Sharing information in a dual-supplier network from a game theoretic perspective

Yi Tao †
School of Management
Guangdong University of Technology, Guangzhou, China
Tel: (+86) 13430350230, Email: kenjimore@gmail.com

Loo Hay Lee
Department of Industrial & Systems Engineering
National University of Singapore (NUS), Singapore
Tel: (+65) 6516-2895, Email: iseleelh@nus.edu.sg

Ek Peng Chew
Department of Industrial & Systems Engineering
National University of Singapore (NUS), Singapore
Tel: (+65) 6516-6554, Email: isecep@nus.edu.sg

Abstract. This paper studies the impact of information sharing in a supply chain consisting of one retailer and two suppliers. When facing supply risk in terms of capacity disruptions, both the retailer's ordering strategy and suppliers' vertical information sharing strategies are analyzed using simultaneous game theory framework. In symmetrical-suppliers scenario, we would like to study how the levels of uncertainties in suppliers' capacities impact their decisions on voluntary vertical information sharing? In addition, how does vertical information sharing help to improve the overall performance of the supply chain? We also established mitigation strategy to encourage information sharing if it does help to improve the performance of the whole supply chain when facing supply disruption.

Keywords: Supply chain disruptions; game theory; vertical information sharing; Nash equilibrium

1. INTRODUCTION

Supply chains face many types of risks, such as environmental risk, supply risk and demand risk. Among these, supply risk is largely due to capacity disruption, sudden spike in production cost as well as the quality uncertainties. For instance, in 2013 August, Danone Dumex called back two batches of PreciNutri Step 2 formula after New Zealand's dairy exporter Fonterra informed that one of its ingredients had a potential quality issue (Associated Press, 2013). In a separate instance, a fire at Toyota's supplier plants forced the automotive production lines to close down 18 plants for nearly two weeks in February 1997. The estimated costs of the 1997 disruption included $195 million in damage and inventory loss with an additional estimated opportunity cost of lost sales of $325 million on 70,000 cars (Converium, 2006). These incidents show that supply chain uncertainties from the supply side have huge impact on the profitability of the downstream companies, such as Danone and Toyota in the two examples. More importantly, drastic profit losses due to supply chain disruptions in these real life accidents provide the motivation for researchers to explore the possibility of reducing the adverse impacts if information about the supply risk can be shared between the upstream and downstream players. Furthermore, one shall study the possibility for voluntary information sharing among the players in order to mitigate the overall profit loss of the whole supply chain when facing supply chain disruptions.

In view of the importance of supply chain risk management, the objective of this research is: 1) To study the ordering pattern made by the retailer and the decision on vertical information sharing made by the suppliers, with and without disruption to suppliers' capacity; 2) To explore the impact of vertical information sharing between the retailer and the suppliers on the performance of the whole supply chain using game theory approach, in the presence of supply risk.

In this paper, the impact of vertical information sharing strategy between one retailer and two suppliers is analysed in a competitive market settings through game theory approach. The analysis can be divided into two stages. At stage one, with the objective of maximizing the total profit, the retailer will decide the ordering quantities allocated to each suppler based on the information about their respective capacity distributions. At stage two, a disruption is introduced into the supply chain and the suppliers make simultaneous decisions about their information sharing strategies. A Nash equilibrium strategy is obtained by observing the payoff matrix. By comparing the outcomes of the Nash equilibrium strategy with those under other strategies, necessary mitigation strategies are to be discussed in order to achieve overall efficiency of the whole supply chain.

2. Literature Review

2.1 Supply Chain Risk Management

The importance of supply chain risk management is evident not only from the real life examples, but also tremendous research effort devoted to this area. Here supply chain risk is broadly defined as the deviation from the expected value of a certain supply chain performance indicator. Cruz (2009) classified supply chain risks into operational risk and disruption risk. While operational risk is also referred as supply-demand risks and arises from failed systems or processes, such as quality or delivery problems, disruption risk is more about man-made or natural disasters such as terrorist attacks, earthquakes and floods. These disruptions have a strong short-term and long-term financial impact on the companies (Cruz, 2009). In view of the significant impact of disruption risks, supply chain risk management become an important area of study in order to maintain industries' stability and profitability. It involves coordination or collaboration among the supply chain partners so as to ensure profitability and continuity (Tang, 2006).

2.2 Information Sharing Strategy

As one of the pillars in supply chain coordination, information sharing among supply chain players plays a significant role and hence lots of research and studies have been devoted to it. Traditionally, research on information sharing focused more on downstream demand-related information. This is because the downstream members of the supply chain, like the retailers, are comparatively better informed about the market demand than the upstream members, such as the suppliers. Thus, to guarantee the success of these new supply chain management practices, it is essential that the better-informed downstream members of the chain share their demand information effectively and efficiently with the less informed upstream members (Chu & Lee, 2005). Nevertheless, in the context of supply chain disruption risk, downstream members instead are comparatively better informed about the changes in their supply conditions, such as capacity distribution and quality control. In view of different types of information, Chen (2010) classified shared information into upstream and downstream information, and thereafter studied the incentive issues in information sharing (Chen, 2003). However, it should be noted that voluntary information sharing may not be always sustainable. For instance, Li (2002) studied the direct and indirect impact of vertical information in a competitive market as well as its impact on the profitability of the whole supply chain. He concluded that the leakage effect of information sharing discourages the retailers from sharing their demand information with the manufacturer while encouraging them to share their cost information. On the other hand, the direct effect always discourages the retailers from sharing their information (Li, 2002). This shows that although better information usually improves the performance of a supply chain, when the supply chain is comprised of independent profit-maximizing players, there are still some obstacles exist in creating an information-sharing agreement. Even when information sharing achieves a better performance outcome for all parties in the supply chain, in many cases there is a tradeoff between overall performance of the whole supply chain and self-interest of individual firms. This tension, which is a type of the famous prisoners' dilemma, can lead to an inefficient equilibrium, in which no-information is shared among competing firms. Hence when voluntary information sharing is not possible, one has to identify conditions under which information can be traded so as to facilitate such information exchange.

2.3 Supply Chain Risk Management

To effectively model and analyze decision making in such situations where the outcome depends on simultaneous decision-making by individual parties, game theory is a natural choice. Game theory provides a mathematical tool for modelling system and generating solutions in a competitive situation. The basic rationality of game theory states that each player will optimize his/her own payoff, taking into account the action of the other player in the same manner. The advantage of game theory approach is to analyze simultaneously the two important aspects of the strategy formation: profit allocation and stability of equilibrium strategies. Due to the fact that equilibrium strategies may not be the optimum for the whole supply chain, numerous researches have been conducted to the formation of contracts or agreements strengthen the commitments of the players through risk, profit or cost sharing. For instance, Ha and Tong (2008) analyzed the impact of different contract types on the performance of the whole supply chain, namely contract menus and linear price contracts (Ha & Tong, 2008). In addition, considering game theory in supply chain risk management, Nagarajan and Sosic (2006) classified the approach into two categories: cooperative and competitive (Sosic, 2006).

3. Model formulation

The model is established based on a single period dual supplier network. Retailer k is the sole seller in the market for product A. He can source from two suppliers at their respective prices and sell in the retail market at retail price. It is assumed that the retail market demand is deterministic and there are no demand uncertainties. However, both suppliers have capacity uncertainties which can be modelled with a discrete probability distribution. It is assumed that under normal condition the capacity distribution information is common knowledge to all members in the supply chain. However, when suppliers' capacities are changed due to disruptions, two suppliers will make simultaneous decisions about their information sharing strategies with the retailer, that is either share or not share. Furthermore, the supplier who decides to sharing information will have to incur some cost due to effort in data collection and analysis. Hence, when there are no disruptions, the retailer will play his ordering strategy based on the common knowledge about the two suppliers' capacity distributions. However, when there is a disruption that causes the two suppliers' capacities to drop, four scenarios based on the suppliers' choices of information sharing strategies will be considered. When either supplier chooses to share the information, the new capacity distribution after disruption will be known to the retailer, if not, the retailer will rely on the previous capacity distribution under normal condition to place his orders.

In summary, the focus of this analysis is to observe any improvement of the overall supply chain performance due to information sharing during supply disruption, as compared to no information sharing during disruption. Since both retailer side and supplier side have different strategies to be considered, we can broadly divide the analysis into two parts. The first part is to analysis the retailer's ordering strategy given the perceived information about the suppliers' capacities. With the objective of profit maximization, the retailer's decision variables are ordering quantities placed on the two suppliers. The second part of the analysis will use simultaneous game theory to search for Nash Equilibrium of suppliers' information sharing strategies when disruption occurs. By observing the payoff matrix for two suppliers, Nash equilibrium will be obtained and interpreted in context of the scenario.

Parameters and variables used in this paper are defined as following:

D: retail market demand
s: retail market price
β: shortage cost (loss of good will in retail market)
e: inventory cost
$l_{i,}$: production costs for supplier i, ($l_1 = l_2$)
c_i: penalty costs for supplier i, ($c_1 = c_2$)
P_i: selling prices from supplier i
ε: cost of information sharing incurred to suppliers (data collection and analysis)

It shall be noted that the cost of information sharing ε incurs only to the supplier who shares the information with the retailer. In addition this cost is a lump sum cost due to effort spent on data collection and analysis to realize the new capacity distribution after disruption.

μ: the fraction of capacities of two suppliers after disruption
X_i: capacity of supplier i
O_i: ordering quantity from supplier i
R_i: realized quantity from supplier i
Note: i= {1, 2}

Here supply chain risk arises from the capacity uncertainties of the two suppliers, as the capacity level could be at either high level H_i or low level L_i. Hence it is modelled as following discrete probability distribution:

$x_i \sim P\ (x_i = H_i) = \rho_i,\ P\ (x_i = L_i) = 1 - \rho_i,$

Hence, there will be four scenarios:

$P\ (x_1 = H_1, x_2 = H_2) = \rho_1 * \rho_2;$
$P\ (x_1 = H_1, x_2 = L_2) = \rho_1 * (1 - \rho_2);$
$P\ (x_1 = L_1, x_2 = H_2) = (1 - \rho_1) * \rho_2;$
$P\ (x_1 = L_1, x_2 = L_2) = (1 - \rho_1) * (1 - \rho_2);$

With profit maximization as the main objective, the retailer's ordering strategy given his perceived information on suppliers' capacity distributions is analysed under normal and disruption conditions respectively. Considering the four scenarios described above, under each scenario i the retailer's profit is as following:

$$\Pi'_{ki} = E\{\ s * min\ (D, R_1 + R_2) - \ P_1 * \ R_1 - P_2 * R_2 \ - \ \beta * max\ (0, D - \ R_1 - R_2) \ - \ e * max\ (0, R_1 + R_2 - D) \ + \ c_1 * max\ (0, O_1 - \ R_1) + c_2 * \ max\ (0, O_2 - \ R_2)\} \tag{1}$$

The expected profit function above consists of five components: market revenue $s * \min\ (D, R_1 + R_2)$, cost of ordering $-P_1 * \ R_1 - P_2 * R_2$, compensation received from suppliers $c_1 * \max\ (0, O_1 - \ R_1) + c_2 * \ \max\ (0, O_2 - R_2)$, shortage cost due to any loss of goodwill in the retail market $-\beta * \max\ (0, \mathrm{D} - R_1 - R_2)$ and possible inventory cost $-\mathrm{e} * \max\ (0, R_1 + R_2 - \mathrm{D})$. Hence, considering the probabilities of four scenarios mentioned above, the objective function of retailer's profit maximization is as following:

$$\underset{O_1.O_2}{max}\, \Pi_k' = \rho_1 * \rho_2 * \Pi_{k1} + \rho_1 * (1 - \rho_2) * \Pi_{k2} + (1 - \rho_1) * \rho_2 * \Pi_{k3} + (1 - \rho_1) * (1 - \rho_2) * \Pi_{k4} \tag{2}$$

$$s.t.\ 0 \le O_1 \le H_1\ , \tag{3}$$

$$0 \le O_2 \le H_2\ , \tag{4}$$

$$max[\rho_1 * H_1 + (1 - \rho_1) * L_1, \rho_2 * H_2 + (1 - \rho_2) * L_2] < D < \rho_1 * H_1 + (1 - \rho_1) * L_1 + \rho_2 * H_2 + (1 - \rho_2) * L_2 \tag{5}$$

Constraint 1 and 2 restrict the ordering quantities to be lower than the maximum capacities of the respective suppliers. This is a necessary and reasonable assumption because suppliers should not allow orders to be out of their maximum capacity. Constraint 3 ensures that to meet the total market demand, retailer has to order from both suppliers but not solely one of them. This is to make sure both suppliers are involved in the supply chain so that the discussion about their strategies is meaningful later on.

In addition, from constraint 3, it is observed that the range of ρ_1, ρ_2 is restricted by parameters L_1, H_1, L_2, H_2. In particular, assuming two suppliers have symmetrical parameters $L_1 = L_2 = L;\ H_1 = H_2 = H$, then the range of ρ is as the following:

$$max(0, \frac{D - 2L}{2H - 2L}) < \rho < min(1, \frac{D - L}{H - L}) \tag{6}$$

Under the formulated objective function and constraints, the retailer will decide for O_1, O_2 that optimize his total profit. After numerical experiments it is observed that the ordering strategy can be summarized into three cases, depending on the magnitude of ρ_1, ρ_2.

4. Retailer's Ordering Strategy

In this section, it is assumed that both suppliers are symmetrical in their capacity distributions as well as their respective prices and productions costs, hence the following equations apply:

$$\rho_1 = \rho_2 = \rho;\ H_1 = H_2 = H;\ L_1 = L_2 = L;\ P_1 = P_2 = P;\ c_1 = c_2 = c;\ l_1 = l_2 = l; \tag{7}$$

It can be proven mathematically that as long as there is a relatively high level of uncertainty in the two suppliers' capacity distributions, which means ρ falls within a medium range that is determined by the parameters defined above, the following ordering strategy always yields the maximum profit for the retailer.

Theorem 1. With symmetrical suppliers, when $\frac{c}{P+c+e} < \rho < \frac{(s+\beta-P-c)+\sqrt{(s+\beta-P-c)^2+4(s+\beta+e)*c}}{2(s+\beta+e)}$, the retailer's ordering strategy is summarized as the following:

Table 1: Retailer's ordering strategy

	Normal	Disruption (S1×S2×)	Disruption (S1×S2√)	Disruption (S1√S2×)	Disruption (S1√S2√)
O_1	D-L_2	D-L_2	D-μ*L_2	D-L_2	D-μ*L_2
O_2	D-L_1	D-L_1	D-L_1	D-μ*L_1	D-μ*L_1

Proof. The upper and lower limits of ρ are formulated by considering the change of the retailer's profit $\Delta\Pi_k$ when $O_1 or\ \ O_2$ is changed by Δ.

Under normal condition, $O_1 = O_2 = \mathrm{D} - L$, Hence

$$\Pi_k^* = s * D - \rho_1 * \rho_2 * e[D - L_1 - L_2] - (1 - \rho_1 - \rho_2 + \rho_1 * \rho_2)(s + \beta)[D - L_1 - L_2] + (1 - \rho_1) * c_1 * [D - L_1 - L_2] + (1 - \rho_2) * c_2 * [D - L_1 - L_2] - (1 - \rho_1) * P_1 * L_1 - (1 - \rho_2) * P_2 * L_2 - \rho_1 * P_1[D - L_2] - \rho_2 * P_2[D - L_1] \tag{7}$$

To prove this is the maximum Π_k, consider $O_1' = O_1 + \Delta$

1) When $\Delta > 0$,

$$\Delta\Pi_k = -\rho * e * \Delta + (1 - \rho) * c * \Delta - \rho * P * \Delta \tag{8}$$

Hence, to have $\Delta\Pi_k < 0$,

$$\rho > \frac{c}{P + c + e} \tag{9}$$

2) When $\Delta < 0$,

$$\Delta\Pi_k = \rho_1 * \rho_2 * e * \Delta - (1 - \rho_1) * c_1 * \Delta + \rho_1 * P_1 * \Delta - (s + \beta) * \rho_1 * (1 - \rho_2) * \Delta \tag{10}$$

Hence, to have $\Delta\Pi_k < 0$,

$$\rho < \frac{(s + \beta - P - c) + \sqrt{(s + \beta - P - c)^2 + 4(s + \beta + e)c}}{2(s + \beta + e)} \tag{11}$$

Combining both cases,

$$\frac{\mathrm{c}}{\mathrm{P + c + e}} < \rho < \frac{(\mathrm{s} + \beta - \mathrm{P} - \mathrm{c}) + \sqrt{(\mathrm{s} + \beta - \mathrm{P} - \mathrm{c})^2 + 4(\mathrm{s} + \beta + \mathrm{e})\mathrm{c}}}{2(\mathrm{s} + \beta + \mathrm{e})} \tag{12}$$

5. Information Sharing Strategies

From the above section, it is observed that for symmetrical suppliers, the magnitude of ρ has a significant impact on the retailer's ordering strategy.

If $max(0, \frac{D-2L}{2H-2L}) < \rho < \frac{c}{P+c+e}$ or $\frac{(s+\beta-P-c)+\sqrt{(s+\beta-P-c)^2+4(s+\beta+e)c}}{2(s+\beta+e)} < \rho < min(1, (D -$

$L)/(H-L))$, it can be observed that since ρ takes extreme values, information sharing does not help to mitigate the adverse impact to the whole supply chain. As a result, these two cases are omitted for the analysis of information sharing on the supply chain performance. Hence case where $\frac{c}{P+c+e} < \ \rho < \frac{(s+\beta-P-c)+\sqrt{(s+\beta-P-c)^2+4(s+\beta+e)c}}{2(s+\beta+e)}$ is the focus of game theory analysis on information sharing strategy. Here the set of responses by each individual supplier is {Yes, No}, where Yes means to share the information, No means not to share the information.

According to the general solution in above section, under disruption the payoff matrix for the two suppliers under different combinations of strategies is as following:

Table 2: Payoff matrix for two suppliers.

		S2	
		No	Yes
S1	No	$\Pi_{11} = (P_1 - l_1) * \mu L_1 + (D - \mu L_1 - L_2) * [\rho_1(P_1 - l_1 + c_1) - c_1]$ $\Pi_{12} = (P_2 - l_2) * \mu L_2 + (D - \mu L_2 - L_1) * [\rho_2(P_2 - l_2 + c_2) - c_2]$	$\Pi_{21} = (P_1 - l_1) * \mu L_1 + (D - \mu L_1 - \mu L_2) * [\rho_1(P_1 - l_1 + c_1) - c_1]$ $\Pi_{22} = (P_2 - l_2) * \mu L_2 + (D - \mu L_2 - L_1) * [\rho_2(P_2 - l_2 + c_2) - c_2] - \varepsilon$
	Yes	$\Pi_{31} = (P_1 - l_1) * \mu L_1 + (D - \mu L_1 - L_2) * [\rho_1(P_1 - l_1 + c_1) - c_1] - \varepsilon$ $\Pi_{32} = (P_2 - l_2) * \mu L_2 + (D - \mu L_2 - \mu L_1) * [\rho_2(P_2 - l_2 + c_2) - c_2]$	$\Pi_{41} = (P_1 - l_1) * \mu L_1 + (D - \mu L_1 - \mu L_2) * [\rho_1(P_1 - l_1 + c_1) - c_1] - \varepsilon$ $\Pi_{42} = (P_2 - l_2) * \mu L_2 + (D - \mu L_2 - \mu L_1) * [\rho_2(P_2 - l_2 + c_2) - c_2] - \varepsilon$

In order to find the Nash Equilibrium, one needs to compare the payoffs for supplier 1 when supplier 2's strategy is taken into consideration. For instance, assuming supplier 2 chooses not to share the information, then we need to compare Π_{11} and Π_{31} to determine supplier 1's corresponding strategy, which in this case is not to share the information either. The same method is used to determine supplier 2's strategies under supplier 1's different actions. Eventually we reach the Nash Equilibrium, which is the set of strategies which neither supplier has any incentive to deviate from.

Hence, the table above shows the payoff matrix given When ε >= 0, Nash Equilibrium NE is (No, No). This shows that voluntary information sharing by the suppliers is impossible as both suppliers have the objective of maximizing their own profit but rather the overall efficiency of the whole supply chain. Furthermore, assuming $\varepsilon < (1-\mu)L_2 * [\rho_2(P_2 - l_2 + c_2) - c_2]$, which means the cost of information sharing is capped at a certain level, since $\Pi_{41} > \Pi_{11}$, $\Pi_{42} > \Pi_{12}$, then both suppliers will be better off if (Yes, Yes) is reached. This is one example of Prisons' Dilemma. Without any influence from the retailer, the suppliers will choose not to share any information about their capacity disruptions with their downstream parties in order to maximize their individual profit. However, this equilibrium is not optimum for the performance of the whole supply chain as the overall efficiency of the supply chain is compromised.

Hence, there is a need for the retailer to intervene by establishing some form of contract to encourage information sharing from the two suppliers. One of possible ways is to have the retailer paying a compensation λ for the information shared by the respective supplier without lowering retailer's own profit in doing so. Here λ and ε are related as following:

$$\lambda = \varepsilon + \Delta, \qquad \Delta \rightarrow 0 \tag{13}$$

The equation above shows that λ should be just slightly higher than ε so as to induce the suppliers to share information about their new capacity distributions while the retailer still has an increase in his profit despite the additional cost of 2λ when the new NE (Yes, Yes) is reached.

With the intervention from the retailer, the new Nash Equilibrium (Yes, Yes) is reached. Under this NE, both upstream and downstream players have an increase in their profits and hence the adverse impact of supply chain risk under the disruption is mitigated for all parties within the supply chain. Hence, from the analysis above, it is observed that if a contact or an agreement about the mitigation strategy on information sharing can be formed between the upstream and downstream players, the ability of the whole supply chain to resist any adverse impact of supply risk is improved. However, one limitation is that the model established is solely for one-period game, hence it tells very little about the sustainability of such contracts or agreements in the long run. Thus as one possible extension, the framework of finite or infinite game on prisoners' dilemma can be explored to study the presence of any grim trigger strategies which depends on the interests of the players towards the long-run profitability.

5. Conclusion

This work employed game theory approach to study the impact of information sharing in a supply chain which consists of one retailer and two suppliers. It shows that information sharing does improve the overall profitability of the supply chain. However, voluntary information sharing is not possible due to the additional cost of information sharing incurred to the suppliers. Hence a mitigation strategy is recommended to improve the overall supply chain efficiency while maximizing individual player's payoffs.

ACKNOWLEDGMENTS

We thank Ms. Bo Fu for her hard work devoted to this paper.

REFERENCES

Associated Press. (2013, August 3). New Zealand botulism scare triggers mass global recall. New Zealand.

Chen, F. (2003). Information sharing and supply chain coordination. In Handbooks in OR & MS. New York: A.G. de Kok and S.C. Graves, Eds.

Chu, W. J., & Lee, C. (2005). Strategic information sharing in a supply chain. Hong Kong: Emerson Electric Asia-Pacific.

Converium. (2006). Case studies: Toyota Motor Company, Inc.

Cruz, T. W. (2009). Supply chain disruption risk management through strategic information acquisition and risk-sharing contract. Memphis, USA: International Journal of Production Research .

Ha, A., & Tong, S. (2008). Contracting and information sharing under supply chain competition. Management Science, 701-715.

Li, L. (2002). Inormation sharing in a supply chain with horizontal competition. Yale School of Management.

Sosic, M. N. (2006). Game-theoretic analysis of cooperation among supply chain agents: Review and extensions. Los Angeles: Sauder School of Business, University of British Columbia, Vancouver.

Tang, C. S. (2006). Perspectives in supply chain risk management. International Journal of Production Economics.