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ROBUST SUPPLY CHAIN DESIGN: A STRATEGIC APPROACH FOR EXCEPTION HANDLING

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ABSTRACT

In this paper, we develop a framework for robust supply chain design i.e. to build supply chains, which can handle disruptive events with minimal loss. There are two obvious steps to handle exceptions: (1) to design chains with built in risk-tolerance and (2) to contain the damage once the undesirable event has occurred. In this paper, we consider design of robust (to risks) supply chains. First we identify all the critical undesirable events that can occur at various stake holders and their interfaces and map out how each of them propagates through the supply chain. In this way, we identify the critical exceptions for various partners of the chain and understand the impact of all these exceptions, particularly on the supply. We develop a simple mixed integer programming optimization model, adapted from the credit risk minimization model, for partner selection as a means towards robust supply chain design. We choose the partners so that the effect of exceptions on the supply chain is minimized.

1. INTRODUCTION

Global manufacturing supply chains are networked organizations, with multiple company members with complementary competencies, distributed around the world, coming together with the purpose of delivering quality products or services to their customers. There are several such supply chain networks in operation now within the electronic, chemical, food, fertilizer, agriculture and other industries. 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. All the partners in the network are globally dispersed, but they achieve a high degree of coordination through tightly integrated electronic communications. Increasingly, competition nowadays is between supply chain networks, and as a result it is important to select partners in the network that provide a distinct competitive advantage. Supply chain networks have two distinct types of organizational models. The first type comprises of chains led and managed by dominant organizations (also called channel masters) such as Dell, GM, Sun or Nike that possess strong design, brand and marketing capabilities. Several contract manufacturers such as Flextronics also come under this category. The second type is characterized by virtual organizations, where partner companies in the supply chain network temporarily link up through electronic exchanges, without any long-term contracts, for exploiting a specific market opportunity.

Supply chain networks are event driven systems. Events occur across both space and time, triggering product movement from suppliers to manufactures and finally to the end consumer. Typical events include loading or unloading of a truck, the beginning of production of a batch of products, etc. Supply chain planning assumes that events happen as planned on time and there is synchronization among the business processes. For e.g. components arrive at the assembler site on time for production to start. But uncertainty rules the supply chain - 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 the 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 disruption. Significant efforts are expended to expedite orders, check order status at frequent intervals, deploy inventory "just-in-case," add safety margins to lead times, among several other creative ways to counter disruptive events. These time and material inventories along with limited communication among the partners hide the problems until it leads 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.

1.1 Exception Management

Exceptions are undesirable events. Discrepancies in quality, amounts delivered, and production and logistics breakdowns and delays are all exception events. Also natural disasters (e.g. the Kobe earthquake, which affected supply networks across the globe, or, more recently, foot and mouth disease, which has affected the food industry, cyclones which effect ocean transportation, etc); terrorist incidents (e.g. events in the USA on 11th September 2001); industrial or direct action (e.g. the fuel price protest of September 2000, which very rapidly impacted on almost every supply network in the U.K.); accidents (e.g. a fire in a component supplier's facilities can have such a serious impact on manufacturers that they are forced to shut down operations, such as Toyota in 1997 – due to problems at its supplier of brake-pressure proportioning valves); and operational difficulties (e.g. production or supply problems at one supplier can impact every organization in the supply network) result in exceptions.[8] Thus, exception management is an important issue in global supply chain networks.

The existing ERP, SCM, EAI and other B2B literature does not address the issue of real-time control of enterprises in the face of above exceptions. Currently, all the ERP, WMS, TMS and SCM vendors offer partial solutions to this problem under the name of Supply Chain Event Management (SCEM). These include track and trace, supply chain visibility and alert messaging solutions [3]. But real-time event management requires monitoring the global supply chain process for exceptions, evaluating their consequences in terms of production and shipments and suggesting actions to the stakeholders to minimize the total cost of disruption. For this to happen, it is important that all stakeholders in the supply chain collaborate and share information and also have proactive response capabilities to the triggers, events and alerts.

1.2 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 1 and 2]. There is also another breed of organizations called virtual organizations, which are also collection of companies under independent ownership coming together towards a purpose such as fighting forest fires or mitigating the risk of oil spills. In terms of relevant work in the area of supply chain reliability analysis and risk management there are a few commercial software solutions and technology implementations to manage supply chain exceptions and events [3]. In [9], one of the authors here has developed a method based on process capability indices to minimize lead-time variance minimization. However, there are no theoretical models or frameworks for such solutions. We wish to provide this theoretical basis in this paper.

1.3 Organization of this Paper

In this paper, we address the problem of robust supply chain design at the strategic level through the selection of suppliers that minimize, in terms of supply shortfall, the impact due to the occurrence of an exception. This way we will be building adaptive capabilities at the planning stage itself. In section 2, we characterize the two different approaches to exception management and describe the two important aspects of supply chain exceptions, and their resulting impact. In section 3, we develop an event tree to map out the impact of supplier non-performance in supply chain networks. In section 4, we develop an optimization model to select suppliers that confer robustness to the supply chain.

2. ANALYSIS FRAMEWORK

In our view the supply chain event management problem is a complex one and needs to be tackled at different levels using different methods.

Accepting the fact that exceptions cannot be completely eliminated, there are two approaches to manage exceptions – preventive and interceptive. The preventive route to exception management seeks to reduce the likelihood of occurrence of an exception through the design of a robust chain. The process starts with identifying the set of exceptions that can occur in the chain including the interfaces. For each of these exceptions one can conduct the root cause analysis and devise ways and means to reduce the probability of their occurrence. One can use fault trees or fish bone diagrams for doing this. This would also enable us to compute the probability of occurrence of these exceptions.

The interceptive approach on the other hands attempts to contain the loss by active intervention once the exception occurs (for e.g. if there is a disruption in the supply of a critical component, buy it in an exchange). This requires a very good understanding of all the available alternatives and their impact on the supply chain.

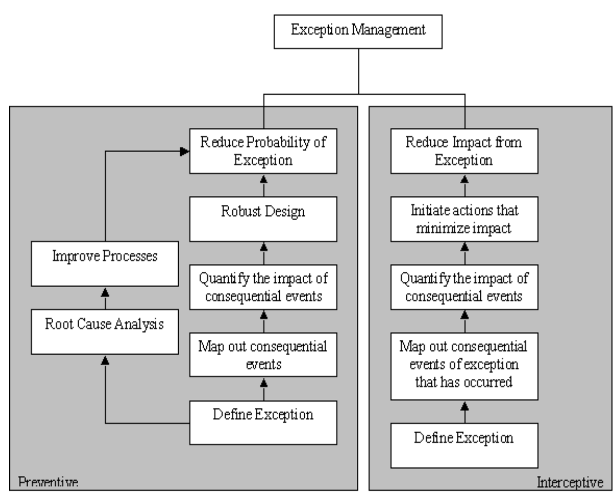

Fig 1: Exception Management Strategies

In both cases it is first 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 the preventive approach, the knowledge of exception probabilities and their resulting impact is employed to design chains that are inherently robust and resilient to exceptions. In the interceptive approach, once an exception occurs, based upon the map of consequential events and their impact actions that minimize the impact of the exception are initiated. This logic can be implemented in a rule-based decision-support system.

Furthermore, both these strategies need to be employed at the operational, tactical and strategic levels. At the operational level, the decision support acting on the information from various partners regarding the exception needs to reschedule activities so that the business processes are synchronized and deliveries are done with in the customer delivery windows. 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 exception handling, and the skills and ability to adapt to changing market conditions will be preferred and selected.

2.1 Supply Chain Exception: Definition

In attempting to analyze supply chain exceptions, our analysis here is based on a simple two tier supply chain structure where the customer demand is directly fulfilled by a manufacturer, who in turn is supplied various components by a set of suppliers. Logistics service providers handle the movement of materials between all the parties as shown in Fig 2.

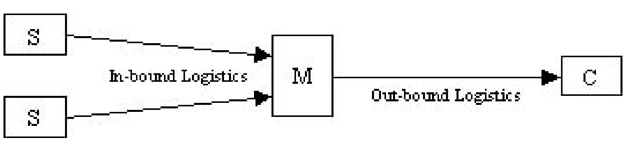

Figure 2 : Simple Model for Analyzing Exceptions

Before we go any further and attempt to calculate the reliability of supply chain networks, it is essential that we define what constitutes an exception in a supply chain network. In trying to differentiate a well-executed supply chain operation from a badly managed operation we are motivated to adopt the well-accepted classical "Seven Rs" definition for the purpose of logistics, which is:

> "To ensure the availability of the right product, in the right quantity, in the right condition, at the right place, at the right time, at the right cost, for the right customer."

We can use this description to define a supply chain failure or exception occurring whenever the supply chain deviates from any one of the above-required specifications- either in terms of delivering the wrong product, in the wrong quantity, in the wrong condition, at the wrong place, at the wrong time, at the wrong cost and to the wrong customer. Whenever a supply chain delivery fails to stay on specification on any one of these dimensions we say that an error has been committed in that dimension. In this paper, we specifically study supplier non-performance, or the failure of a supplier to deliver components to the manufacturer.

3. EXCEPTION MANAGEMENT IN SUPPLY CHAIN NETWORKS

In this paper, we address the problem of risk mitigation/ reliability enhancement in supply chain networks lead by channel master. Specifically we address exception management at the strategic level through the preventive selection of supply chain partners that mitigate risk in the network. What are the characteristics of such organizations?

1. The organizations are distributed globally and each has their own goals, policies and cultures. The channel master who occupies a dominant position in the chain basically has all the information on its partners, including costs and schedules of the suppliers, the logistics providers, etc.
2. Exceptions or failures occur due to root causes such as transport or machine failure, inventory inaccuracies, etc; due to natural or human-made disasters,
3. Exceptions propagate along the chain sometimes with serious consequences. This is called supply chain vulnerability.

Exception management can be through a centralized decision support system, which is possible in channel master driven chains or through fluidity or flexibility of the organizations to restructure and regroup in response to changes in the environment.

Exception management in supply chains should follow a systematic methodology and the capability to manage exceptions should be built in to the design. For example the supply chain members should have the capability to communicate with all other partners and also execute recommended actions should exceptions occur. In order to manage one must identify and understand the exceptional events, situations that lead to them and also map their consequences. Then exception management involves reducing the impact due to the occurrence of the undesirable events and also to design a robust supply chain through carefully selected partnerships that minimize the risk of supply chain non-performance.

3.1 Event Propagation: 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. However, given our interest in developing models for supplier selection, we employ these cause consequence diagrams to specifically analyze the effect of supplier non-performance on the supply chain and to estimate the associated shortfalls in supply. For this purpose we develop the cause consequence diagram for supplier non-performance as given below in Fig. 3.

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.

Failure Event	Inventory Check	Alternate Procure-ment	Customer Notification	Rescheduling of Mfg Capacity	Rescheduling of supply for other components	Cost Impact
Supplier Non-Performance	No Compo-nents in Inventory	Cannot procure componen ts from the spot market or alternative sources	Customer unwilling to take late delivery	Idle Mfg capacity resulting from disruption sold	Orders for supply of other components cancelled	Lost Sales Cost
					Orders for supply of other components not cancelled	Lost Sales & Holding cost for other components
				Idle Mfg capacity resulting from disruption unsold	Orders for supply of other components cancelled	Lost Sales, Cost of Unusec Mfg capacity
					Orders for supply of other components not cancelled	Lost sales, Cost of Unused Mfg capacity & Holding cost for other components
			Customer willing to accept late delivery	Idle Mfg capacity resulting from disruption sold	Supplies for other components postponed.	No cost impact
					Supplies for other components not postponed	Holding cost for other components
				Idle Mfg capacity resulting from disruption unsold	Supplies for other components postponed	Cost of Unused Mfg capacity
					Supplies for other components not postponed	Cost of Unused Mfg capacity & Holding cost fo other components
		Can procure components from the spot market or alternative sources				Cost of Procurement from Alternative sources
	Components available in inventory					Inventory holding cost

Fig. 3: Cause Consequence Diagram for Supplier non-performance and the resulting outcome.

4. PARTNER SELECTION MODEL FOR EXCEPTION MANAGEMENT

With the probabilities for supplier non-performance and knowledge of supply shortfalls under various resulting end-states, 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.

Identifiers

$j \in J$: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.

Parameters

K :Quantity required by the manufacturer.

x_i :Quantity supplied by supplier i.

R_j :Relation cost of including supplier j into the supply chain.

C_j :Capacity of supplier j.

Variables

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

y_i :Shortfall in total supply to manufacturer in scenario i.

Model

Minimize

$$\sum_{i=1}^{I} p_i y_i + \sum_{j=1}^{J} R_j F_j \quad \ldots(1)$$

Subject to

$$K - \sum_{j=1}^{J} x_j = y_i \quad forall \quad i \in I \quad \ldots(2)$$

$$x_j = F_j * C_j \quad forall \quad j \in J \quad \ldots(3)$$

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. 2) 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. 3). When the supplier is included into the supply chain network his supplies are equivalent to his capacity.

The model was formulated in Microsoft Excel and solved using the Solver add-in. The 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.

Table 1: Probabilities of various supply situations.

Scenarios	Explanation	Probability
1	Supplier 1 Disrupted	0.05
2	Supplier 2 Disrupted	0.04
3	Supplier 3 Disrupted	0.08
4	Supplier 4 Disrupted	0.01
5	Supplier 5 Disrupted	0.02
6	Suppliers 1 & 2 Disrupted	0.0015
7	Suppliers 1 & 3 Disrupted	0.0015
8	Suppliers 1 & 4 Disrupted	0.0005
9	Suppliers 1 & 5 Disrupted	0.0015
10	Suppliers 2 & 3 Disrupted	0.0016
11	Suppliers 2 & 4 Disrupted	0.0004
12	Suppliers 2 & 5 Disrupted	0.0008
13	Suppliers 3 & 4 Disrupted	0.0008
14	Suppliers 3 & 5 Disrupted	0.0048
15	Suppliers 4 & 5 Disrupted	0.0001

16	Suppliers 1, 2 & 3 Disrupted	0.0045
17	Suppliers 1, 2 & 4 Disrupted	0.0015
18	Suppliers 1, 2 & 5 Disrupted	0.0045
19	Suppliers 1, 3 & 4 Disrupted	0.0015
20	Suppliers 1, 3 & 5 Disrupted	0.0045
21	Suppliers 1, 4 & 5 Disrupted	0.0015
22	Suppliers 2, 3 & 4 Disrupted	0.0016
23	Suppliers 2, 3 & 5 Disrupted	0.0032
24	Suppliers 2, 4 & 5 Disrupted	0.0008
25	Suppliers 3, 4 & 5 Disrupted	0.0048
26	Suppliers 1, 2, 3 & 4 Disrupted	0.000045
27	Suppliers 1, 2, 3 & 5 Disrupted	0.000135
28	Suppliers 1, 2, 4 & 5 Disrupted	0.000045
29	Suppliers 1, 3, 4 & 5 Disrupted	0.000045
30	Suppliers 2, 3, 4 & 5 Disrupted	0.000032
31	All Suppliers Disrupted	0.00000135
32	None Disrupted	0.75779665

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.

5. CONCLUSION

We have developed a mixed integer-programming model for partner selection in supply chains. We call this robust design since we take into account the uncertainty of supplier performance into our planning and choose partners that minimize the impact due these uncertainties. The model is based on the probability distribution of supplier non-performance as obtained from our analysis of supply chain exceptions and also the event trees. 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, suppliers of critical components who can arrange for alternate sources in case of disruptions in their plants will be preferred than one who cannot make such guarantees. Finally we may mention that our mapping of exception consequences can also be used to build decision support systems for exception management.

6. REFERENCES

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