Proceedings of the 2004 IEEE
International Conference on Robotics & Automation
New Orleans, LA • April 2004

A Conceptual and Analytical Framework for the Management of Risk in Supply Chains

Roshan Gaonkar
The Logistics Institute – Asia Pacific
National University of Singapore
Singapore – 119260
E-mail: roshan@nus.edu.sg

N. Viswanadham
The Logistics Institute – Asia Pacific
National University of Singapore
Singapore – 119260
E-mail: mpenv@nus.edu.sg

Abstract— **In this paper, we develop a framework to classify supply chain risk management problems and approaches for the solution of these problems. We argue that risk management problems need to be handled at three levels strategic, operational and tactical. In addition, risk within the supply chain might manifest itself in the form of deviations, disruptions and disasters. To handle unforeseen events in the supply chain there are two obvious approaches: (1) to design chains with built in risk-tolerance and (2) to contain the damage once the undesirable event has occurred. Both of these approaches require a clear understanding of undesirable events that may take place in the supply chain and also the associated consequences and impacts from these events. We can then focus our efforts on mapping out the propagation of events in the supply chain due to supplier non-performance, and employ our insight to develop two mathematical programming based preventive models for strategic level deviation and disruption management. The first model, a simple integer quadratic optimization model, adapted from the Markowitz model, determines optimal partner selection with the objective of minimizing both the operational cost and the variability of total operational cost. The second model, a simple mixed integer programming optimization model, adapted from the credit risk minimization model, determines optimal partner selection such that the supply shortfall is minimized even in the face of supplier disruptions. Hence, both of these models offer possible approaches to robust supply chain design.**

Keywords-***Supply Chain Risk Management, Risk Management, Supply Chain Management, Partner Selection, Supplier Portfolio Optimization.***

I. INTRODUCTION

Manufacturing supply chains today tend to be global in nature, comprising of complex interactions and flows between tens, even hundreds and thousands of companies and facilities geographically distributed across regions and countries. Such chains are currently in operation in a variety of industries such as electronics, automotive, aerospace, etc. Despite their complexity, most manufacturing supply chains are structurally similar. The member companies in a typical manufacturing supply chain network include the suppliers and their suppliers, assembly plants, distributors, retailers, inbound and out bound logistics providers and financing institutions. In fact under the intense competitive scenario prevalent today, competition is no longer between companies but between supply chain networks with similar product offerings, serving the same customer.

The winning supply chain networks are usually characterized by the presence of dominant organizations (also called channel masters) such as Dell, GM, Sun or Nike that possess strong domain knowledge, design, brand and marketing capabilities, around which they congregate. Furthermore, these supply chains are able to achieve a high level of efficiency through the sophisticated use of pervasive information and logistics networks that hold the supply chain together, and facilitate the easy movement of information and goods throughout the chain. Given their influence and consequentially the role of controller within the supply chain, the channel masters are typically responsible for supply chain planning incorporating [1]:

1. Selection of appropriate partners to form the supply chain based on market requirements.
2. Synchronization of activities between selected partners for optimal profit.

In a perfect world, the plans generated by the channel master would allow all the partners to synchronize their activities and business processes leading to greater efficiencies and profits for everyone. For e.g. components would arrive at the assembler site on time for production to start, adequate inventory of all components would be available before production and demand would be deterministically predictable. However in the practical world uncertainty rules. Consequentially, sales routinely deviate from forecasts; components are damaged in transit; production yields fail to meet plan; and shipments are held up in customs. In truth, schedule execution as per plans generated by supply chain planning is just a myth.

Because supply chain performance is inherently unpredictable and chaotic, supply chain practitioners often must seek safety mechanisms to protect against unforeseen events. Significant efforts are expended to expedite orders, to check order status at frequent intervals, to deploy inventory “just-in-case” and to add safety margins to lead times, among several other creative ways to counter the occurrence of unforeseen events. These time and material inventories along with limited communications among the partners hide the problems until they lead to serious consequences. Whilst risk has always been present in the process of reconciling supply with demand, there are a number of factors, which have emerged in the last decade or so, which might be considered to have increased the level of risk. These include - a focus on efficiency rather than effectiveness; the globalization of supply chains; focused factories and centralized distribution; the trend towards outsourcing; reduction of the supplier base; volatility of demand; lack of visibility and control procedures. As a result, it has become extremely important for channel masters to employ risk management tools in the management of their supply chains.

However, the existing ERP, SCM, EAI and other B2B solutions are designed to improve efficiency of the supply chains and not to enhance their reliability or robustness under uncertainty. Some of the vendors offer partial solutions to this problem under the name of Supply Chain Event Management (SCEM). These offerings include track and trace, supply chain visibility and alert messaging solutions [2], which merely notify the human operator of unexpected occurrences and leave him to resolve the issue. In such a scenario, there is a critical need for a framework and for suitable tools that would allow companies and managers to better understand the presence and significance of various types of risks and allow them to manage it better. In this paper we attempt to address these needs from the perspective of a channel master.

A. Previous Work

In a very general sense, research from high reliability organizations (HROs), networked organizations, and inter-organizational systems is relevant in the study of supply chain reliability, trust and risk [See 3 and 4]. Some of the research within this area focuses on risk management in a special breed of organizations, called virtual organizations, which are also a collection of companies under independent ownership that come together for a common purpose such as fighting forest fires or mitigating the risk of oil spills. However, in terms of directly relevant work in the area of supply chain risk management, Paulsson [5] provides a good survey of the recent literature in the field. Sheffi [6] provides a dual sourcing approach to handle supply risks in the face of unforeseen events in the supply chain brought about by international terrorism. In addition, there are a few commercial software solutions and technology implementations to manage supply chain exceptions and events [2]. In [7], one of the authors has developed a method based on process capability indices to minimize lead-time variance minimization. Despite these publications, since the area of supply chain risk management is an emerging area of research, there are limited perspectives, theoretical models and frameworks addressing the area. We wish to provide exactly such a theoretical basis in this paper.

B. Organization of this Paper

In this paper, we present a conceptual framework for the classification of supply chain risks and associated approaches to handling them. In particular, we focus on the design of robust supply chains at the strategic level through the selection of suppliers that minimize the variability of supply chain performance in terms of cost and output. In this manner we are able to build robustness into the supply chain at the planning stage itself. In section 2, we present a conceptual framework for the classification of supply chain risks and associated approaches to building robustness in the supply chain. In section 3, we develop models for supply chain risk management at the strategic level. In section 4, we share some of our computational results and observations and finally we conclude in section 5 with a discussion on the possibilities for future work.

II. Conceptual Framework to Approach Supply Chain Risk Problems

A. Classification of SC Risk Problems

Based on its nature, uncertainty in the supply chain may manifest itself in three broad forms – deviation, disruption and disaster – as explained below.

Deviation: A deviation is said to have occurred when one or more parameters, such as cost, demand, lead-time, etc., within the supply chain system stray from their expected or mean value, without any changes to the underlying supply chain structure.

Examples of deviations:

1. Variations in demand.
2. Variations in supply.
3. Variations in procurement, production and logistics costs.
4. Variations in transportation and production lead-times.

Disruption: A disruption occurs when the structure of the supply chain system is radically transformed, through the non-availability of certain production, warehousing and distribution facilities or transportation options due to unexpected events caused by human or nature.

Examples of disruptions:

1. Disruptions in production (Taiwan earthquake resulted in disruption of IC chip production, Component production for disrupted due to a fire in Toyota's supplier's factory in Mexico resulting in downstream factory shutdown)
2. Disruptions in supply (Meat-supply was disrupted due to spread of foot-and-mouth disease in England).
3. Disruptions in logistics (US port shutdown disrupted the transportation of components from Asia to the US)

Disaster: A disaster is defined as a temporary irrecoverable shut-down of the supply chain network due to unforeseen catastrophic system-wide disruptions.

Examples of disasters:

1. Terrorist Action (The entire US economy was temporarily shutdown due to the downturn in consumer spending, closure of international borders and shut-down of production facilities in the aftermath of the terrorist attacks on the 11th of September 2001.)

In general, it is possible to design supply chains that are robust enough to profitably continue operations in the face of expected deviations and unexpected disruptions. However, it is impossible to design a supply chain network that is robust enough to react to disasters. This arises from the constraints of any system design, which is limited by its operational specification.

Furthermore, supply chains need to be robust at three levels, strategic, tactical and operational and they need to be to handle minor regular operating deviations and major disruptions at each of these three levels. For example, at the operational level, companies require decision support systems that can act on information from various partners regarding various deviations and disruptions to reschedule activities so that the business processes are synchronized and deliveries are undertaken within customer delivery windows and cost limitations. At the tactical level, plans need to have redundancies in terms of human and machine resources and also logistics and supply organizations. At the strategic level, more reliable partners with intrinsic capabilities in deviation and disruption handling, and the skills and ability to adapt to changing market conditions will be preferred and selected.

A complete classification of risk management issues, with examples, at various levels and of various scopes is presented below, with examples in Table 1.

TABLE I. TYPES OF DEVIATIONS

Planning Level	Type of Event	Example
Strategic	Deviation	Logistics/Manufacturing Capacity Addition
	Disruption	Supplier bankruptcy
Tactical	Deviation	Order forecast
	Disruption	Port strike
Operational	Deviation	Lead-time variation
	Disruption	Machine/Truck breakdown

B. *Mathematical Progamming Models*

Within the context of the broad classification of risk management issues suggested above a number of different analytical and computational methods can be employed to design robust supply chains, mathematical programming being one of the most preferred tools amongst them.

Mathematical planning models can be employed to select and schedule processes and partners such that the overall supply chain is by design robust to internal and external stimuli. In particular, portfolio optimization models commonly applied in finance can be used to select a portfolio of suppliers such that the total supply chain cost variability and the consequences from supplier non-performance are within manageable limits, as demonstrated in the later sections of this paper. In addition, recent work in the area of robust optimization can also be used to generate supply chain solutions that maintain their optimality under minor deviations in environmental conditions.

C. *Basics of Uncertainty Management*

To better manage the uncertainties in the supply chain it is necessary to identify the exceptions that can occur in the chain, estimate the probabilities of their occurrence map out the chain of immediate and delayed consequential events that propagate through the chain and quantify their impact. In this context, it becomes important to identify the possible exceptions in a supply chain and their consequences before proceeding to the development of analytical models.

1) *Failure or Disruption Modes*

In a supply chain exceptions can occur at various nodes - on the supply side, demand side, during transport or in storage – and due to a variety of different causes. There could be failures of power and communications or employee strikes. There is also a risk of breach of trust by partners, by outside elements. It is not possible to list all of them but we have the following possible modes of disruption.

TABLE II. EXAMPLES OF FAILURE OR DISRUPTION MODES

Mode of Disruptions	Description
Supply side	Delay or unavailability of materials from suppliers, leading to a shortage of inputs that could paralyze the production.
Transportation	Delay or unavailability of either inbound and outbound transportation to move goods due to carrier breakdown or weather problems
Facilities	Breakdown of machines, power or water failure leading to delay or unavailability of plants, warehouses and office buildings.
Breaches in freight or partnerships	Violation of the integrity of cargoes, products (can be due either to theft or tampering with criminal purpose, e.g. smuggling weapons inside containers) or company proprietary information.
Failed Communications	Failure of information and communication infrastructure due to line, computer hardware or software failures or virus attacks, leading to the inability to coordinate operations and execute transactions.
Wild demand fluctuations	Sudden loss of demand due to economic downturn, company bankruptcies, war, etc.

In this paper, we specifically study supplier non-performance, in terms of the complete failure of a supplier to deliver components to the manufacturer or the inability of the supplier to deliver components at the promised price.

2) *Cause-Consequence Diagrams*

Cause-consequence diagrams or event trees are tools commonly used in reliability analysis to study the overall impact of a particular failure on the entire system. Based on the supply chain configuration, we can develop cause-consequence diagrams for each failure described above. However, given our interest in developing models for supplier selection, we employ cause-consequence diagrams to specifically analyze the effect of supplier non-performance on the supply chain and to estimate the associated shortfalls in supply.[9]

Given the probability of occurrence of the initiating event, which is supplier non-performance, and the probabilities for the various intermediary events, we can calculate the probability of occurrences for each of the end states or outcomes. Furthermore, each of these end states may result in different levels of supply shortfalls and financial cost. Hence, given the probability of each end state and the supply shortfall or financial cost for each end state, we can calculate the expected shortfall or financial risk for the non-performance of a given supplier. Such an analysis can be repeated for each supplier, and the least risky supplier can be identified as the one whose non-performance results in the least expected supply disruption or least expected financial loss.

III. Problem Formulations for Strategic Level Risk Management

With the above foundation in the basics of supply chain risk management we now highlight the above approach by presenting two representative models for strategic level supply chain risk management, from the perspective of the channel master. With reference to our classification presented earlier the first model falls under the class of strategic level problems for deviation management and the second falls under the class of strategic level disruption management models. Both models employ the preventive approach to risk management based on the use of mathematical modeling techniques as described below.

1. Strategic-level Deviation Management Model: Given the expected costs and variability (deviation) of costs for all suppliers, the first problem relates to the selection of an optimal group of suppliers such that the expected cost of operating the entire supply chain and the risk of variations in total supply chain costs is minimized.
2. Strategic-level Disruption Management Model: Given the expected probabilities for various supplier disruption scenarios and the supply shortfalls under each of these scenarios the objective for the manufacturer is to choose a set of suppliers that minimize the expected shortfall during the operation of the supply chain.

In addition, we make the assumption that the supply chain is distributed globally and each player within the chain has its own goals, policies and cultures. The channel master who occupies a dominant position in the chain has all the information on its partners, including costs and schedules of the suppliers, the logistics providers, etc to be able to make a rational decision in the interest of minimizing risk.

A. Strategic Level Deviation Management Model

We propose an integer quadratic programming model for partner selection that tries to minimize the overall cost impact from the deviation in supplier costs. Such a model will be very useful to supply chain owners and channel masters. The model is an adaptation of the Markowitz model for financial portfolio management, for the purpose of managing a portfolio of suppliers. For this model, we define the impact in terms of the risk as given by the deviation of the total supply chain cost from its expected mean value. Given the expected costs and the variability of costs for all suppliers and manufacturers the objective is to choose a set of suppliers and manufacturers that minimize the expected cost of operating the entire supply chain and at the same time minimize the risk of variations in the total supply chain cost. The selection of these partners also considers the allocation of orders between these selected partners. The mean costs and variability of the costs for each supplier can be obtained from an analysis of their historical performance or by considering the probabilities of their non-performance and the associated costs of handling the consequent impacts. Furthermore, due to the stochastic nature of events in the cause-consequence diagram we can safely assume that in general the final outcomes and associated costs of supplier non-performance will be normally distributed.

Identifiers

$m \in M$:Manufacturer identifier.

$i \in I$:Component identifier.

$s \in S_{mi}$:Supplier identifier amongst the set of suppliers for component i to a specific manufacturer m.

Parameters

C :Mean cost of the supply chain entity.

V :Cost variability for the supply chain entity.

N :Minimum number of entities to procure from.

μ :Risk aversion parameter ($0 < \mu < \infty$).Large values for μ emphasize risk minimization and small values cost minimization.

Variables

X :Fraction of orders and hence costs allocated between manufacturers. ($0 < x < 1$).

Y :Fraction of orders and hence costs allocated between suppliers for a specific manufacturer. ($0 < y < 1$).

F :0 if supply chain entity is not selected and 1 if selected.

Model

Minimize

$$\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{s=1}^{S_{mi}} y_s C_s F_s + \sum_{m=1}^{M} x_m C_m Y_m + \mu\left(\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{s=1}^{S_{mi}} y_s^2 V_s F_s + \sum_{m=1}^{M} x_m^2 V_m Y_m\right) \quad \ldots(1)$$

Subject to:

$$\sum_{m=1}^{M} x_m F_m = 1 \quad \ldots(2)$$

$$\sum_{s=1}^{S_{mi}} y_s F_s = F_m \qquad forall \qquad m \in M \;\&\; i \in I \quad \ldots(3)$$

$$F_m \geq F_s \qquad forall \qquad m \in M \;\&\; s \in S_{mi} \quad \ldots(4)$$

$$\sum_{m=1}^{M} F_m \geq N_m \quad \ldots(5)$$

$$\sum_{s=1}^{S_{mi}} F_s \geq N_{mi} \quad forall \quad m \in M \,\&\, i \in I \quad \ldots(6)$$

The objective of the model is to choose manufacturers and their suppliers and allocate order quantities between them in a manner such that the expected cost of operating the supply chain is minimized and also the variability of the overall costs is minimized as well. This is subject to the constraint that the selected set of manufacturers, between, them fulfill the order (Eq. 2) and that the selected set of suppliers for these manufacturers, between them, fulfill the demand for all components (Eq. 3). Suppliers are part of the supply chain only when the manufacturers they supply to are involved (Eq. 4). Furthermore, there might be other policies that require a minimum number of manufacturers or suppliers to be engaged at each level of the chain for the sake of redundancy and greater reliability (Eq. 5 & Eq. 6).

B. *Strategic Level Disruption Management Model*

With the probabilities for supplier non-performance and knowledge of supply shortfalls under various resulting end-states (as obtained from the cause-consequence diagram), we propose a mixed integer-programming model for partner selection that tries to minimize the overall impact on the supply shortfall consequential from the exception of supplier non-performance. Such a model will be very useful to manufacturers, supply chain owners and channel masters who want to incorporate robustness into their supply chains. The model is an adaptation of the credit risk minimization model employed in financial portfolio management, for the purpose of managing a portfolio of suppliers. For this model, we define the impact in terms of the risk as given by the expected shortfall in the total supply from its expected value. Given the expected probabilities for various exception scenarios and the supply shortfalls under each of these scenarios the objective for the manufacturer is to choose a set of suppliers that minimize the expected shortfall during the operation of the supply chain.

<u>Identifiers</u>

$s \in S$:Supplier identifier.

$i \in I$:Scenario (state) identifier. I is the set of all supply scenarios (states), which is obtained as a mix of all combinations of supplier non-performance events for all the suppliers in the set J.

<u>Parameters</u>

K :Quantity required by the manufacturer.

x_i :Quantity supplied by supplier i.

R_j :Cost of including supplier j in supply chain.

C_j :Capacity of supplier j.

<u>Variables</u>

F_j : 0 if supplier j is not selected and 1 if selected.

y_i :Total supply shortfall to manufacturer in scenario i.

<u>Model</u>

Minimize

$$\sum_{i=1}^{I} p_i y_i + \sum_{s=1}^{S} R_s F_s \quad \ldots(7)$$

Subject to:

$$K - \sum_{s=1}^{S} x_s = y_i \quad forall \quad i \in I \quad \ldots(8)$$

$$x_s = F_s * C_s \quad forall \quad s \in S \quad \ldots(9)$$

The objective of the model is to choose suppliers such that the expected shortfall in supply, in the face of supplier disruptions is minimized. This is subject to the constraint (Eq. 8) which calculates the shortfall for each possible supply scenario. Also, the quantity supplied by any supplier is dependent on its capacity and also on the decision whether or not the supplier is included into the supply chain network (Eq. 9). When the supplier is included into the supply chain network his supplies are equivalent to his capacity.

IV. COMPUTATIONAL RESULTS

Both the models described above were formulated in Microsoft Excel and solved using the Solver add-in.

A. *Strategic-Level Deviation Management Model*

This model was solved for a problem with 5 manufacturers, dealing with 5 suppliers each, for each of the two components required in their manufacturing. The risk aversion factor was taken as 25 and it was required that atleast 2 manufacturers be selected for fulfilling the orders.

TABLE III. COST AND VARIANCE OF COST FOR EACH PARTNER

Manufacturer			**Component 1**			**Component 2**		
Mfg	C	V	Sup	C	V	Sup	C	V
Mfg 1	90	8	S 1	10	4	S 1	44	7
			S 2	15	3	S 2	45	6
			S 3	25	1	S 3	47	5
			S 4	20	2	S 4	43	6
			S 5	12	2	S 5	45	6
Mfg 2	81	7	S 1	13	3	S 1	50	4
			S 2	17	2	S 2	45	6
			S 3	19	1	S 3	44	6
			S 4	15	3	S 4	47	5
			S 5	10	3	S 5	43	7
Mfg 3	84	8	S 1	14	2	S 1	42	7
			S 2	16	3	S 2	46	5
			S 3	15	2	S 3	49	4
			S 4	11	4	S 4	48	4
			S 5	15	2	S 5	44	6
Mfg 4	93	6	S 1	12	3	S 1	45	5
			S 2	10	3	S 2	45	6
			S 3	20	3	S 3	48	4
			S 4	19	2	S 4	46	6
			S 5	18	2	S 5	50	3

Mfg 5	99	5	S 1	16	2	S 1	48	5
			S 2	18	2	S 2	47	6
			S 3	21	1	S 3	51	4
			S 4	14	2	S 4	51	5
			S 5	12	3	S 5	48	5

Mfg = Manufacturer ; Sup = Supplier

Due to the non-linear nature of the problem, the final solution obtained depends very much on the initial values of the variables. Moreover, the choice of manufacturers is the most critical decision since it also decides to a large extent the choice of suppliers. Hence, the model was solved for various initial solutions corresponding to all the possible combinations of supplier selection. The optimal solution obtained as a result is given below.

TABLE IV. COST AND VARIANCE OF COST FOR EACH PARTNER

Manufacturers		**Component 1**		**Component 2**	
Selected	Share	Sup	Share	Sup	Share
Mfg 4	0.46	S 1	0.167	S 1	0.179
		S 2	0.167	S 2	0.149
		S 3	0.167	S 3	0.224
		S 4	0.25	S 4	0.149
		S 5	0.25	S 5	0.299
Mfg 5	0.54	S 1	0.176	S 1	0.197
		S 2	0.176	S 2	0.164
		S 3	0.353	S 3	0.246
		S 4	0.176	S 4	0.197
		S 5	0.118	S 5	0.197

Sup = Supplier; Share = Fractional allocation of demand

B. Strategic-Level Disruption Management Model

This model was solved for a problem with a single manufacturer (located in the US), dealing with 5 suppliers. The probabilities of supplier disruption for all the suppliers (individually and in various combination) were considered as given. The relation cost was taken as $5000 and the quantity required by the manufacturer was 520 units. Supplier 1 (capacity: 250) was assumed to be based in Ireland with disruption possibilities due to Terrorist Attacks and Union Strikes. The second supplier (capacity: 250) is assumed to be in Taiwan with disruptions possibly resulting from Earthquakes and exposure to port closures on the US West Coast. The third supplier (capacity: 280) is a non-reliable supplier based in Malaysia and the fourth (capacity: 340) a reliable supplier in Singapore, both of whom are susceptible to the risk resulting from closure of US ports. The fifth supplier (capacity: 250) is assumed to be a local supplier. In addition, probability of all the different supply scenarios based on the location of the suppliers was considered. For example, the probability that only supplier 3 was disrupted was assumed to be 0.08 (much higher than the probability of disruption for other suppliers, given the fact that the supplier was non-reliable and based in a country less developed). Similarly the probability of suppliers 1,2 and 5 being simultaneously disrupted was taken to be 0.0045 due to the greater susceptibility of each of them to natural and terrorist disasters. The probabilities for all supply scenarios (all possible combinations of supplier disruptions) were considered. The model was solved with the above data. The optimal selection of suppliers included Suppliers 4 & 5, with an objective value of 10017. It might be noticed that these two suppliers are the most reliable suppliers.

V. CONCLUSION

We have developed a conceptual framework for the classification of supply chain risks and associated approaches to handling them. In particular, we focus on the design of robust supply chains, at the strategic level, that are resilient to deviations and disruptions that may occur at the supplier end. Our analysis is based on the identification of unforeseen events that may occur at the supplier end propagate down the supply chain leading to cost variability and supply shortfalls. Robustness is build into our supply chain design by selecting a portfolio of suppliers that minimize the variability of supply chain performance in terms of cost and output. The models we develop are preventive in nature and employ mathematical programming tools. Our efforts here are an attempt to formulate and solve problems in the emerging area of supply chain risk management. For example using our algorithm, the value of reliable suppliers and of adopting dual sourcing strategies in a supply chain can be easily determined. Finally we may mention that our mapping of exceptions and their associated consequences can also be used to build decision support systems for exception management.

REFERENCES

[1] Roshan Gaonkar, “Dynamic Configuration and Synchronization of Collaborative E-Supply Chain Networks”, PhD Dissertation, National University of Singapore, 2003.

[2] Michael Bittner, “E-Business Requires Supply Chain Event Management”, AMR Research, November 2000.

[3] Martha Grabowski, Jason R.W. Merrick, John R. Harrald, Thomas A. Mazzuchi and J Rene van Dorp, “ Risk Modelling in Distributed, Large-Scale Systems”, IEEE Transactions on Systems, Man and Cybernetics, Vol. 30, No. 6 November 2000.

[4] Martha Grabowski and Karlene H. Robots, “Risk Mitigation in Virtual Organisations”, Organisation Science, Vol. 10 No. 6, Nov-Dec 1999.

[5] Ulf Paulsson, “Managing Risks in Supply Chains – An Article Review”, Presented at NOFOMA 2003, Oulu, Finland, 12-13 June 2003.

[6] Yossi Sheffi, “Supply Chain Management under the Threat of International Terrorism”, The International Journal of Logistics Management, Volume 12, Number 2, 1-11, 2001.

[7] D. Garg, Y. Narahari, and N. Viswanadham, "Design of Six Sigma Supply Chains", to appear in IEEE Transactions on Automation Science and Engineering (first issue), April 2004.

[8] N. Viswanadham, “Analysis of Manufacturing Enterprises – An Approach to Value Delivery Processes for Competitive Advantage”, Kluwer Academic, Boston, 1999.

[9] Roshan Gaonkar and N. Viswanadham, “Robust Supply Chain Design: A Strategic Approach to Exception Handling”, *Proceedings of the ICRA 2003.*

[10] Savi Technology, http://www.savi.com.

[11] Vigilance, http://www.vigilanceinc.com

[12] Eventra, http://www.eventra.com