Global Supply Chain Network Competition under Exchange Rate Uncertainty

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Abstract: In this paper, we analyze the impact of foreign exchange uncertainty on global supply chain networks. We develop a variational inequality model that considers multiple competitive multinational firms who make decisions regarding procurement, global production, product allocation, transportation, and sales of the products. Our computational studies revealed interesting managerial insights regarding the operation strategies of supply chain networks under exchange rate uncertainty as well as the impacts of such strategies on the firms' profits and risks.

1. Introduction

Over the past decade, globalization has reshaped supply chains into complex networks that connect suppliers, production facilities, distribution facilities, and demand markets located in multiple countries. For instance, Samsung, the electronic producer headquartered in Korea, operates more than ninety production, engineering, distribution, and sales subsidies in all continents except Antarctic. The globalization of supply chain networks has not only lowered the production and material costs but also helped the multinational firms access the fast growing markets in emerging economies around the world. For example, in 2010, General Motors Co.'s first-half sales in China surpassed those in the U.S. for the first time which helped GM make $2.2B profit in the first two quarters of 2010 after posting $ 4.3B losses in 2009.

However, while multinational firms enjoy the benefits of the supply chain globalization, they are also exposed to various risks arising from global operations and international trades including: foreign exchange risk, production disruption risk, political risk, quality risk, etc. The focus of our paper is the impact of the foreign exchange risk which has been consistently considered to be on the list of top concerns of supply chain executives. For instance, a study conducted by The Economist surveyed 500 multinational firm executives who are responsible for risk management, and showed that exchange rate uncertainty was ranked as the second most important risk factor in 2009 and the number one risk concern in 2010 (The Economist Intelligent Unit, 2009). Moreover, the rising volatility of the euro and possible appreciation of the Chinese yuan have caused significant risks to many supply chain firms involved in global operations and international trades.

In the literature of supply chain risk management various issues related to the foreign exchange risk have been examined by researchers. Huchzermeier and Cohen (1996) the value of operational flexibility of global supply chains under exchange rate risk using dynamic programming models. Cohen and Huchzermeier (1999) also developed a lattice programming model to estimate the benefit of supply chain flexibility under exchange risk and demand uncertainty. Dasu and Li (1997) focused on firms' optimal operating strategies under foreign exchange risk where the authors used linear programming to facilitate the development of the optimal policy. Kazaz, Dada, and Moskowitz (2005), in turn, studied production policies under the foreign exchange risk when the allocation decision can be postponed. Goh, Lim, and Meng (2007) proposed a stochastic model to study multi-stage global supply chains where foreign exchange risk, demand and supply risk as well as disruption risk are considered. These studies, however, only focus on the optimal decisions of an individual firm and did not consider the competitions between supply chain players. Nagurney et al (2003, 2005), in contrast, proposed a modeling framework to analyze the dynamics of global supply chains with risk management. The authors assumed competitive firms and modeled three tiers of decision-makers: manufacturers, retailers, and consumers and derived a variational inequality formulation to investigate the global supply chain network, along with qualitative properties. Liu and Nagurney (2010) focused on supply chain offshore-outsourcing decisions under foreign exchange risk and competition where the authors also used simulation studies to derive managerial insights.

Our paper differs from the above-mentioned studies in that we focus on how multinational firms with different risk attitudes manage their global supply chain networks under competition and exchange rate uncertainty. Our model explicitly considers the firms' optimal decisions regarding procurement, global production, product allocation, transportation, and sales, and studies when the exchange rate uncertainty vary, and how such decisions affect their profits and risks.

In our paper, we model the multinational firms' decision making using the classic mean-variance framework. In particular, we assume that each firm maximizes its expected profit and minimizes its frisk where the risk is represented by the variance of the profit. Moreover, we allow firms to have different risk attitudes by assigning different weights to the variance terms in their objective functions.

The mean-variance (MV) framework was originally developed by the Nobel laureate Harry Markowitz. The MV framework provides an intuitive and practical approach to quantify the economic behaviors of rational decision makers, and has become part of the foundations of modern finance theory. The MV approach has also been increasingly used to describe the behaviors of decision-makers under risk and uncertainty in the supply chain management literature. Hodder (1984), Hodder and Jucker (1985a, 1985b), and Hodder and Dincer (1986) first applied an MV method to model facility location problems under risk and uncertainty.

Gan, Sethi, and Yan (2004, 2005) studied a supply chain coordination problem using the MV approach. The MV approach has also been utilized to model the newsvendor problem where the decision-maker behaved under the MV assumption (Choi et al. 2001; Wu et al., 2009). Kim, Cohen, and Netessine (2007) applied the MV approach to study performance-based contracting in after-sale supply chains. Choi and Chow (2008) analyzed the quick response program in fashion supply chains via a mean-variance method. Tsay (2002) studied how the manufacturer-retailer relationship is influenced by risk-sensitivity under various assumptions of strategic power, and how a manufacturer return policy could affect these dynamics. Wei and Choi (2010) investigated the wholesale pricing and profit sharing scheme in supply chains under the mean-variance framework. For additional research that analyzed risk-averse supply chain decision-makers using the MV framework, see (Chen and Federgruen, 2000; Choi et al. 2008; Martinez-de-Albeniz and Simchi-Levi, 2006)

This paper is organized as follows: In Section 2, we develop the global supply chain network model under foreign exchange risk. We allow the decision-makers to have different risk attitudes, construct the equilibrium conditions, and develop the variational inequality formulation. We also show the existence of the solution.

In Section 3, we utilize computational examples to study the supply chain decision-making of multinational firms under exchange rate risk, and how such decisions affect their profits and risks.

Our results indicate that as the exchange rate uncertainty increases the multinational firms with higher operation costs have larger decreases in profits and larger increases in risks than the firms with lower operation costs. Our results also suggest that as the exchange rate volatility increases the more risk-averse firms try to balance the net cash flow in each country's/area's currency. Although such strategy may reduce the total profit of the firm it can provide operational hedging the firm needs to lower the overall exchange rate risk. On the other hand, if a firm is not very much concerned about risk, it can increase the production flow from the developing country to the developed country in order to grow its market shares in its major markets. Such decisions, however, will further unbalance the cash flows in each country's/area's currency, and increase the exposure to the foreign exchange risk. Consequently, as the exchange rate volatility increases the profits of more risk-averse firms will decline more than those of less risk-averse firms, and the risks of more risk-averse firms will increase less than those of less risk-averse firms. Moreover, our results show that the market prices of the product in importing countries are not affected by the exchange rate volatility while the product prices in exporting countries will decrease as the exchange rate volatility increases since risk-averse firms will try to sell more products in the local markets in exporting countries in order to balance the cash flows. Section 4 highlights the managerial insights and concludes the paper.

2. The Global Supply Chain Network Operations with Competition and Exchange Rate Uncertainty

In this section we develop the supply chain model that studies the multinational firms' operations and competitions under foreign exchange risk from a network perspective. We consider M multinational firms that operate global supply chain networks in A countries. The firms produce a product that requires K materials and vender-supplied parts. In particular, we use $i = 1, \ldots, A$, $j = 1, \ldots, A$, and $l = 1, \ldots, A$ to denote the country indices of the material/part supply markets, the manufacturing plants, and the demand markets, respectively. The notation of the model is presented in Table 1. An equilibrium solution is denoted by "*". All vectors are assumed to be column vectors, except where noted otherwise.

Table 1: Notation for the Supply Chain Network Model

Notation	**Definition**
u_{mkij}	the quantity of material/part k purchased by multinational firm m from supply market in county i and shipped to manufacturing plant in country j. We group all u_{mkij}s of firm m into the KA^2 dimensional vector U_m, and group all u_{mkij}s into the MKA^2 dimensional vector U.
v_{mjl}	the quantity of the finished product manufactured by multinational firm m in county j and shipped to the demand market in country l. We group all v_{mjl}s of firm m into the KA^2 dimensional vector V_m, group all v_{mjl}s into the MA^2 dimensional-vector Y.
q_{ml}	the quantity of the product sold by multinational firm m at the demand market in country l. We group all q_{ml}s of firm m into the A dimensional vector Q_m, group all q_{ml}s into the MA dimensional-vector Q.
d_l	the demand of the product at the market in country l. We group all d_ls into the MA dimensional-vector D.
c_{ki}	the unit purchasing cost of material/part k in country i
h_{mj}	the unit production cost of the product at firm m's manufacturing plant in country j
t^1_{kij}	the unit transportation cost of the material/part k from country i to country j
t^2_{jl}	the unit transportation cost of the the product from country i to country j
w_{mkj}	the quantity of material/part k needed to produce one unit of the product at firm m's manufacturing plant in country j
θ_i	the exchange rate between U.S. dollar and the currency of country i
COV_θ	the covariance matrix of the exchange rates between U.S. dollar and other countries' currencies
β_m	Firm m's degree of risk aversion
ρ_l	the price of the product at the market in country l
$d_l(\rho_l) = a - b\rho_l$	demand function at the demand market in country l

Multi-Criteria Decision-Making Behavior of the Multinational-Firms and Their Optimality Conditions

The multinational-firms, which manage global supply chain networks that span multiple countries, make decisions regarding the procurement, manufacturing, transportation, and sales of the product. We assume that the multinationals consider both profitability and risk in their operations. The total profit (in U.S. dollars) of multinational firm m can be expressed as follows:

$$Profit_m = \sum_{l=1}^{A} \theta_l \rho_l^* q_{ml} - \sum_{k=1}^{K} \sum_{i=1}^{A} \theta_i c_{ki} \sum_{j=1}^{A} u_{mkij}$$
$$- \sum_{j=1}^{A} \theta_j h_j \sum_{l=1}^{A} v_{mjl} - \sum_{k=1}^{K} \sum_{i=1}^{A} \sum_{j=1}^{A} \theta_i t^1_{kij} u_{mkij} - \sum_{j=1}^{A} \sum_{l=1}^{A} \theta_j t^2_{jl} v_{mjl}, \quad (1)$$

where the first term represents the total revenue from all markets; the second, third, fourth, and fifth terms represent the global procurement cost, the manufacturing cost, the transportation cost of materials and vender-supplied parts, and the transportation cost of finished goods, respectively. Note that tariffs can be incorporated as part of the transportation costs, t^1_{kij} and t^2_{ij}. In addition, firm m's profit from country n (in country n's currency), S_{mn}, can be written as:

$$S_{mn} = \rho_n^* q_{mn} - \sum_{k=1}^{K} c_{kn} \sum_{j=1}^{A} u_{mknj} - h_n \sum_{l=1}^{A} v_{mnl}$$
$$- \sum_{k=1}^{K} \sum_{i=1}^{A} t^1_{kin} u_{mkin} - \sum_{j=1}^{A} t^2_{jn} v_{mjn}, \quad (2)$$

The multinationals also consider the exchange rate risk induced by the global operation using a mean-variance framework. The mean-variance framework has been widely used in the risk management in supply chains (see, for example, ..). In particular, we define firm m's total risk as: $r_m(U_m, V_m, Q_m, \rho^*) = S_m^T COV_\theta S_m$, where COV_θ represents the covariance matrix of the exchange rates.

The optimization problem faced by multinational firm m can be expressed as follows:

$$P^m_{U_m,V_m,Q_m} \equiv \sum_{l=1}^{A} \theta_l \rho_l^* q_{ml} - \sum_{k=1}^{K}\sum_{i=1}^{A} \theta_i c_{ki} \sum_{j=1}^{A} u_{mkij} - \sum_{j=1}^{A} \theta_j h_j \sum_{l=1}^{A} v_{mjl} - \sum_{k=1}^{K}\sum_{i=1}^{A}\sum_{j=1}^{A} \theta_i t^1_{kij} u_{mkij}$$

$$- \sum_{j=1}^{A}\sum_{l=1}^{A} \theta_l t^2_{jl} v_{mjl} - \beta_m S_m^T COV_\theta S_m, \tag{3}$$

subject to:

$$\sum_{i=1}^{A} u_{mkij} = w_{mkj} \sum_{l=1}^{A} v_{mjl}, \quad j = 1, \ldots, A; k = 1, \ldots, K; \tag{4}$$

$$\sum_{l=1}^{A} v_{mjl} \leq CAP_{mj}, \quad j = 1, \ldots, A; \tag{5}$$

$$\sum_{j=1}^{A} v_{mjl} \geq q_{ml}, \quad l = 1, \ldots, A; \tag{6}$$

$$u_{mkij} \geq 0,\ v_{mjl} \geq 0,\ q_{ml} \geq 0 \quad k = 1, \ldots, K;\ i = 1, \ldots, A;\ j = 1, \ldots, A;\ l = 1, \ldots, A. \tag{7}$$

We assume that the multinational firms compete in a noncooperative manner in the sense of Nash (1950, 1951). The optimality conditions for all multinational firms simultaneously, under the above assumptions (see also Gabay and Moulin (1980), Bazaraa, Sherali, and Shetty (1993), Bertsekas and Tsitsiklis (1989), and Nagurney (1993)), coincide with the solution of the following variational inequality: determine $(U^*, V^*, Q^*) \in \mathcal{K}^1$ satisfying

$$\sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{i=1}^{A}\sum_{j=1}^{A} \left[\theta_i c_{ki} + \theta_i t^1_{kij} + \beta_m \frac{\partial r_m(U^*, V^*, Q^*, \rho^*)}{\partial u_{mkij}}\right] \times [u_{mkij} - u^*_{mkij}]$$

$$+ \sum_{m=1}^{M}\sum_{j=1}^{A}\sum_{l=1}^{A} \left[\theta_j h_j + \theta_l t^2_{jl} + \beta_m \frac{\partial r_m(U^*, V^*, Q^*, \rho^*)}{\partial v_{mjl}}\right] \times [v_{mjl} - v^*_{mjl}]$$

$$+ \sum_{m=1}^{M}\sum_{l=1}^{A} \left[\beta_m \frac{\partial r_m(U^*, V^*, Q^*, \rho^*)}{\partial q_{ml}} - \theta_l \rho_l^*\right] \times [q_{ml} - q^*_{ml}] \geq 0, \quad \forall (U, V, Q) \in \mathcal{K}^1, \tag{8}$$

where $\mathcal{K}^1 \equiv \{(U, V, Q) | (U, V, Q) \in R_+^{MKA^2+MA^2+MA}$ and (4), (5), and (6) holds$\}$.

Equilibrium Conditions for the Demand Markets

Since the demand functions are given, the market equilibrium conditions at demand market l then take the form:

$$\sum_{m=1}^{M} q_{ml} \begin{cases} = d_l(\rho_l^*), & \text{if} \quad \rho_l^* > 0, \\ \geq d_l(\rho_l^*), & \text{if} \quad \rho_l^* = 0. \end{cases} \tag{9}$$

equivalently,

$$\sum_{m=1}^{M} q_{ml} \begin{cases} = d_l(\rho_l^*), & \text{if} \quad \theta_l \rho_l^* > 0, \\ \geq d_l(\rho_l^*), & \text{if} \quad \theta_l \rho_l^* = 0. \end{cases} \tag{10}$$

The interpretation of conditions (9) and (10) is as follows: If the price the consumers are willing to pay for the product is positive then the total quantity purchased by the consumers is equal to the demand; if the equilibrium price at the demand market is zero then the total shipment to the market exceed the demand. We assume that the market demands are non-negative:

$$d_l(\rho_l) \geq 0. \tag{11}$$

Using the definition of $d_l(\rho_l)$ in Table 1, we have that (11) is equivalent to the following constraints:

$$\rho_l \leq \frac{a}{b}. \tag{12}$$

The equivalent variational inequality governing all the demand markets takes the form: determine $(\rho) \in \mathcal{K}^2$, such that

$$\left[\sum_{l=1}^{A} q_{ml}^* - d_l(\rho_l^*)\right] \times [\rho_l - \rho_l^*] \geq 0, \quad \forall (\rho) \in \mathcal{K}^2, \tag{13}$$

where $\mathcal{K}^2 \equiv \{(Q, D) | (Q, D) \in R_+^A \text{ and (12) holds}\}$.

The Equilibrium Conditions for the Global Supply Chain Network with Exchange Risk Uncertainty and Competition Concerns

In equilibrium, the optimality conditions for all the multinational firms, and the equilibrium conditions for all the demand markets must be simultaneously satisfied so that no firm has any incentive to alter his decisions. We now formally state the equilibrium conditions for the entire global supply chain network.

Definition 1: Global Supply Chain Network Equilibrium with Exchange Rate Uncertainty and Competition

The equilibrium state of the global supply chain network with exchange rate uncertainty and competition is one where the product flows and prices satisfy the sum of conditions (8) and (13).

We now state and prove:

Theorem 1: Variational Inequality Formulation of the Global Supply Chain Network Equilibrium under Exchange Rate Risk and Competition

The equilibrium conditions governing the global supply chain network according to Definition 1 coincide with the solution of the variational inequality given by: determine $(U^*, V^*, Q^*, \rho^*) \in \mathcal{K}^3$ *satisfying:*

$$\sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{i=1}^{A}\sum_{j=1}^{A}\left[\theta_i c_{ki} + \theta_i t^1_{ij} + \beta_m \frac{\partial r_m(U^*, V^*, Q^*, \rho^*)}{\partial u_{mkij}}\right] \times [u_{mkij} - u^*_{mkij}]$$

$$+\sum_{m=1}^{M}\sum_{j=1}^{A}\sum_{l=1}^{A}\left[\theta_j h_j + \theta_l t^2_{jl} + \beta_m \frac{\partial r_m(U^*, V^*, Q^*, \rho^*)}{\partial v_{mjl}}\right] \times [v_{mjl} - v^*_{mjl}]$$

$$+\sum_{m=1}^{M}\sum_{j=1}^{A}\sum_{l=1}^{A}\left[\beta_m \frac{\partial r_m(U^*, V^*, Q^*, \rho^*)}{\partial q_{ml}} - \theta_l \rho^*_l\right] \times [q_{ml} - q^*_{ml}] + \sum_{m=1}^{M}\left[\sum_{l=1}^{A} q_{ml} - d^*_l(\rho^*_l)\right] \times [\rho_l - \rho^*_l] \geq 0,$$

$$\forall (U, V, Q, \rho) \in \mathcal{K}^3, \tag{14}$$

where

$$\mathcal{K}^3 \equiv \{(U, V, Q, \rho) | (U, V, Q, \rho) \in R_+^{MKA^2+MA^2+MA+A} \textit{and } (4),\ (5),\ (6),\ \textit{and } (12)\ \textit{hold}\}.$$

Proof: Clearly, (14) is the sum of the optimality conditions (8) and the equilibrium conditions (13), and is, hence, according to Definition 1 a supply chain network equilibrium. □

Remark

Note that, in the above model, we have assumed that each multinational firm considers the exchange rate risk (to a certain degree) in decision-making depending upon the degree of risk aversion denoted by β_m; $m = 1, \ldots, M$. We will use numerical examples to show how firms with different β_ms make supply chain decisions under competition and exchange rate risk.

The variational inequality problem (14) can be rewritten in standard variational inequality form (cf. Nagurney (1993)) as follows: determine $X^* \in \mathcal{K}$ satisfying

$$\left\langle F(X^*)^T, X - X^* \right\rangle \geq 0, \quad \forall X \in \mathcal{K}, \tag{15}$$

where $X \equiv (U, V, Q, \rho)^T$, $\mathcal{K} \equiv \mathcal{K}^3$, and

$$F(X) \equiv (F_{mkij}, F_{mjl}, F_{ml}, F_l)$$

with indices $m = 1, \ldots, M$; $k = 1, \ldots, K$ $i = 1, \ldots, A$; $j = 1, \ldots, A$; and $l = 1, \ldots, A$, and the functional terms preceding the multiplication signs in (14), respectively. Here $< \cdot, \cdot >$ denotes the inner product in Ω-dimensional Euclidian space where $\Omega = MKA^2 + MA^2 + MA + A$.

Theorem 2: Existence

If the feasible set $\mathcal{K}^3$ is nonempty, variational inequality (14) admits a solution.

Proof: The feasible set $\mathcal{K}$ is compact because of limited capacities of manufacturing plants and the constraint (12). Therefore, we can derive existence of a solution X^* to (14) simply from the assumption of continuity of functions that enter $F(X)$, which is the case in this model (see Kinderlehrer and Stampacchia (1980) and Nagurney (1993)). Therefore, if the feasible set is nonempty, the variational inequality (14) has a solution. $\square$.

3. Computational Studies

In this section, we present two examples to show the impacts of exchange rate risk on global supply chain network operations and competitions. In particular, the first example focuses on how the exchange rate uncertainty influences the profitability of global supply chain networks with different costs. The second example compares the strategies of multinational firms with different levels of risk aversion under competition and foreign exchange risk. We solved the model using the modified projection method (see Korpelevich, 1977; Nagurney, 1993).

Example 1

In this example, we focus on the impact of exchange rate uncertainty on the profitability of the global supply chains with different costs. In particular, we consider four multinational firms where firms 1 and 2 have lower operation costs while firms 3 and 4 have higher operation costs. We will compare the profits of the four global supply chain networks under competition and different levels of exchange rate uncertainty.

In addition, we consider four countries where the fourth country is the United States. We assume that the firms have manufacturing facility located in the United States, and purchase two types of materials/parts to manufacture the product. Table 2 specifies the production parameters and demand functions

Table 2: Production and Demand Parameters

Parameter	**Country 1**	**Country 2**	**Country 3**	**Country 4**
Production Capacity of Firm 1	0	0	0	20
Production Capacity of Firm 2	0	0	0	20
Production Capacity of Firm 3	0	0	0	20
Production Capacity of Firm 4	0	0	0	20
Unit Production Cost of Firm 1	N/A	N/A	N/A	1
Unit Production Cost of Firm 2	N/A	N/A	N/A	2
Unit Production Cost of Firm 3	N/A	N/A	N/A	1
Unit Production Cost of Firm 4	N/A	N/A	N/A	2
Unit Cost of Material 1	2	2	2	2
Unit Cost of Material 2	1.5	1.5	1.5	1.5
Inverse Demand Function	$d_1(\rho_1)$=40-2ρ_1	$d_2(\rho_2)$=40-2ρ_2	$d_3(\rho_3)$=40-2ρ_3	$d_4(\rho_4)$=40-2ρ_4
Exchange Rate with U.S. dollar	1	1	1	1

Table 3: Covariance Matrix of Exchange Rates

	Country 1	Country 2	Country 3	Country 4 (U.S.)
Country 1	σ^2	0	0	0
Country 2	0	σ^2	0	0
Country 3	0	0	σ^2	0
Country 4 (U.S.)	0	0	0	0

Table 4: Profits and Relative Risks of the Multinational Firms at Different Levels of Exchange Rate Risk

	Profit (million U.S. dollars)		Coefficient of Variation	
σ^2	Firms 1&3	Firms 2&4	Firms 1&3	Firms 2&4
0.000	80.00	60.00	0.000	0.000
0.004	76.57	56.57	0.071	0.096
0.008	64.39	44.39	0.100	0.145
0.012	51.05	31.06	0.107	0.176
0.016	50.00	30.00	0.109	0.183
0.020	44.00	24.00	0.111	0.204

We let the material transportation costs, $t^1_{kij} = 1, \forall k, i \neq j$ and $t^1_{kij} = 0, \forall k, i = j$; and the finished product transportation costs, $t^2_{jl} = 2, j \neq l$ and $t^1_{kjl} = 2, j = l$. The covariance matrix of exchange rates (with the U.S. dollar) COV_θ is specified in Table 3.

In this example we change the foreign exchange risk by varying σ^2 from 0 to 0.02 which is equivalent to varying the standard deviation, σ, from 0% to 14.14%. We assume that the four firms have the same level of risk aversion, $\beta_m = 1$, $m = 1, \ldots, 4$. The results of the model are shown in Table 4.

The coefficient of variation in Table 4 measures the relative risk, and is defined as the standard deviation divided by the profit. Table 4 shows that when the foreign exchange risk increases, the profits of the multinationals will decrease while the values of the coefficient of variation will increase which indicates that the uncertainty of the profitability of the firms will increase. Moreover, when foreign exchange risk increases the global supply chains with higher operation costs (firms 3 and 4) will not only have lower profits but also have higher risks (coefficient of variation) than the firms with lower operation costs (firms 1 and 2).

Example 2

The second example compares four multinational firms with different levels of risk aversion, and shows how they response differently to the increase of the foreign exchange risk under competition. In particular, we consider two countries, the United States and China, and assume that the four firms operate manufacturing facilities and sell finished products in both countries. The current exchange rate between Chinese Yuan and U.S. dollar is 0.143:1 (1:7), and the variance, σ^2, is 0.0001 according to the historical data of the past ten years. Since it is well-known that exchange rate volatility is not constant over time, in our study we vary the variance from 0 to 0.0003 with the interval of 0.0005. We assume that the levels of risk aversion of Firms 1, 2, 3, and 4, $\beta_m, m = 1, \ldots, 4$, are 2, 1, 0.5, and 0.1, respective, where Firm 1 is the most risk averse while Firm 4 is the least risk averse. We then compare the supply chain decisions, profits, and risks of the four firms under competition. The parameters of the model are specified in the Tables 5 and 6.

Table 5: Production and Demand Parameters

Parameter	**United States**	**China**
Production Capacity of Firm 1 (million units)	10	10
Production Capacity of Firm 2 (million units)	10	10
Production Capacity of Firm 3 (million units)	10	10
Production Capacity of Firm 4 (million units)	10	10
Unit Production Cost of Firm 1	4 dollars	7 yuans
Unit Production Cost of Firm 2	4 dollars	7 yuans
Unit Production Cost of Firm 3	4 dollars	7 yuans
Unit Production Cost of Firm 4	4 dollars	7 yuans
Unit Cost of Material 1	2 dollars	14 yuans
Unit Cost of Material 2	1.5 dollars	10.5 yuans
Demand Function (in local currency)	$d_1(\rho_1)$=60-2ρ_1	$d_2(\rho_2)$=40-2$\theta_2\rho_2$
Exchange Rate with U.S. dollar (θ_2)	1	0.143

Table 6: Unit Transportation Costs

Unit International Transportation Costs of Materials 1 and 2		
From/To	United States	China 2
United States	0	1 dollar
China	7 yuans	0
Unit International Transportation Costs of Finished Products		
From/To	United States	China
United States	0	2 dollars
China	14 yuans	0

Table 7: Profit and Relative Risk of the Multinational Firms at Different Levels of Exchange Rate Risk

	Profit(million U.S. dollars)				Coefficient of Variation			
σ^2	Firms 1	Firms 2	Firms 3	Firms 4	Firms 1	Firms 2	Firms 3	Firms 4
0.00000	9.94	9.94	9.94	9.94	0.000	0.000	0.000	0.000
0.00005	9.43	9.44	9.47	9.67	0.008	0.017	0.034	0.165
0.00010	8.92	8.95	9.00	9.42	0.013	0.026	0.051	0.244
0.00015	8.37	8.41	8.49	9.16	0.017	0.034	0.067	0.314
0.00020	7.83	7.88	8.00	8.92	0.022	0.043	0.085	0.379
0.00025	7.23	7.30	7.45	8.65	0.027	0.053	0.104	0.446
0.00030	6.62	6.71	6.89	8.39	0.033	0.065	0.126	0.515

Table 8: Allocation of the Products Manufactured in China (million units)

	Sold in China				Sold in the United States			
σ^2	Firms 1	Firms 2	Firms 3	Firms 4	Firms 1	Firms 2	Firms 3	Firms 4
0.00000	7.25	7.25	7.25	7.25	2.75	2.75	2.75	2.75
0.00005	8.53	8.31	7.88	4.42	1.47	1.69	2.12	5.59
0.00010	8.59	8.37	7.92	4.37	1.41	1.63	2.08	5.63
0.00015	8.66	8.43	7.97	4.32	1.34	1.57	2.02	5.69
0.00020	8.73	8.49	8.03	4.25	1.27	1.51	1.98	5.74
0.00025	8.80	8.56	8.07	4.19	1.20	1.44	1.93	5.81
0.00030	8.88	8.63	8.13	4.12	1.12	1.37	1.87	5.87

Table 9: Allocation of the Products Manufactured in the U.S. (million units)

	Sold in China				Sold in the United States			
σ^2	Firms 1	Firms 2	Firms 3	Firms 4	Firms 1	Firms 2	Firms 3	Firms 4
0.00000	0.00	0.00	0.00	0.00	8.50	8.50	8.50	8.50
0.00005	0.00	0.00	0.00	0.00	8.54	8.53	8.53	8.53
0.00010	0.00	0.00	0.00	0.00	8.57	8.56	8.56	8.55
0.00015	0.00	0.00	0.00	0.00	8.61	8.60	8.59	8.58
0.00020	0.00	0.00	0.00	0.00	8.64	8.62	8.62	8.61
0.00025	0.00	0.00	0.00	0.00	8.68	8.66	8.65	8.64
0.00030	0.00	0.00	0.00	0.00	8.71	8.70	8.68	8.67

Table 10: Net Revenue from the United States and China (million U.S. dollars)

	Net Revenue from China				Net Revenue from the United States			
σ^2	Firms 1	Firms 2	Firms 3	Firms 4	Firms 1	Firms 2	Firms 3	Firms 4
0.00000	-10.64	-10.64	-10.64	-10.64	20.60	20.60	20.60	20.60
0.00005	-1.60	-3.21	-6.43	-32.19	11.04	12.66	15.91	41.89
0.00010	-1.63	-3.27	-6.56	-32.80	10.55	12.22	15.56	42.25
0.00015	-1.67	-3.34	-6.67	-33.51	10.04	11.75	15.17	42.69
0.00020	-1.70	-3.41	-6.84	-34.13	9.53	11.30	14.84	43.08
0.00025	-1.74	-3.48	-6.97	-34.88	8.97	10.79	14.43	43.57
0.00030	-1.78	-3.56	-7.13	-35.63	8.40	10.28	14.03	44.06

Table 11: Product Market Prices (in local currencies)

σ^2	**United States**	**China**
0.00000	7.50	38.44
0.00005	7.50	38.03
0.00010	7.50	37.61
0.00015	7.50	37.18
0.00020	7.50	36.74
0.00025	7.50	36.30
0.00030	7.50	35.83

Table 7 shows that when the foreign exchange risk, σ^2, increases, the profit of each multinational firm will decrease, and the coefficient of variation, which represents the risk, will increase. In addition, we observe that when σ^2 increases the profits of more risk averse firms decrease faster than those of the less risk averse firms while the risks of more risk-averse firms increase slower than those of the less risk averse firms. For example, when σ^2 increases from 0 to 0.00030, the profit of Firm 1 decreases from 9.94 to 6.62 while that of Firm 4 decreases from 9.94 to 8.39; and the risk of Firm 1 increases from 0 to 0.033 while the risk of Firm 4 increases from 0 to 0.515.

Tables 8, 9, and 10 compare the multinational firms' supply chain operation decisions in response to the increase of foreign exchange risk. First, Table 10 shows that for each firm the net revenue from China is negative while the net revenue from the United States is positive, which indicates that the main manufacturing activities occur in China and the main sales activities occur in the United States.

It is interesting to compare the supply chain decisions of the firms with different risk-averse levels as the exchange rate risk increases. Table 8 shows that when σ^2 increases more risk-averse firms will sell more products made in China in the Chinese market, and ship fewer products made in China to the U.S. market. For example, when σ^2 increases from 0 to 0.00030 the sales of Firm 1's Chinese manufactured product in the Chinese market increases from 7.25 to 8.88 while the sales of such product in the U.S. market decreases from 2.75 to 1.12. In addition, we can observe that the higher the degree of risk aversion, the larger the changes of the product allocations. The least risk-averse multinational, Firm 4, however, operates in the opposite way where when σ^2 increases it sells more products made in China in the U.S. market while sells fewer Chinese manufactured products in the Chinese market. For example, when σ^2 increases from 0 to 0.00030 the sales of Firm 4's Chinese manufactured product in the Chinese market decreases from 7.25 to 4.12 while the sales of such product in the U.S. market increases from 2.75 to 5.87. Table 9 shows that the firms never sell products manufactured in the U.S. to the Chinese market, and that when σ^2 increases the production activities in the U.S. manufacturing plants increase.

As a consequence of the firms' supply chain decisions, Table 10 shows that the net revenues of Firms 1, 2, and 3 from the operations in China become less negative due to the increase of sales while the net revenues of the three firms from the U.S. market decline because of the decrease of sales. For instance, when σ^2 rises from 0 to 0.00030 the revenue of Firm 1 from China increases from -10.64 to -1.78 while its revenue from the U.S. decreases from 20.60 to 8.60. The revenues of Firm 4, however, exhibit the opposite trends: The net revenue of Firm 4 decreases in China and increases in the United States. For example, when σ^2 increases from 0 to 0.00030 the revenue of Firm 1 from China declines from -10.64 to -35.63 while its revenue from the U.S. increases from 20.60 to 44.06.

We now explain the reason that the multinational firms with different levels of risk aversion use different strategies when the foreign exchange risk increases. When the variance is zero selling Chinese manufactured products in the U.S. market can significantly save production costs, and make the supply chain networks more profitable. Such supply chain strategy can be risky when the foreign exchange rate is volatile since the large negative cash flow in the Chinese yuan can impair the profit if the yuan appreciates significantly. Therefore, when the more risk-averse firms (Firms 1, 2, and 3) face such foreign exchange uncertainty, they will sell more products made in China in the Chinese Market, and manufacturer more products in the U.S. for the U.S. market so that the revenues from the two countries are more balanced which results in lower total risk. The consideration of the foreign exchange risk, however, will lead to lower overall average profits of the firms.

The least risk-averse firm, Firm 4, however, changes his decisions in the opposite way as the exchange rate risk rises. The reason is as follows: The products sold in the U.S. market have higher margins than the same products sold in the Chinese market. However, the increasing exchange rate uncertainty makes Firms 1, 2, and 3 sell more products in the local Chinese market, and ship fewer products from China to the U.S., which gives Firm 4 more opportunities to increase its market share in the U.S. market by selling the lower cost products manufactured in China. Since Firm 4 is the least risk-averse company it focuses more on the profit opportunities, and is not concerned about the risk caused by the negative cash flow from the operations in China as much as the other firms are. As a result, Table 7 shows that Firm 4 has the highest expected profit and the highest risk exposure as the foreign exchange uncertainty increases.

Table 11 exhibits the trends of product prices in the two countries. We can see that the price in the U.S. market remains the same as the exchange rate volatility rises. This is due to the fact that the price in the U.S. market is determined by higher marginal cost of the U.S. production facilities of the firms. The product price in China, decreases from 38.44 yuans to 35.83 yuans as σ^2 increases. This is because the more risk-averse firms increase their sales in China which increases the total supply of the product in the Chinese market.

5. Managerial Insights and Conclusion

This paper studies the operation strategies of global supply chain networks under foreign exchange risk. In particular, we developed a variational inequality model which consists of multiple international firms who compete globally. In our model each supply chain firm manages a global supply chain network, and optimally makes decisions regarding material procurement, production, transportation, and sales of products.

We then presented two sets of computational examples which revealed interesting managerial insights. In particular, the first set of examples compare the profits and risks of firms with different production costs as the foreign exchange rate uncertainty increases. Our results show that all the firms are negatively affected by the rising exchange rate uncertainty while the firms with higher production costs have large decreases in profits and large increases in risks than the firms with lower production costs.

Our second set of examples studies how the exchange rate uncertainty influences the decisions, profits, and risks of global supply chain firms with different risk attitudes. Our results show that as the exchange rate volatility increases the more risk-averse firms should try to make the net cash flow in each country's/area's currency be balanced. For example, if a multinational firm has major production activities in a developing country when the exchange rate volatility becomes higher the firm should also make an effort to sell the products in the local markets. Although such strategy may reduce the total profit of the global firm since the profit margin in the developing country may not be as high as that in the developed countries, this strategy, however, can provide operational hedging to lower the overall exchange rate risk. On the other hand, if a firm is not very much concerned about risk, it may consider to increase the product flow from the developing country to the developed country in order to grow its market shares. Consequently, as the exchange rate volatility increases the profits of more risk-averse firms will decline more than those of less risk-averse firms, and the risks of more risk-averse firms will increase less than those of less risk-averse firms.

In addition, our results show that the product prices in importing countries are not influenced by the exchange rate volatility due to the existence of local production facilities while the product prices at the local markets in exporting countries will decrease as the exchange rate volatility increases since risk-averse firms tend to sell more products in the local markets to balance the cash flows.

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