease) due to using financial hedging as $K_{2,II}^* - K_{2,I}^*$. Figures 5(a) and (b) present the utility improvement and capacity increase with financial hedging assuming the demand and exchange rate are correlated. Recall that Figure 4 shows that when the demand and exchagne rate are independent to each other, financial hedging will benefit the firm by reducing exchange rate exposure, for risk-averse firms in particular. Thus, the above figures suggest another two observations. First, with financial hedging, utility and capacity of a risk-averse firm become large when demand and exchange rate is negatively correlated. This is because when demand decreases and the exchange appreciates, the financial hedging will help the risk-averse firm significantly reduce the exchange rate exposure. On the other hand, when demand increases and the exchange rate depreciates, the financial hedging is able to minimize the high volatility in the expected profit. Second, the utility improvement and capacity increases exhibit asymmetric U-shape curves with respect to $\rho_{\mathbf{xy}}$, which results from both the magnitude and the sign of $\rho_{\mathbf{xy}}$. This implies as the absolute value of $\rho_{\mathbf{xy}}$ increases, the net profit π_T in Equation (12) can be hedged more effectively so that hte benefit of financial hedging is further enhanced.



(a) $\Delta_{II-I}(\rho_{\mathbf{xy}}, \gamma)$ vs $\rho_{\mathbf{xy}}$ (b) $\left(K^*_{2,II} - K^*_{2,I}\right)$ vs $\rho_{\mathbf{xy}}$

Figure 5 Sensitivity Analysis on the Magnitude of Financial Hedging Effect – Single Supplier Case

In this section, we show that, with one supplier, the financial hedging is always an effective strategy to hedge against the risk of exchange rate and volatile expected profit. The gains from financial hedging are realized in the utility improvement and capacity reservation. The gains achieve their highest levels when demand and exchange rate are negatively correlated for a risk-averse firm.

4.2. Choice of Single-supplier and Two-supplier Strategies

In this section, we study the case of single supplier with financial hedging versus two suppliers without and with financial hedging. Pantzalis et al. (2001b) proxy the firm's ability to hedge against demand and exchange rate risks by two strategies: the "breadth" that is defined as outsourcing's spread across many foreign countries and the "depth" that is defined as the firm's concentration on one or a few foreign countries. In reality, we know small firms like the depth since using financial hedging is less expensive and large firms prefer the breadth because operational flexibility can be obtained by geographically-spread operations.

We now denote $\rho_{\mathbf{x}}$ as the correlation between x_{12} and x_{13}, with x_{12} and x_{13} as the exchange rate changes against US dollars in China and Vietnam. For the profit by contracting two suppliers, we may rewrite the profit function at time T as,

$$\begin{aligned} \pi_T &= \pi_T\left(K_2, K_3; x_{12}, x_{13}, y_1\right) \\ &= \left(p_1 - c_{31}x_{13}\right)^+ \min\left(y_1, K_3\right) + \left(p_1 - c_{21}x_{12}\right)^+ \min\left(\left(y_1 - K_3\right)^+, K_2\right) \\ &\quad + \left[\left(p_1 - c_{21}x_{12}\right)^+ - \left(p_1 - c_{31}x_{13}\right)^+\right]^+ \left[\min\left(y_1, K_3\right) - \min\left(\left(y_1 - K_2\right)^+, K_3\right)\right] \end{aligned} \tag{13}$$

The first and second terms are the net profits from Vietnam and China when Vietnam's net unit profit is higher. The third term is the adjustment to when China's net unit profit is higher.

To evaluate the benefits of contracting one supplier by using financial hedging, and contracting two suppliers by using operational hedging, we compare the utility improvements of $\Delta_{II-I}(\rho_{\mathbf{x}}, \gamma)$ and $\Delta_{III-I}(\rho_{\mathbf{x}}, \gamma)$, respectively, in Proposition 4, assuming the unit costs at both suppliers are equal. Note that both $\Delta_{II-I}(\rho_{\mathbf{x}}, \gamma)$ and $\Delta_{III-I}(\rho_{\mathbf{x}}, \gamma)$ are functions of $\rho_{\mathbf{x}}$ and γ.

PROPOSITION 4. *If the unit costs are identical for both China and Vietnam, then when the two exchange rates are perfectly positively correlated, the benefits of contracting a single supplier with financial hedging for a risk-averse firm are larger than those derived from contracting two suppliers with no financial hedging. For a risk-neutral firm, the benefit from operational hedging by contracting two suppliers is always higher than that from a single supplier with financial hedging. That is, (1)* $\Delta_{II-I}(1, \gamma) \geq \Delta_{III-I}(1, \gamma)$, *and (2)* $\Delta_{II-I}(\rho_{\mathbf{x}}, 0) \leq \Delta_{III-I}(\rho_{\mathbf{x}}, 0)$.

The proof is direct because both $\Delta_{III-I}(1, \gamma)$ and $\Delta_{II-I}(\rho_{\mathbf{x}}, 0)$ are equal to zero. In Proposition 4, the first inequality suggests that financial hedging is preferred when $\rho_{\mathbf{x}}$ is high, while the second inequality suggests that operational hedging is preferred when the risk attitude is low. Proposition 4 suggests that the risk-neutral firm usually prefers operational hedging to financial hedging. The reason is that the risk-neutral firm solely focuses on the expected profit. Figure 6 provides numerical results by comparing Cases II and III for general $\rho_{\mathbf{x}}$ and γ, and the results are consistent with Proposition 4. Figure 6 indicates that operational hedging seems superior to financial hedging

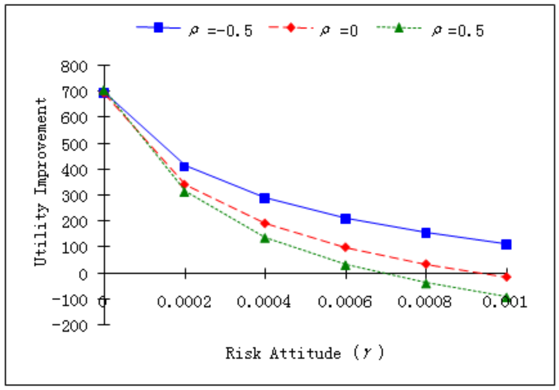


Figure 6 Comparison between Operational and Financial Hedging: $\Delta_{III-II}(\rho_{\mathbf{x}}, \gamma)$ **vs** γ

because the optimal utility of Case III, in most instances, is higher than that of Case II. However, when the firm becomes very risk-averse and the correlation between the two exchange rates approaches positive, financial hedging becomes superior to operational hedging. Figure 6 implies that both operational and financial hedging are important strategic tools with different orientations. The operational hedging creates more production flexibility and the financial hedging reduces the foreign currency exposures. When two exchange rates are negatively correlated, by contracting the supplier in Vietnam, the firm can shift the production for lower costs and pose competitive advantages. When the correlation is positive, the financial hedging suggest the risk-averse firm to secure its expected profit despite volatile exchange rates.

We conclude this section by proposing the following guidelines: for a risk-averse firm, when the exchange rates are negatively correlated, the firm should consider adding a supplier in Vietnam for lower costs due to depreciating Vietnam currency. However, if the exchange rates are positively correlated, the firm would adopt financial hedging at the existing supplier in China. If the firm is risk-neutral or close to risk-neutral, a two-supplier strategy seems superior to a single-supplier strategy with financial hedging.

4.3. The Roles of Financial and Operational Hedges

In this sub-section, we would like to achieve three goals. First we demonstrate the utility improvement by adding financial hedging to operational hedging. Second, we provide numerical results to illustrate that adding financial hedging might lead to lower operational flexibility. Finally, we show that the financial hedging and the total optimal capacity become strategic complements in most cases, with the exception of some conditions. To analytically prove the strategic complements between the total optimal capacity and the financial hedging, we examine a slightly different objective function and assume the financial hedging is applied to one country.

When the financial hedging is used for two suppliers, the financial options in home currency (e.g., US dollar) can be derived from (13) in the previous section and are described as below:

PROPOSITION 5. *When the firm considers both China and Vietnam as suppliers, the optimal financial hedging policy includes three options: (i) a put option* $\left(\frac{p_1}{c_{31}}s_{13,0} - s_{13,T}\right)^+$ *with notional amount* $\frac{c_{31}}{s_{13,0}}\mathbb{E}\left[\min\left(y_1, K_3\right)\right]$ *(VND); (ii) a put option* $\left(\frac{p_1}{c_{21}}s_{12,0} - s_{12,T}\right)^+$ *with notional amount* $\frac{c_{21}}{s_{12,0}}\mathbb{E}\left[\min\left(\left(y_1 - K_3\right)^+, K_2\right)\right]$ *(CNY); and (iii) an (exotic) option that corresponds to the real option to switch the production between two countries or* $\left\{\left(\frac{p_1}{c_{21}}s_{12,0} - s_{12,T}\right)^+ \frac{c_{21}}{s_{12,0}} - \left(\frac{p_1}{c_{31}}s_{13,0} - s_{13,T}\right)^+ \frac{c_{31}}{s_{13,0}}\right\}^+$ *with quantity* $\mathbb{E}\left[\min\left(y_1, K_3\right) - \min\left(\left(y_1 - K_2\right)^+, K_3\right)\right]$.

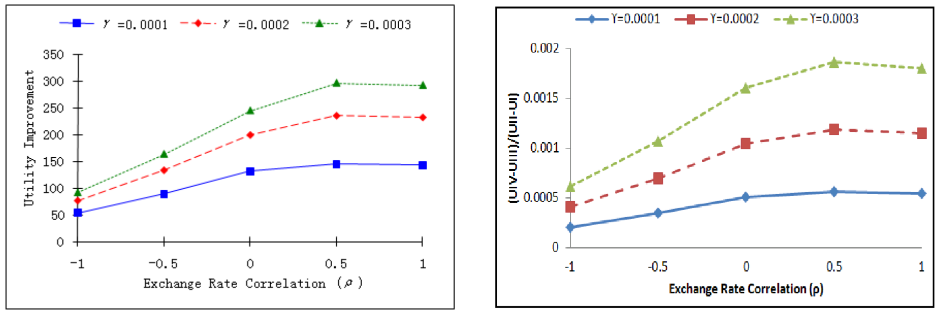
In Proposition 5, VND in (i) and CNY in (ii) are the abbreviations for Vietnamese dong and Chinese yuan. In the following Proposition, we show the optimal utility improvement from III to IV is always positive and we denote the improvement as $\Delta_{IV-III}(\rho_{\mathbf{x}}, \gamma) := U_{IV}^* - U_{III}^*$.

PROPOSITION 6. *The utility improvement of financial hedging equals*

$$\Delta_{IV-III}(\rho_{\mathbf{x}}, \gamma) = \frac{\gamma}{2} Var\left\{\mathbb{E}\left[\pi_T(\mathbf{K}_{rn}^*)|\mathbf{x}\right]\right\} + o(\gamma),$$

where $\mathbf{K}_{rn}^*$ *is a two-dimensional vector that represents the risk-neutral capacity levels for two suppliers, and the little-o notation means* $o(\gamma)/\gamma \to 0$ *as* $\gamma \to 0$.

Proposition 6 states that if the firm is slightly risk-averse (γ close to 0), the utility improvement increases with γ because the coefficient $\frac{1}{2} Var\left\{\mathbb{E}\left[\pi_T(\mathbf{K}_{rn}^*)|\mathbf{x}\right]\right\} > 0$. For large γs and any $\rho_{\mathbf{x}}$, we verify the claim through numerical experiments. Demand and exchange rates follow the same assumption as in the previous section and are lognormally distributed and independent from each other with



(a) $\Delta_{IV-III}(\rho_{\mathbf{x}},\gamma)$ vs $\rho_{\mathbf{x}}$ (b) $\dfrac{U_{IV}-U_{III}}{U_{II}-U_{I}}$ vs $\rho_{\mathbf{x}}$

Figure 7 Sensitivity Analysis on the Magnitude of Financial Hedging Effect – Two-supplier Case

$\mu_{y_1}=\ln(1000), \sigma_{y_1}=1$, $\sigma_{x_{12}}=\sigma_{x_{13}}=1$, $\mu_{x_{12}}=\mu_{x_{13}}=0$. However, the exchange rates x_{12} and x_{13} are correlated with $\rho_{\mathbf{x}}$. Other parameters are set at $p_1=12$, $c_{21}=3$, $c_{31}=2$, $c_{K_2}=c_{K_3}=5$. Here, we assume the unit cost of Vietnam is 67% of that of China (that is, \$2 vs. \$3) to illustrate the major difference in unit cost between the two suppliers.

Figure 7 (a) shows the optimal *utility improvement* from III to IV, and Figure 7 (b) provides the ratio of utility improvement from III to IV, $(U_{IV}-U_{III})$, over the utility improvement from I to II, $(U_{II}-U_{I})$. We make three observations by Figure 7. First, similar to the previous section, Figure 7(a) shows that as a firm becomes more risk-averse, the financial hedging effect becomes more significant in utility improvement, which is in line with Proposition 6. This observation implies that adopting financial hedging in addition to operational hedging helps the firm avoid financial problems caused by volatile exchange rate exposure, to the risk-averse firm in particular. Second, we notice that the utility improvement from using financial hedging becomes lower when $\rho_{\mathbf{x}}<0$ than that when $\rho_{\mathbf{x}}>0$. Our results demonstrate the degree of reduction in profit variances varies with $\rho_{\mathbf{x}}$. The explanation is as follows: When $\rho_{\mathbf{x}}$ is negative, variance of the net profit is not high because diversifying capacity locations has a natural hedge. In other words, the firm can effectively reserve capacity with the supplier of decreasing exchange rate. Thus financial hedging becomes less effective. Nevertheless, when $\rho_{\mathbf{x}}$ is positive, the effect of natural hedging is weakened so that financial hedging plays a role in controlling variances. Third, we observe that, in Figure 7 (b), the ratios of $\left(\frac{U_{IV}-U_{III}}{U_{II}-U_{I}}\right)$ are rather small with the maximum of 0.18%. This indicates that if the firm is already engaged in operational hedging, the utility improvement by using financial hedging, although positive, is rather marginal and much smaller in comparison to the effect of financial hedging when only one is used.

We now examine the effect of financial hedging on operational flexibility that is defined in Section 1: the excess capacity that allows manufacturers to switch production among global sources. Thus, we measure the degree of operational flexibility as below:

$$\text{Operational flexibility} = \frac{K_2^*}{K_3^*}.$$

The ratio increases with Chinese capacity. Chod et al. (2010) develop a similar ratio called product postponement flexibility, namely, the ability to postpone production decisions for two different products until demand is known.

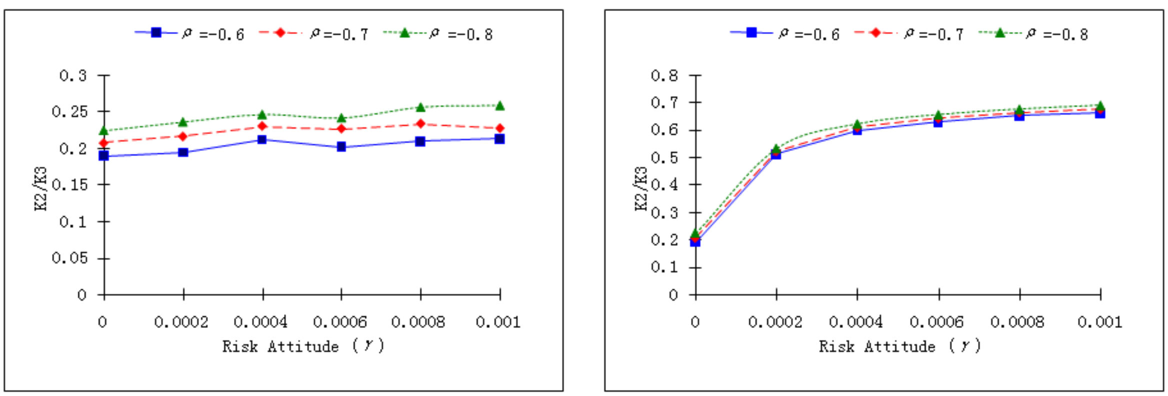
Following this definition, we now examine the effect of financial hedging on operational flexibility. Assume that the two exchange rates in both countries follow Bernoulli distributions and are negatively correlated. That is, x_{12} and x_{13} are negatively correlated with probability of 0.5 up to x_H and probability of 0.5 down to x_L. Demand also follows a Bernoulli distribution, with probability of 0.5 up to 1 and probability of 0.5 down to 0. The capacity reservation costs are identical between the two countries and are denoted as $c_{\mathbf{K}}$. However, production cost in Vietnam is lower than that in China, that is, $c_{31} < c_{21}$. Under the condition $1 - \frac{4c_{\mathbf{K}}}{p - c_{21}x_L} \geq 0$ (a necessary condition for the existence of operational hedging, which can be obtained during the solving process), we obtain the optimal capacity levels for III and IV from Proposition 2:

$$K^*_{2,III} = \frac{\left\{1 - \left(\frac{3c_{\mathbf{K}}}{p - c_{21}x_L} + \frac{c_{\mathbf{K}}}{p - c_{31}x_L}\right)\right\}}{p - c_{21}x_L}\frac{2}{\gamma}, K^*_{3,III} = \frac{\left\{1 - \left(\frac{c_{\mathbf{K}}}{p - c_{21}x_L} + \frac{3c_{\mathbf{K}}}{p - c_{31}x_L}\right)\right\}}{p - c_{31}x_L}\frac{2}{\gamma},$$
$$K^*_{2,IV} = \frac{\left\{1 - \frac{4c_{\mathbf{K}}}{p - c_{21}x_L}\right\}}{p - c_{21}x_L}\frac{2}{\gamma}, K^*_{3,IV} = \frac{\left\{1 - \frac{4c_{\mathbf{K}}}{p - c_{31}x_L}\right\}}{p - c_{31}x_L}\frac{2}{\gamma}.$$

It is clear that the degree of operational flexibility in IV is smaller than that in III:

$$\frac{K^*_{2,IV}}{K^*_{3,IV}} < \frac{K^*_{2,III}}{K^*_{3,III}}.$$

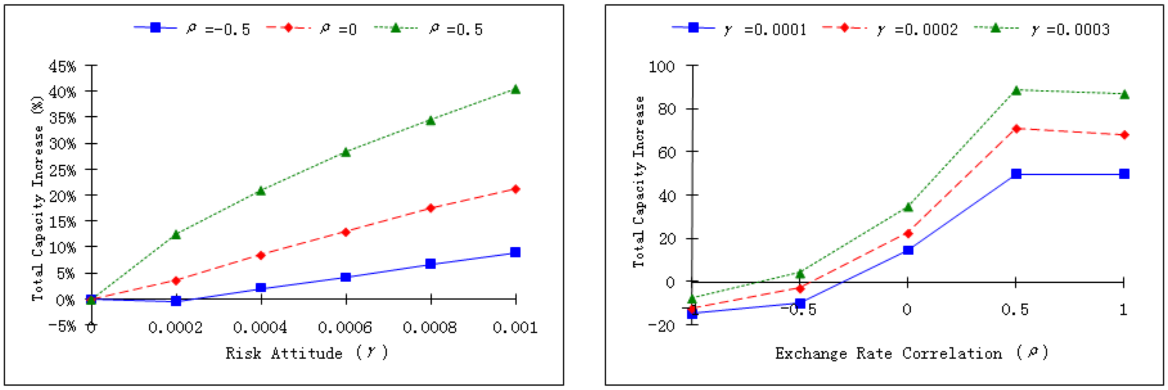
Thus, our analytical results show that adding financial hedging to operational hedging may reduce operational flexibility. We now denote the capacity differences by $(K^*_{2,IV} - K^*_{2,III})$ and $(K^*_{3,IV} - K^*_{3,III})$. Figure 8 (a) and Figure 8 (b) compare the operational flexibility for cases III and IV. Figure 8 (a) shows that with financial hedging, operational flexibility is below 25%, but Figure 8 (b) shows that without financial hedging, flexibility is above 50%, or close to 70%. Interestingly, without financial hedging, operational flexibility increases with risk-averse attitude, but with financial hedging, flexibility remains the same at about 25%. This implies that financial hedging may offset part of the operational flexibility and plays a partial substitute to the operational flexibility. In what follows, we investigate how the total optimal capacity and the financial hedging interact with each other and become complements.



(a) $\dfrac{K_{2,IV}}{K_{3,IV}}$ (b) $\dfrac{K_{2,III}}{K_{3,III}}$

Figure 8 Effects of Financial Hedging on Operational Flexibility: $K_{2,IV}/K_{3,IV}$ **vs.** $K_{2,III}/K_{3,III}$

To investigate the strategic complementary roles between optimal capacity and financial hedging, we follow the definition by Milgrom and Roberts (1995): Doing more of one thing increases the returns to doing more of another. This implies that adding financial hedging will increase total expected utility by reserving more optimal capacity. Figures 9 (a) and (b) provide clear indication that, by adding financial hedging to operational hedging, the total optimal capacity increases from III to IV which leads to increased optimal utility as demonstrated in Figures 7(a) and 7(b). However, it is difficult to verify the numerical results analytically. Thus, we consider a special case



(a) Total capacity v.s. γ (b) Total capacity v.s. $\rho_{\mathbf{x}}$

Figure 9 Total capacity change from III to IV with respect to γ and $\rho_{\mathbf{x}}$, respectively.

to analytically show that the optimal capacity and the financial hedging are strategic complements. That is, adding financial hedging to operational hedging always increases both optimal utility and total optimal capacity. For this special case, we assume the risk-averse firm adopts financial hedging only in one low-cost country. This assumption, in some cases, seems realistic. For example, between China and Vietnam, the firm might only be concerned about the appreciation of Chinese currency. Proposition 7 below illustrates such a special case.

Proposition 7. *We denote* $\mathbf{K}_o^*$ *and* $\mathbf{K}_{of}^*$ *as the optimal capacities for utilities* (5) *and* (6) *respectively. We assume that the corporate profits without and with financial hedging are symmetrically distributed. The financial hedging is applied to only one low-cost country. Then we conditionally have* $\mathbf{K}_{of}^* \geq \mathbf{K}_o^*$ *under the scenarios of uncertainty* $\hat{\mathbf{x}}$ *and* $\hat{\mathbf{y}}$ *such that*

$$\mathbb{E}\left[\pi_{of}\left(\mathbf{K};\hat{\mathbf{x}},\hat{\mathbf{y}}\right)\right] \geq \pi_{of}\left(\mathbf{K};\hat{\mathbf{x}},\hat{\mathbf{y}}\right) \ \textit{and} \ \mathbb{E}\left[\pi_{o}\left(\mathbf{K};\hat{\mathbf{x}},\hat{\mathbf{y}}\right)\right] \geq \pi_{o}\left(\mathbf{K};\hat{\mathbf{x}},\hat{\mathbf{y}}\right).$$

The proof of this is in the companion appendix.

In this section, we study the impact of adding financial hedging to the operational hedging and show that optimal utility always increases by adding financial hedging. Both analytical and numerical results demonstrate that adding financial hedging reduces operational flexibility but both operational and financial hedges are important tools in demand and exchange rate risk management. As demand and exchange rate become more volatile, the benefits attributed to the operational hedging and financial hedging increase. Nevertheless, a risk-averse firm would not substitute one hedging with another. These findings suggest that in order to achieve optimal utility, a risk-averse firm should use both hedges as strategic tools to mitigate risks when contracting multiple suppliers in low-cost countries.

In conclusion, the operational and financial hedges differ in two ways for a risk-averse firm. First, the financial hedging reduces the exchange rate exposure and the operational hedging may improve the firms expected profit by contracting suppliers in multi-locations. Second, by contracting suppliers in different low-cost countries, the operational hedging provides the firm a competitive edge by reducing production costs while the financial hedging helps the firm mitigate the adverse effects associated with fluctuations in the firms expected profit. As shown in this paper, although financial hedging may substitute part of operational flexibility, it increases the total optimal capacity as well as the optimal utility. Therefore, the enterprise risk management (ERM) in any MNC should integrate operational and financial hedges to mitigate both operational and financial risks. If the firm considers the two as pure substitutes, it may end up forgoing considerable benefits that two hedges could offer in a very volatile environment.

5. Conclusion

The objective of this research is to study the roles of operational and financial hedges and the impact of a risk-averse attitude on outsourcing decisions. We develop a multi-country-supplier model with the objective to maximize a risk-averse firm's utility by reserving optimal capacity levels with its suppliers. Financial and operational hedges are key tools that the risk-averse firm can employ to offset demand and exchange rate risks.

In this study, we first develop a general model that considers multiple suppliers. We derive the first-order conditions of the optimal solutions and show that optimal capacity and financial hedging decisions not only depend on the firm's risk attitude, but also on the risk premium in the financial market. We demonstrate that by using financial hedging, when the demand and exchange rates are perfectly correlated, the risk-averse firm could achieve the same optimal capacity and utility levels as a risk-neutral firm. Secondly, we examine a special case with two suppliers and present more analytical and numerical results. We show that the effect of financial hedging increases with risk aversion; therefore, a highly risk-averse firm should consider financial hedging over operational hedging. In addition, the effects of financial hedging and operational hedging depend on factors such as risk attitude and correlations among exchange rates. We find that financial hedging is most effective when the firm is very risk-averse and the exchange rate risks in two countries are positively correlated, but operational hedging is otherwise. Both analytical and numerical results illustrate that adding financial hedging to operational hedging might reduce operational flexibility. More importantly, in general, the optimal utility will be improved by reserving more optimal capacity if both hedges are used, with the exception of when the firm is only slightly risk-averse or when the two exchange rates are very negatively correlated.

This paper completes the study of the role of operational hedging and financial hedging in a two-stage model. Therefore, our future research will mainly focus on multi-stage or continuous-time models. Specifically, in one follow-up paper, we will examine the optimal capacity investment problem over an infinite time horizon with or without financial hedging.

Appendix. Technical Details and Proofs of Propositions

State price density ξ in equation (1) **Consider an abstract set Ω and its sigma algebra $\mathcal{F}$. A function $P:\mathcal{F}\rightarrow[0,1]$ is called a probability measure on $(\Omega,\mathcal{F})$. A sample space $(\Omega,\mathcal{F})$ equipped with a probability measure P is called a probability space and denoted $(\Omega,\mathcal{F},P)$.** In Equation (1), variable ξ can also be expressed as Radon-Nikodym derivative between physical measure P and risk-neutral measure N in the financial market. For example, if one domestic country and one foreign country exists in our model, by Girsanov theorem ((Musiela and Rutkowski 2005, Chapter 4)), ξ can be expressed as

$$\xi=\frac{dN}{dP}=\exp\left(-\lambda W_T-\frac{1}{2}\lambda^2T\right)\ \text{with}\ \lambda=\frac{\mu_{\mathbf{x}}+r_f-r_d}{\sigma_{\mathbf{x}}},$$

where W_T is a standard Wiener process at time T, r_f and r_d are risk-free interest rates in the foreign and domestic countries, and $\mu_{\mathbf{x}}$ and $\sigma_{\mathbf{x}}$ are the drift rate and volatility of the exchange rate. In the above equation, λ is referred to as the market price of risk or market risk premium (Hull (2008)). Since ξ is associated with λ, for simplicity, we assume ξ as a proxy for market risk premium λ. Note that when $\xi=1$, we say the risk premium in the financial market is zero.

Specifically, Inci and Lu (2007) mention that the Radon-Nikodym derivative is a currency risk premium in the financial currency market. Han (2010) makes similar comments in that the Radon-Nikodym derivative determines the possible risk measures.

Proof of Proposition 1 With financial hedging, the utility for any operational policy can be written as:

$$\begin{aligned} U_{of}(\mathbf{K},\pi_f) &= \mathbb{E}[\pi_o+\pi_f] - \frac{\gamma}{2}Var[\pi_o+\pi_f] \\ &= \mathbb{E}[\pi_o] - \frac{\gamma}{2}Var[\pi_o] + \mathbb{E}[\pi_f] - \frac{\gamma}{2}Var[\pi_f] - \gamma Cov(\pi_o,\pi_f). \end{aligned}$$

Then, maximizing $U_{of}(\mathbf{K},\pi_f)$ is equivalent to maximizing $\mathbb{E}[\pi_f] - \frac{\gamma}{2}Var[\pi_f] - \gamma Cov(\pi_o,\pi_f)$.

Consider any financial hedging contract π_f, whose payoff at time T is g, then

$$\pi_f = \mathbb{E}[\xi g] - g.$$

We will show that for $\forall g$, the corresponding expected utility is lower than that from financial hedging contract π_f^*, whose payoff at time T is $\mathbb{E}[\pi_o|\mathbf{x}] + \frac{\xi}{\gamma}$.

Let function Γ be

$$\begin{aligned} \Gamma(g) &= \mathbb{E}[\pi_f] - \frac{\gamma}{2}Var[\pi_f] - \gamma Cov(\pi_o,\pi_f) \\ &= \mathbb{E}[\mathbb{E}[\xi g] - g] - \frac{\gamma}{2}Var[\mathbb{E}[\xi g] - g] - \gamma Cov(\pi_o, \mathbb{E}[\xi g] - g) \\ &= \mathbb{E}[\xi g] - \mathbb{E}[g] - \frac{\gamma}{2}Var[g] + \gamma Cov(\pi_o, g) \\ &= Cov(\xi, g) - \frac{\gamma}{2}Var[g] + \gamma Cov(\pi_o, g). \end{aligned}$$

Then, if we denote $\phi := \mathbb{E}[\pi_o|\mathbf{x}] + \frac{\xi}{\gamma}$, the proof shows that

$$\Gamma(g) - \Gamma(\phi) \leq 0, \text{ for } \forall g.$$

The difference can be re-written as

$$\begin{aligned} \Gamma(g) - \Gamma(\phi) &= \Gamma(g-\phi) + \frac{\gamma}{2}[2Var[\phi] - 2Cov(g,\phi)] \\ &= Cov\left(\xi, g - \mathbb{E}[\pi_o|\mathbf{x}] - \frac{\xi}{\gamma}\right) - \frac{\gamma}{2}Var\left[g - \mathbb{E}[\pi_o|\mathbf{x}] - \frac{\xi}{\gamma}\right] + \gamma Cov\left(\pi_o, g - \mathbb{E}[\pi_o|\mathbf{x}] - \frac{\xi}{\gamma}\right) \\ &\quad + \frac{\gamma}{2}\left\{2Var[\mathbb{E}[\pi_o|\mathbf{x}]] + 2Var\left[\frac{\xi}{\gamma}\right] + 4Cov\left(\mathbb{E}[\pi_o|\mathbf{x}], \frac{\xi}{\gamma}\right) - 2Cov(g, \mathbb{E}[\pi_o|\mathbf{x}]) - 2Cov\left(g, \frac{\xi}{\gamma}\right)\right\} \\ &= -\frac{\gamma}{2}Var\left[g - \mathbb{E}[\pi_o|\mathbf{x}] - \frac{\xi}{\gamma}\right] + \gamma Cov\left(\pi_o, g - \mathbb{E}[\pi_o|\mathbf{x}] - \frac{\xi}{\gamma}\right) \\ &\quad + \gamma Var[\mathbb{E}[\pi_o|\mathbf{x}]] + \gamma Cov\left(\mathbb{E}[\pi_o|\mathbf{x}], \frac{\xi}{\gamma}\right) - \gamma Cov(g, \mathbb{E}[\pi_o|\mathbf{x}]) \end{aligned}$$

or

$$\begin{aligned}
\left\{\Gamma(g)-\Gamma(\phi)\right\}\frac{2}{\gamma} &= -Var\left[g-\frac{\xi}{\gamma}\right]-Var\left[\mathbb{E}\left[\pi_o|\mathbf{x}\right]\right]+2Cov\left(g-\frac{\xi}{\gamma},\mathbb{E}\left[\pi_o|\mathbf{x}\right]\right)\\
&\quad+2Cov\left(\pi_o,g-\mathbb{E}\left[\pi_o|\mathbf{x}\right]-\frac{\xi}{\gamma}\right)+2Var\left[\mathbb{E}\left[\pi_o|\mathbf{x}\right]\right]+2Cov\left(\mathbb{E}\left[\pi_o|\mathbf{x}\right],\frac{\xi}{\gamma}-g\right)\\
&= Var\left[\mathbb{E}\left[\pi_o|\mathbf{x}\right]\right]-Var\left[g-\frac{\xi}{\gamma}\right]+2Cov\left(\pi_o,g-\frac{\xi}{\gamma}\right)-2Cov\left(\pi_o,\mathbb{E}\left[\pi_o|\mathbf{x}\right]\right)\\
&= Var\left[\pi_o-\mathbb{E}\left[\pi_o|\mathbf{x}\right]\right]-Var\left[\pi_o-\left(g-\frac{\xi}{\gamma}\right)\right].
\end{aligned}$$

Let $\psi := g-\frac{\xi}{\gamma}$, then

$$\begin{aligned}
\left\{\Gamma(g)-\Gamma(\phi)\right\}\frac{2}{\gamma} &= \mathbb{E}\left[\left(\pi_o-\mathbb{E}\left[\pi_o|\mathbf{x}\right]\right)^2\right]-\mathbb{E}\left\{\left(\pi_o-\psi\right)^2\right\}+\left(\mathbb{E}\left[\pi_o-\psi\right]\right)^2\\
&= \mathbb{E}\left[\mathbb{E}\left[\pi_o|\mathbf{x}\right]^2\right]-2\mathbb{E}\left[\pi_o\mathbb{E}\left[\pi_o|\mathbf{x}\right]\right]+\mathbb{E}\left[2\pi_o\psi\right]-\mathbb{E}\left[\psi^2\right]+\left(\mathbb{E}\left[\pi_o-\psi\right]\right)^2\\
&= -\mathbb{E}\left\{\mathbb{E}\left[\pi_o|\mathbf{x}\right]^2-2\psi\mathbb{E}\left[\pi_o|\mathbf{x}\right]+\psi^2\right\}+\left(\mathbb{E}\left[\pi_o-\psi\right]\right)^2\\
&= -\mathbb{E}\left\{\left(\mathbb{E}\left[\pi_o|\mathbf{x}\right]-\psi\right)^2\right\}+\left\{\mathbb{E}\left[\mathbb{E}\left[\pi_o|\mathbf{x}\right]-\psi\right]\right\}^2\\
&= -Var\left[\mathbb{E}\left[\pi_o|\mathbf{x}\right]-\psi\right]\le 0.
\end{aligned}$$

So that

$$\Gamma(g)-\Gamma\left(\mathbb{E}\left[\pi_o|\mathbf{x}\right]+\frac{\xi}{\gamma}\right)\le 0 \text{ for } \forall g.$$

This proves the optimality of the financial hedging contract.

The objective utility becomes

$$\begin{aligned}
U_{of} &= \mathbb{E}\left[\pi_o\right]-\frac{\gamma}{2}Var\left[\pi_o\right]+\mathbb{E}\left[\pi_f^*\right]-\frac{\gamma}{2}Var\left[\pi_f^*\right]-\gamma Cov\left(\pi_o,\pi_f^*\right)\\
&= \mathbb{E}\left[\pi_o\right]-\frac{\gamma}{2}Var\left[\pi_o\right]+\mathbb{E}\left[\xi\mathbb{E}\left[\pi_o|\mathbf{x}\right]\right]-\mathbb{E}\left[\pi_o\right]+\frac{\mathbb{E}\left[\xi^2\right]-1}{\gamma}\\
&\quad-\frac{\gamma}{2}Var\left[\mathbb{E}\left[\pi_o|\mathbf{x}\right]+\frac{\xi}{\gamma}\right]+\gamma Cov\left(\pi_o,\mathbb{E}\left[\pi_o|\mathbf{x}\right]+\frac{\xi}{\gamma}\right)\\
&= \mathbb{E}\left[\xi\mathbb{E}\left[\pi_o|\mathbf{x}\right]\right]-\frac{\gamma}{2}Var\left[\pi_o\right]+\frac{Var\left[\xi\right]}{\gamma}\\
&\quad-\frac{\gamma}{2}Var\left[\mathbb{E}\left[\pi_o|\mathbf{x}\right]+\frac{\xi}{\gamma}\right]+\gamma Var\left(\mathbb{E}\left[\pi_o|\mathbf{x}\right]\right)+\gamma Cov\left(\mathbb{E}\left[\pi_o|\mathbf{x}\right],\frac{\xi}{\gamma}\right)\\
&= \mathbb{E}\left[\xi\mathbb{E}\left[\pi_o|\mathbf{x}\right]\right]+\gamma Var\left[\frac{\xi}{\gamma}\right]-\frac{\gamma}{2}Var\left[\pi_o\right]+\frac{\gamma}{2}Var\left[\mathbb{E}\left[\pi_o|\mathbf{x}\right]\right]-\frac{\gamma}{2}Var\left[\frac{\xi}{\gamma}\right]\\
&= \mathbb{E}\left[\xi\mathbb{E}\left[\pi_o|\mathbf{x}\right]\right]-\frac{\gamma}{2}\left\{Var\left[\pi_o\right]-\left(Var\left[\mathbb{E}\left[\pi_o|\mathbf{x}\right]\right]+Var\left[\frac{\xi}{\gamma}\right]\right)\right\}
\end{aligned}$$

□

Proof of Proposition 2 When the firm is risk-neutral, the objective function is equation (2) and $\gamma = 0$. That is,

$$U_{rn}^* = \mathbb{E}\left[\pi_o\left(\mathbf{K}_{rn}^*\right)\right]$$

Note that the function $-\pi_o(\mathbf{K}^*_{rn})$ may not be differentiable (e.g., piecewise linear and concave) and we, therefore, use the sub-gradient. Since the function U_{rn} is a concave function, it is trivial that the sub-gradients is defined for the function $-U_{rn}$. With a slight abuse of notation, we denote the $\partial(-U^*_{rn}(\mathbf{K}))$ as the sub-differential which is a set of all the sub-gradient at point $\mathbf{K}$ and $\frac{\partial(-U^*_{rn})}{\partial \mathbf{K}}$ is one sub-gradient to this very set. When we assume for every scenario, $|\pi_o(\mathbf{K}^*_{rn})| < \infty$ which implies we can obtain a bounded U^*_{rn}, the FOC condition is:

$$\frac{-\partial U_{rn}}{\partial \mathbf{K}} = -\frac{\partial}{\partial \mathbf{K}}\mathbb{E}[\pi_o] = \mathbb{E}\left[-\frac{\partial}{\partial \mathbf{K}}\left(\pi_T - c^T_{\mathbf{K}}\mathbf{K}\right)\right] = 0 \Rightarrow \mathbb{E}\left[-\frac{\partial \pi_T}{\partial \mathbf{K}}\right] = -c_{\mathbf{K}} \in \partial(-U^*_{rn}).$$

When the risk-averse firm uses only operational hedging, the objective function is given by equation (2) and the FOC condition is:

$$\begin{aligned}
\frac{\partial U_o}{\partial \mathbf{K}} &= \frac{\partial}{\partial \mathbf{K}}\left\{\mathbb{E}[\pi_T] - c^T_{\mathbf{K}}\mathbf{K} - \frac{\gamma}{2}Var[\pi_T]\right\} \\
&= \mathbb{E}\left[\frac{\partial \pi_T}{\partial \mathbf{K}}\right] - c_{\mathbf{K}} - \frac{\gamma}{2}\frac{\partial}{\partial \mathbf{K}}\left\{\mathbb{E}\left[\pi_T^2\right] - \mathbb{E}[\pi_T]^2\right\} \\
&= \mathbb{E}\left[\frac{\partial \pi_T}{\partial \mathbf{K}}\right] - c_{\mathbf{K}} - \frac{\gamma}{2}\left\{\mathbb{E}\left[2\pi_T\frac{\partial \pi_T}{\partial \mathbf{K}}\right] - 2\mathbb{E}[\pi_T]\,\mathbb{E}\left[\frac{\partial \pi_T}{\partial \mathbf{K}}\right]\right\} \\
&= \mathbb{E}\left[\frac{\partial \pi_T}{\partial \mathbf{K}}\right] - c_{\mathbf{K}} - \gamma Cov\left(\frac{\partial \pi_T}{\partial \mathbf{K}}, \pi_T\right) = 0 \rightarrow 0 \in \partial(-U^*_o).
\end{aligned}$$

When the firm adopts both operational and financial hedging, the FOC condition is given by Proposition 2. The objective function is immediate from equation (4) by using the law of total variance: $Var[\mathbf{y}] = \mathbb{E}[Var[\mathbf{y}|\mathbf{x}]] + Var(\mathbb{E}[\mathbf{y}|\mathbf{x}])$.

Notice that when $Var[\xi/\gamma]$ is not a function of $\mathbf{K}$, then the first-order condition can be obtained similarly.

□

On Financial Contract Size The following analysis defines financial hedging when domestic demand y_1 and exchange rate x_{12} are mutually independent.

In Case II, if the demand and exchange rates are mutually independent, the optimal financial hedging is to sell a put option at exercise price $\frac{p_1}{c_{21}}s_{12,0}$, with the notional amount equivalent to $\frac{c_{21}}{s_{12,0}}\mathbb{E}\{\min(y_1, K_2)\}$ in Chinese yuan.

From equation (11) in Section 3,

$$\begin{aligned}
\pi_f &= \left\{\mathbb{E}[p_1/c_{21} - x_{12}]^+ - (p_1/c_{21} - x_{12})^+\right\} c_{21}\mathbb{E}[\min(y_1, K_2)] \\
&= \mathbb{E}\left[\left(\frac{p_1}{c_{21}}s_{12,0} - s_{12,T}\right)^+\right]\frac{c_{21}}{s_{12,0}}\mathbb{E}\{\min(y_1, K_2)\} - \left(\frac{p_1}{c_{21}}s_{12,0} - s_{12,T}\right)^+\frac{c_{21}}{s_{12,0}}\mathbb{E}\{\min(y_1, K_2)\}.
\end{aligned}$$

Proof of Proposition 3 Given $\forall\ \gamma_1, \gamma_2$, such that $0 \le \gamma_1 \le \gamma_2$. First, consider the case with financial hedging. Let $U_{II}(K_2;\gamma_1)$ and $U_{II}(K_2;\gamma_2)$ be the utility functions with parameter γ_1 and γ_2, respectively. From equation (9),

$$\frac{\partial U_{II}(K_2;\gamma_1)}{\partial K_2} - \frac{\partial U_{II}(K_2;\gamma_2)}{\partial K_2} = (\gamma_2 - \gamma_1)\,\mathbb{E}\left[Cov\left(\frac{\partial}{\partial K_2}\pi_T(K_2;\mathbf{x},\mathbf{y}),\pi_T(K_2;\mathbf{x},\mathbf{y})\middle|\,\mathbf{x}\right)\right] \ge 0,$$

where $\mathbb{E}\left[Cov\left(\frac{\partial}{\partial K_2}\pi_T,\pi_T\middle|\,\mathbf{x}\right)\right] \ge 0$ is obtained from Theorem 236 of Hardy et al. (1964). Note that, both corporate profits $\pi_o(\mathbf{K};\mathbf{x},\mathbf{y})$ and $\pi_{of}(\mathbf{K};\mathbf{x},\mathbf{y})$ are symmetrically distributed, both $U_{II}(K_2;\gamma_1)$ and $U_{II}(K_2;\gamma_2)$ are concave with respect to capacity K_2; therefore, the inequality implies that $K^*_{2,II}(\gamma_1) \ge K^*_{2,II}(\gamma_2)$.

As for the utility,

$$\begin{aligned} U^*_{II}(K^*_2;\gamma_1) - U^*_{II}(K^*_2;\gamma_2) &= \int_0^{K^*_2(\gamma_1)} \frac{dU_{II}(K_2;\gamma_1)}{dK_2}dK_2 - \int_0^{K^*_2(\gamma_2)} \frac{dU_{II}(K_2;\gamma_2)}{dK_2}dK_2 \\ &= \int_0^{K^*_2(\gamma_2)}\left[\frac{dU_{II}(K_2;\gamma_1)}{dK_2} - \frac{dU_{II}(K_2;\gamma_2)}{dK_2}\right]dK_2 + \int_{K^*_2(\gamma_2)}^{K^*_2(\gamma_1)} \frac{dU_{II}(K_2;\gamma_1)}{dK_2}dK_2 \\ &\ge 0. \end{aligned}$$

□

Proof of Proposition 6 Applying a Taylor expansion

$$\Delta_{IV-III}(\gamma) = \Delta_{IV-III}(0) + \left.\frac{d\Delta_{IV-III}}{d\gamma}\right|_{\gamma=0}\gamma + o(\gamma) = \left.\frac{d\Delta_{IV-III}}{d\gamma}\right|_{\gamma=0}\gamma + o(\gamma)$$

where $\Delta_{IV-III}(0) = 0$ and we need to know $\left.\frac{d\Delta_{IV-III}}{d\gamma}\right|_{\gamma=0}$.

From equations (8) and (10),

$$\Delta_{IV-III}(\gamma) = U^*_{IV} - U^*_{III} = \left\{\mathbb{E}[\pi_o(K^*_{IV})] - \frac{\gamma}{2}\mathbb{E}[Var[\pi_o(K^*_{IV})|\,\mathbf{x}]]\right\} - \left\{\mathbb{E}[\pi_o(K^*_{III})] - \frac{\gamma}{2}Var[\pi_o(K^*_{III})|\,\mathbf{x}]\right\}$$

where $K^*_{IV}(\gamma)$ and $K^*_{III}(\gamma)$ depend on γ. Let $\Delta_{IV-III}(\gamma) = \Delta_{IV-III}(\gamma;K^*_{III},K^*_{IV})$ to use the total derivative,

$$\begin{aligned} \left.\frac{d}{d\gamma}\Delta_{IV-III}(\gamma)\right|_{\gamma=0} &= \left\{\frac{\partial}{\partial\gamma}\Delta_{IV-III}(\gamma;K^*_{III},K^*_{IV}) + \frac{\partial\Delta_{IV-III}}{\partial K^*_{III}}\frac{dK^*_{III}}{d\gamma} + \frac{\partial\Delta_{IV-III}}{\partial K^*_{IV}}\frac{dK^*_{IV}}{d\gamma}\right\}_{\gamma=0} \\ &= \frac{1}{2}\left\{Var[\pi_o(K^*_{III})] - \mathbb{E}[Var[\pi_o(K^*_{IV})|\,\mathbf{x}]]\right\}_{\gamma=0} \\ &= \frac{1}{2}\left\{Var[\pi_o(\mathbf{K}^*_{rn})] - \mathbb{E}[Var[\pi_o(\mathbf{K}^*_{rn})|\,\mathbf{x}]]\right\} \\ &= \frac{1}{2}Var\left\{\mathbb{E}[\pi_o(\mathbf{K}^*_{rn})|\,\mathbf{x}]\right\}. \quad \square \end{aligned}$$

Proof of Proposition 7 Since π_f is actually a function of $\mathbf{K}$, $\mathbf{x}$ and the random factor $\mathbf{x}$ is removed by expectation; therefore, the utility functions become functions with respect to $\mathbf{K}$. The utilities in (5) and (6) can thus be re-formulated as follows:

$$\max_{\mathbf{K}}\ U_o(\mathbf{K}) = \mathbb{E}[\pi_o(\mathbf{K};\mathbf{x},\mathbf{y})] - \frac{\gamma}{2}\mathbb{E}\left\{([\mathbb{E}[\pi_o(\mathbf{K};\mathbf{x},\mathbf{y})] - \pi_o(\mathbf{K};\mathbf{x},\mathbf{y})]^+)^2\right\}. \tag{14}$$

$$\max_{\mathbf{K}}\ U_{of}(\mathbf{K}) = \mathbb{E}\left[\pi_{of}(\mathbf{K};\mathbf{x},\mathbf{y})\right] - \frac{\gamma}{2}\mathbb{E}\left\{(\left[\mathbb{E}\left[\pi_{of}(\mathbf{K};\mathbf{x},\mathbf{y})\right] - \pi_{of}(\mathbf{K};\mathbf{x},\mathbf{y})\right]^+)^2\right\} \tag{15}$$

where $(a)^+ := \max\{a, 0\}$. Note that although the above objectives in (15) and (14) differ from (2), they are indeed concave with respect to $\mathbf{K}$ in Ahmed (2006). When both corporate profits $\pi_o(\mathbf{K};\mathbf{x},\mathbf{y})$ and $\pi_{of}(\mathbf{K};\mathbf{x},\mathbf{y})$ are symmetrically distributed, both objectives coincide with their MV counterparts according to Ruszczynski and Shapiro (2003). Therefore, we are still pursuing risk-averse decisions by the MV utility.

First, we assume that domain of the objective is compact and the objective function is continuous. Therefore, it has the Lipschitz property and the integration becomes exchangeable. Second, we need to assume the differentiability. Of course, neither the function $\mathbb{E}(\mathbb{E}[\pi_o(\mathbf{K};\mathbf{x},\mathbf{y})] - \pi_o(\mathbf{K};\mathbf{x},\mathbf{y}))^+]$ nor $\mathbb{E}(\mathbb{E}[\pi_{of}(\mathbf{K};\mathbf{x},\mathbf{y})] - \pi_{of}(\mathbf{K};\mathbf{x},\mathbf{y}))^+]$ could be differentiable. As a solution, we need to adopt the sub-differential discussion which only complicates the proof by set arguments. Thus, in order to present the idea in a concise way, without loss of generality, we can show the proof by relaxing the problem to be differentiable.

By the definition of $\mathbf{K}_o^*$, we have $\dfrac{\partial U_o(\mathbf{K}^*)}{\partial K_i} = 0, i = 1, \ldots, n$. When the firm places financial hedging at the ith low-income country *only*, the

$$\pi_{of}(\mathbf{K};\mathbf{x},\mathbf{y}) := \pi_o(\mathbf{K};\mathbf{x},\mathbf{y}) + \pi_f(\mathbf{x}),\ \mathbb{E}[\pi_{of}(\mathbf{K};\mathbf{x},\mathbf{y})] = \mathbb{E}[\pi_o(\mathbf{K};\mathbf{x},\mathbf{y})] \tag{16}$$

where $\pi_f(\mathbf{x})$ is the financial payoff function. In our problem, at a given exchange rate realization $\mathbf{x}$, the $\pi_f(x)$ is a concave function with respect to $\mathbf{K}$ when the company is to hedge against the financial risk rather than speculating. Thus, if for any $\hat{\mathbf{x}}, \hat{\mathbf{y}}$ such that $\pi_{of}(\mathbf{K};\hat{\mathbf{x}},\hat{\mathbf{y}}) \leq \mathbb{E}[\pi_{of}(\mathbf{K};\hat{\mathbf{x}},\hat{\mathbf{y}})]$, we have

$$\pi_f(\hat{\mathbf{x}}) \geq 0, \tag{17}$$

then $\dfrac{\partial \mathbb{E}[\pi_o(\mathbf{K};\hat{\mathbf{x}},\hat{\mathbf{y}})]}{\partial K_i} = \dfrac{\partial \mathbb{E}[\pi_{of}(\mathbf{K};\hat{\mathbf{x}},\hat{\mathbf{y}})]}{\partial K_i}$ and $(\mathbb{E}[\pi_{of}(\mathbf{K};\hat{\mathbf{x}},\hat{\mathbf{y}})] - \pi_{of}(\mathbf{K};\hat{\mathbf{x}},\hat{\mathbf{y}}))^+ \leq (\mathbb{E}[\pi_o(\mathbf{K};\hat{\mathbf{x}},\hat{\mathbf{y}})] - \pi_o(\mathbf{K};\hat{\mathbf{x}},\hat{\mathbf{y}}))^+$. Since $\pi_f(\hat{\mathbf{x}})$ is indeed a linear function of $\mathbf{K}$ with positive slope at any given $\hat{\mathbf{x}}$, which satisfies (17), then we have

$$\frac{\partial(\mathbb{E}[\pi_{of}(\mathbf{K};\hat{\mathbf{x}},\hat{\mathbf{y}})] - \pi_{of}(\mathbf{K};\hat{\mathbf{x}},\hat{\mathbf{y}}))^+}{\partial K_i} \leq \frac{\partial(\mathbb{E}[\pi_o(\mathbf{K};\hat{\mathbf{x}},\hat{\mathbf{y}})] - \pi_o(\mathbf{K};\hat{\mathbf{x}},\hat{\mathbf{y}}))^+}{\partial K_i} \tag{18}$$

Therefore,

$$\frac{\partial \mathbb{E}[U_{of}(\mathbf{K};\hat{\mathbf{x}},\hat{\mathbf{y}})]}{\partial K_i} \geq \frac{\partial \mathbb{E}[U_o(\mathbf{K};\hat{\mathbf{x}},\hat{\mathbf{y}})]}{\partial K_i} = 0$$

Since both U_o and U_{of} are concave functions, and $\dfrac{\partial U_o(\mathbf{K}^*)}{\partial K_i} = 0, i = 1, \ldots, n$, we obtain $\mathbf{K}_o^* \leq \mathbf{K}_{of}^*$ for this special case.

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