A MODEL FOR SUPPLY CHAIN RISK RESILIENCY MEASUREMENT AND PLANNING

Kanchan Das (dask@ecu.edu, 252-737-1905), Technology Systems Department, East Carolina University, Greenville, NC 27858, USA

Reza S. Lashkari (lash@uwindsor.ca, 519-253-3000 X2609)**,** Department of Industrial and Manufacturing Systems Engineering, University of Windsor, Windsor, Ontario, N9B 3P4 CANADA

ABSTRACT

This paper proposes supply chain (SC) risk readiness and resiliency measures and a model for planning and controlling select internal business factors to create desired risk resiliency in order to avert potential risks and mitigate their after effect. SCs may be affected by disasters that are generated internally within the chain's business operations, or externally in the market, in the transportation system, or due to natural calamities or terrorism. The proposed model and the measures will guide SCs through the process of identification, planning and controlling the internal factors that make the chain resilient to internal and several external risks.

Key words: Risk readiness and resiliency measures, risk factors, supply risk, production and quality failure risk

INTRODUCTION

Risk has been defined as the probability, extent and significance of the loss to an organization due to an adverse event (Harland *et al.*, 2003). A resilient supply chain has the ability to withstand the risk, recover to its original state, or even move to a more desirable state after being disturbed (Christopher and Peck, 2004). Rice and Caniato (2003) pointed out the need for "secure and resilient" supply networks, where 'resilient' refers to the ability of the network to 'recover from unexpected disruptions. Following the literature, risk management process may be described as the identification of risks, risk assessment, and planning and implementation of risk aversion and/or risk mitigation (Kleindorfer and Saad, 2005). Process control, demand, supply and environment are the four common SC risk sources. Following the guidelines in Sheffi and Rice (2005), except a limited number of severe natural calamities, it is possible to estimate the likelihood and the extent of the intensity of a risk, and develop a plan to avert and/or mitigate it. For an SC to be resilient with respect to a risk it needs to attain the required readiness that involves expensive resources as well as planning steps. As such, there should be a metric to measure the SC's current readiness against the required readiness. In this paper, we define this metric as resiliency. The objectives of this research are: 1) defining SC risk readiness and risk resiliency, 2) developing a SC planning model involving risk factors, impacts, and costs and benefits; and 3) to analyze resiliency measures using a what-if approach.

LITERATURE SURVEY

Christopher and Peck (2000) recommended the SC design to be resilient such that several options, such as creating redundancy, supplier flexibility, identifying pinch points, etc., should be kept open for strategic decision process. Based on the analysis of the MIT's response to terrorism study, Rice and Caniato (2003) identified planning flexibility, redundancy in operational stages, designing systems to fail smartly, training personnel on security and resilience requirements, making security and resilience a part of the company culture, and business continuity planning. Sheffi and Rice (2005) comprehensively described several risks and uncertainties faced by SCs. Chopra and Sodhi (2004) identified several broad categories of risks along with their drivers and proposed various mitigation strategies for the risks. Tang and Tomlin (2008) presented a framework and five models for implementing a strategic risk management program using flexibility. Lee (2004) recommended alignment, agility and adaptability as the three principles for reducing the negative effects of supply, process and demand risks. Knemeyer *et al.*(2009) proposed a risk management framework and a systematic approach based on the recommendations in the literature to proactively plan for disaster management.

The literature review highlighted the importance of SC risk readiness and the creation of resiliency. But it clearly reveals lack of comprehensive approaches to the estimation of quantitative risk readiness measures for SCs, and the identification of trade-off options in relation to achieving readiness and resiliency status. This research attempts address these gaps.

DEFINING SUPPLY CHAIN RISK RESILIENCY

Let us define business risk resiliency as R_j for risks $j \in J$. Business risks may be generated in internal operations of a business; or external risks that are generated in the environment external to the business. The internal risks are designated as $j' \in J'$,{ $J' = 1,2,3,...,n$ } and the external risks as $j'' \in J''$, { $J'' = n+1, n+2, n+3,..., m$ }; then, the overall risks for a business are $J = J' \cup J''$.

Risk may be defined as the probability of loss and the significance of that loss to the organization. Risk management decisions are mostly influenced by the possible supply chain outcomes, their likelihood, and their subjective values (March and Shapira, 1987). March and Shapira also observed that the managers could perceive the maximum extent of loss viewing risk as the negative outcomes. Based on these risk related concepts, SC risk readiness may be defined as the deployment of resources and strategies for containing a potential risk. Assuming that a SC may estimate, for a risk *j'*, the required internal risk readiness $ED_{j'}$ as well as the current status of risk readiness $CD_{j'}$. Then the SC resiliency for risk *j'* may be expressed as $r_{j'} = CD_{j'}/ED_{j'}$ which is a ratio ≤ 1. The readiness may be measured in dollar value, quantity, or capacity value, of the resources needed to create flexibility, built-in quality system, robust design, networking, partnering, extra inventory, etc., relevant to the risk under consideration. Considering the interconnected SC business functions, the overall internal risk resiliency *IR* for a set of risks may be defined as: $IR = \prod_{j'=1}^{n} r_{j'}$. In the same manner, the expected and current readiness for an external risk *j''* may be defined as $EX_{j''}$ and $CX_{j''}$, respectively, and the resiliency as $r_{j''} = CX_{j''}/ EX_{j''}$. The overall external risk resiliency *ER* for a set of external risks may be defined as: $ER = \prod_{j''=n+1}^{m} r_{j''}$ .Most of the external risks are such that SC has very few, or no, options to prevent them. As such SC is left with the option of taking steps to mitigate external risks by working on appropriate internal factors. Let $i \in I, \{I = 1,2,3,..., m\}$ be the factors that can be worked on to avert/mitigate internal risks, and in the process, mitigate external risks. Examples of such internal factors are plant capacity, plant capability, supply quality, etc. For instance, creating flexibility in plant capacity would mitigate against the risk associated with production and output management. We assume the cost involved in influencing factor *i* to create and enhance internal risk readiness is IC_i, and the corresponding cost for external risk readiness is XC_i. To avert/mitigate, an internal or an external business risk a SC will be required to work on several select factors at the same time. In some cases it may be the creation of extra inventory; in other cases, it may be flexibility, etc. At this point, it is also noted that when the required readiness for internal or external risks is planned, a set of risks may be influenced by some common factor with its performance at different levels. Let $NC_{ij'}$ be the cost involved in using factor *i* to influence the internal risk *j*', and $MC_{ij''}$ be the cost involved in using factor *i* to influence the external risk *j''*. We may then define:

$$IC_i = \max_{over\ j' \in J} NC_{ij'} \quad \forall i \qquad XC_i = \max_{over\ j'' \in J} MC_{ij''} \quad \forall i \tag{1}$$

As such, the internal and external risk resiliency in terms of cost is defined, respectively, as:

$$r_{j'} = \sum_{i \in I} \alpha_i IC_i / \sum_{i \in I} IC_i \text{ and } r_{j''} = \sum_{i \in I} \beta_i XC_i / \sum_{i \in I} XC_i \tag{2}$$

where α_i and β_i parameters are ≤ 1, denoting the fact that, in general, the current level of readiness due to the influence of factor *i* is less than the required readiness. In this case, the total cost of creating the required risk resiliency, *TCR*, for a SC may be expressed in (3): In this equation the minimum readiness cost for a factor is subtracted to avoid double counting.

$$TCR = \sum_{i \in I} IC_i + \sum_{i' \in I} XC_{i'} - \sum_{i \in I \,\&\, i' \in I \,\&\, i = i'} \min\{IC_i, XC_{i'}\} \tag{3}$$

MODEL FORMULATION

The model formulates the problem of a globally operated SC that manufactures a set of products $p \in P$ in plants $l \in L$ using inputs $r \in R$ from suppliers $s \in S$, and transports the products to a set of distribution centers (DC) $w \in W$, and from there to a set of market locations, $m \in M$. The SC foresees a set of internal and external risks $j' \in J'$ and $j'' \in J''$, respectively**,** that may disrupt their business operations. Based on past data and day to day monitoring of business conditions the SC identifies the following two internal risks and two external risks that have the potential to significantly disrupt their operations. The **two internal risks** are**:** 1) *Supply risk* due to quality failure of supply inputs, or insufficient, or no input quantity (referred as short-supply or no-supply), 2) *Production risk* caused by significant machine breakdowns, and quality failure of the products; and **two external risks**: 1) *Product recall* due to product quality failure in the market that could create media attraction, 2) *Failure to supply* the required product quantity to the market. Since risk resiliency creation involves considerable investment it is needed to be integrated in the strategic business decision model. Thus, a mathematical model is proposed to assess the risks, identify the contribution of mitigation/aversion factors, and optimize the costs.

Internal Risks: 1) To create *supply risk readiness* or *resiliency*, quality affiliated partner suppliers and acceptable quality cost-based suppliers using the suppliers' performance following the approach in (Das, 2011a) are created. This approach designates suppliers either at the level of high quality partners (thus providing an alternative source of high quality inputs), or at the level of acceptable quality cost-based suppliers (thus providing additional supplier flexibility) following approach in (Das, 2011b). Assuming the SC has determined the pool of suppliers discussed above, the outcomes of the quality affiliation are integrated into the model. **2)** To create *production risk readiness* or *resiliency*, we consider two cases. When the production risk is caused by the quality failure of the products, we similarly follow the above approach to create a pool of 'quality capable plants operated by the SC and the network partners (Das, 2011a) in order to generate capacity flexibility as explained in (Das, 2011b). In case the plants operated by the SC fail, the capacity flexibility manages the production from network based partner plants. When the *production risk* is due to machine breakdowns, we consider breakdown (BM), preventive (PM) and condition-based (CBM) maintenance policies to contain the risk.

External risks: After considering **internal risk** readiness factors it is evident that most of the **external risks** are already addressed in this case. The product recall risks would be prevented by assigning inputs to high quality partner suppliers and the output or shipment quality and product safety will be ensured by allocating production to quality capable plants. The risk of no-supply, or short-supply of products to the market will be arrested if input supply is taken from partners and if there is a pool of suppliers to create flexibility. The next internal risk is the *production risk* caused by significant machine breakdowns and quality failure of the products. The plant capacity flexibility and following CBM based maintenance policy will take care of short-or no- supply situations. As such, by adopting the policies and decisions described above, the SC is creating risk resiliency to avert/mitigate the identified risks.

The Mathematical Model

The SC strategic planning model that focuses on factors in creating risk readiness, resiliency and provide options to conduct what-if analyses is presented in this section. Due to space limitation only objective function and important constraints are described here: Interested readers may send request to first author for details of model.

Objective Function: maximize: *Profit* = *GR-TC* (4)

where *GR* is the gross revenue, and *TC* is the total cost defined below:

$$GR = \sum_{p\in P}\sum_{m\in M}(\sum_{w\in W} y_{pwm} - RY_{pm})V_{pm} \tag{5}$$

The gross revenue *GR* is earned from selling effective quantities of products to customers at market prices (V_{pm}). Effective sold quantity is the difference of gross amount of a product sold (y_{pwm}), and product returned by the customers (RY_{pm}) due to quality or other problems.

$$TC = INC+PRDC+MTC+TRDC+CCSP \tag{6}$$

where, *INC*=input cost; *PRDC*= production cost; *MTC*= maintenance cost; *TRDC* = transportation and distribution cost; and *CCSP* = customer complaint and short supply cost.

Constraints include : 1) balancing the market demand with the product distributed to the market after adjusting for short supplies; 2) limiting the production quantities based on the effective capacities of the plants operated by the SC and by the network partners; 3) allocating production only to the quality capable SC-operated plants when they have enough capacity, otherwise to the network partner plants that SC-operated plants cannot accommodate; 4) assign the entire requirements of an input to high quality partner suppliers (HQPS from here on) if their combined capacity is sufficient, otherwise to acceptable quality suppliers (AQCS from here on) that cannot be fulfilled by HQPS, and 8) several technical and integrality constraints.

A NUMERICAL EXAMPLE

We assume a SC network produces 10 products using 15 components procured from several suppliers, transports products from its production plants to 8 DCs, and then distributed to 12 markets. Assuming that the SC faces a number of ‘disasters' that cause input quality problems, delayed supplies, plant breakdowns, production quality failures, and shipment delays in its own operations. Using the model the SC first affiliates and integrates a set HQPS and a pool of AQCS for each of the inputs in the strategic decision process. Table 1 presents a model output for typical list of quality affiliated suppliers for inputs 1, 6, and 11.

TABLE 1: INPUT SUPPLIERS AFFILIATED AT HQPS (SHOWN AS PS) AND AQCS POOLS (SHOWN AS CS)

Input	Affiliation of **Suppliers**	**Input**		**Input**	
1	**PS** 1, 2, 3,8,9,13, 16, 18, 19, 20 **CS** 4,5,6,7,10,11,12,14,15,17	**6**	**PS** 4,5,6,710,11,12,14,15,17 **CS**1,2,3,8,9,13,16,18,19,20	**11**	**PS**1,2,3,8,9,13,16,18,19,20 **CS** 4,5,6,7,10,11,12,14,15,17

In the next step **the model** identifies and integrates in the strategic decision process 5 plants operated by the SC and 2 plants operated by network partners as quality capable plants. By this it allocates production only to the quality capable plants. The model also integrates in its strategic decision process the option of including BM, PM or CBM maintenance program for each plant. We used input data on plant maintenance on availability (85% for BM, 95% PM and ≈100% for CBM) including relevant costs; production capacity, market demand and prices for the products, input usage. Based on a study, SC determined that the 3% to 5% (let this range be Δ), of product returns were generated when manufactured using the inputs from AQCSs. Out of these returns 15% to 25% (let this range be Φ) are translated into customer complaints. We present typical model output for Φ =20% in the top part and Φ =25% at the bottom part of Table 2. The higher profits in case (1) were mainly due to the lower input cost from AQCS that

TABLE 2: BUSINESS PERFORMANCES AT DIFFERENT DECISION STATES

Performance	Maintt :PM/BM Δ =3% (case1)	Maintt: PM/BM Δ =4% (Case 2)	Maintt CBM) Δ =5%-Case 3	HQPS inputs, Maintt: CBM Case 4
Profits ($)	30,150,480.00	27,392,170.00	24,962,850.00	28,395,010.00
Gross revenue ($)	119,413,500.00	118,235,000.00	117,699,000.00	155,526,300.00
Input supply cost ($)	52,640,070.00	53,748,500.00	55,427,320.00	94,442,800.00
	Δ =**5%,** Φ = 25%,Maintt: PM/BM- Case 5		HQPS lower input cost by 10%, maintt:CBM-Case 6	
Profits ($)	24,207,730.00		37,835,550.00	
Gross revenue ($)	118,638,700.00		155,526,300.00	
Input supply cost ($)	56,812,910.00		85,002,260.00	

faded away when Δ =4%**,** and then Δ = 5%. Also presented (case 5) when the business works with HQPS to lower the input cost by only 10%, and thus the profits soar to $ 37.85M.

Analysis of risk resilience: Based on the numerical example, the risk resiliency with respect to quality failure was found to be 0.95 when SC takes inputs from AQCS. Considering the fact that the buyer is using a pool of acceptable quality suppliers, due to supply flexibility non-supply instances are almost zero. As such risk resilience due to the supply failure ≈1. Overall risk resilience for supply failure = 0.95*1=0.95. For production risk due to machine breakdowns, when CBM is used risk readiness ≈1, compared to readiness 0.85 for BM. Since business allocated production to the quality capable plants, quality failure is almost: 0. So overall resiliency for production risk =0.85 *1 =0.85. Since external risks are very well addressed by the internal risk readiness, overall SC risk resiliency for these identified internal and external risks is: 0.85*0.95= 0.81.Once the SC follows CBM and takes inputs from HQPS, their resiliency ≈1.

CONCLUSION

The research introduced risk readiness and resiliency definition and derived practicable expressions for the measures. These measures and proposed model will facilitate SC managers to evaluate their positions and create long and short term achievement target in relation to potential risks. The model will aid them to take strategic and short term decisions more confidently.

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