SUPPLY CHAIN SYSTEMS: A RELIABILITY EVALUATION

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ABSTRACT

Along each supply chain, numerous links exist, embracing material suppliers, production facilities, distribution services, warehouses, service centers and customers - in a cohesive entity. These chain partners co-ordinate and collaborate with their decisions and activities, thus creating sustainable competitiveness. However, as the efficiency of the supply chain increases, the risk of disruption or breakdown increases. The inability to deliver a supply part due to disruption can have a significant impact on the performance of a Supply chain. Reliability plays an important role in dealing with the risk of disruptions. This article incorporates aspects of reliability into the traditional Supply Chain model and evaluates the supply chain system through reliability analysis.

Key words: Supply chain, Reliability

INTRODUCTION

Supply chains are highly complex, dynamic, and in many cases, globally distributed systems. Supply chains, particularly global supply chains, are exposed to a large variety of risks, which compromise the performance of suppliers and the supply chain as a whole. These risks include, for example, natural disasters, strikes and terrorism. A failure of a supplier or a subsystem results in a loss of supply or in the worst case in a total disruption.

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Supply Chain design models have treated the world as if we knew everything about it with certainty. Moreover, even if all the parameters of the supply chain are known with certainty, the system may face disruptions from time to time, for example, due to inclement weather, labor actions, or sabotage. In a highly competitive environment, supply chain disruptions can have a severe if not existential impact on the success of the involved companies. In such an environment, competitive advantage implies the ability to provide products to customers at any time. Lost sales, decreased market share and large contractual penalties are possible results of disruptions.

The inability of a supplier to provide the necessary amount of supply can have a major impact on the profitability of the entire supply chain. Martha and Vratimos (2002) give various examples of companies that encountered severe problems when their supply chains were disrupted. The U.S car manufacturer Ford experienced severe disruptions in transportation caused by the terror attacks of September 11, 2001. The company had to shut down five manufacturing sites in the U.S for several days because they ran out of supply. The result was a 13% decrease in manufactured cars in the fourth quarter of 2001. An earlier example is the earthquake of September 21, 1999 in Taiwan, which caused severe supply problems to the computer manufacturer *Apple*. The destruction of major suppliers of semiconductor components delayed the production of the iBook and the power Macintosh G4 desktop computers during a period of market growth. Daimler Chrysler and Continental Teves on the other hand were better prepared. These two companies had contingency plans and alternative transportation modes for their suppliers to which they resorted when their supply chains were disrupted after September 11. Navas (2003) gives an example of car manufacturers, which have started to build up pools of secondary suppliers to mitigate the risk of failures of primary suppliers.

A recent series of crises and catastrophes has attracted public attention. Natural disasters like Hurricane Katrina devastating the Gulf Coast of the United States in 2005, terrorist acts such as the attacks of September 11, 2001, and epidemics like SARS in South-East Asia in 2003 are violent reminders that we live in an unpredictable and increasingly unstable world. Moreover, there is strong evidence that such catastrophic events are becoming more frequent (Coleman, 2006). Elkins et al. (2005) observed that there has been an increase both in the potential for disruptions and in their magnitude.

In summary, we find a relatively unstable world on one hand, and increasingly sensitive supply chains on the other. Many supply chain decision-makers were caught off-guard by the intensity of the recent disasters, which highlighted the lack of preparedness in many supply chains. The above discussion shows the inability of traditionally designed supply chains to deal with disruptions due to unanticipated events. Traditional models focus on cost-efficiency of the system, thus not considering redundancies in the form of inventories and multiple supplier arrangements and developing long-term relationships with a smaller supplier base, Nahmias (2001). Just-in-time supply chains have become state of the art in many industries. These models, however, are based on the assumption that every element in the supply chain will always perform as planned.

LITERATURE REVIEW

This section provides a review of how risk in general and the risk of supplier failures in particular have been discussed in the supply chain management literature. Supply chains face various sources of risk. Besides manufacturing processes and customer demand, Davis (1993) identifies the performance of suppliers as a major source of risk, which influences the efficiency of a supply chain. van der Vorst et.al. (1998) name order forecast horizon, input data, administrative and decision processes as well as inherent uncertainties, depending on the typology of the supply chain, as major risk clusters. Van Landeghem and van Maele (2002) present a list of various sources of uncertainty that endanger the efficiency of global supply chains and indicate the most appropriate supply chain planning level to address them. Risks incurred due to demand variations and information distortions are classical issues in the supply chain management literature. The effect of demand volatility amplification along the supply chain due to information distortion is called the "bullwhip effect" and was first discovered by Forrester (1961). Based on Forrester's findings, research on this effect has been elaborated by many other authors.

Van Landegnem and van Maele (2002) introduce a robust planning approach to tactical supply chain planning under uncertainty. Monte Carlo simulation is used to characterize joint distributions of performance outcomes to allow for better decision making, e.g. in terms of safety stock levels or for the identification of uncertain factors with large impacts on the supply chain performance. For a literature review on strategic supply chain design, we refer to the survey articles of Vidal and Goetschalckx (1997, 2000). They present an approach that includes supplier reliability as a design criterion. A constraint is formulated which guarantees that the probability of all suppliers of critical materials being on time satisfies at least a given target probability at each plant in the network. Sheffi (2001) suggests dual supply arrangements in a strategic supply chain design. The author also opts for the installation of strategic emergency stock in the supply chain. Snyder and Daskin (2003) introduce a facility location model, which performs well under both normal operating conditions and when distribution centers in the network fail. Retail nodes in a distribution system are assigned to a hierarchy of distribution centers. If a distribution center on a higher level in this hierarchy fails, the retailer will then be served by the one on the next lower stage.

In a very general sense, research from high reliability organizations, networked organizations, and inter-organizational systems is relevant in the study of supply chain reliability. 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. Paulsson (2003) provides a good survey. A more detailed review of researches connected with risks is presented by Tang (15) (2005). Klimov (2008) investigates problems related to supply chain risk and evaluates a supply chain through reliability analysis using a simulation model.

THE CONCEPT OF RELIABILITY

Reliability is the probability that a system performs its specified function as intended, within a given time horizon and environment. A system consisting of different components can only perform as intended if every component fulfils its system-relevant functions. Here, supplier is a component and the supply chain is a system.

Supplier reliability refers to the probability that the supplier operates as planned. Failure is the inability of a supplier to ship any of the required amounts of material to its customers for a certain duration of time. Failure results from various reasons, such as strikes, destruction of production facilities, natural disasters, terrorism or war. Supply Chain reliability is used to express the probability of a supply chain to completely fulfil the demand of a final product without any loss of supply resulting from failures of suppliers. The following model is proposel and evaluated.

Assumptions of the Model:

1. A supplier either delivers zero or the full amount of its designated supply. Let r_v denote the reliability of a supplier v over the strategic supply chain planning horizon. Assuming independent supplier reliabilities, supply chain reliability R, is

$$R = \prod_{\text{All suppliers}} r_v \qquad (1)$$

i.e. 'R' can be calculated as the product of all individual reliabilities in the supply chain.

Problem Statement:

Given a set of suppliers, the task is to design an inbound supply chain for a manufacturer and to evaluate the model for reliability. We consider the number of regions where suppliers are located as G. Let us denote by P the set of all suppliers, which for ease of notation includes the manufacturer. P is portioned in k stages S_i, i ϵ (1…k). A stage consists of all possible suppliers for a specific product which is required as a component for the manufactured product in the succeeding stage. We represent the supply chain design problem as a network. The nodes of the network correspond to suppliers P. We denote by nε P the final manufacturer node, which by definition is on stage Sk. An arc e = (u, v) corresponds to a feasible supply channel from supplier u to customer v. We denote by A the set of all arcs.

Component manufacturers, which consist of the nodes on intermediate stages Si, iε (2, .., k-1) are simultaneously suppliers to the nodes on the next stage and customers to the nodes on the previous stage.

With every arc eεA, a unit cost of production pc_e, a unit cost of transportation tc_e, Procurement cost prc_e and fixed costs for an open supply channel f_e are associated. The fixed costs can include, for example, administrative and overhead cost for establishing and maintaining supplier customer relations. We consider only critical supply items, of which a shortage results in an interruption of the production process. The manufacturer has to meet an aggregated demand of D units of the final product over the strategic planning horizon. For transparency reasons, only one final product as well as one critical supply item per stage is considered.

MODEL

The model is a deterministic mixed integer programming model. It has two types of decision variables. For every arc eεA, the binary variable Y_e is one, if this link is used in the supply chain, and zero if it is inactive. The continuous variable X_e represents the amount of units flowing along arc e. A flow $X_e > 0$ can only be assigned to an arc if it is active, i.e $Y_e = 1$.

The objective function of the base model is to minimize the total procurement, production, transportation and fixed costs, given by:

$$\sum_{e \in A} [(pc_e + tc_e + proc_e).X_e + f_e.Y_e] \qquad (2)$$

For every vϵUsᵢ, let α_v be the bill-of-materials parameter that expresses how many input units are required for the production of one output unit. The sum of the incoming material flows to the final manufacturer node must equal the aggregated demand D, multiplied by the bill-of-materials parameter, which is expressed as

$$\sum_{e \varepsilon I_n} X_e = \alpha_n . D \tag{3}$$

Nodes on intermediate stages Si, $i \varepsilon \{2, \ldots, k-1\}$ are technically transshipment nodes, for which the total flow into this node has to equal the total flow out. The supply inputs to these nodes are transformed into component flows to the next stage. Considering the bill of materials relationship, the following flow balancing constraints

$$\sum_{e \varepsilon I_v} X_e = \alpha v. \sum_{e \varepsilon O_v} X_e \quad \text{for all } v \epsilon \bigcup_{i=2}^{k-1} S_i \tag{4}$$

guarantee that there are no additional sources than those on the first stage and no additional sinks except the end manufacturer node. Each supplier v has a production capacity limit mv that must not be exceeded:

$$\sum_{e \varepsilon O_v} Xe \leq m_v \quad \text{for all } v \varepsilon P/\{n\} \tag{5}$$

With every arc e, a minimum flow q_e is associated. This represents, for example, minimum order quantities demanded by the suppliers and prevents unreasonably low flows.

$$q_e . Ye \leq X_e \quad \text{for all } e \varepsilon A \tag{6}$$

The following constraints guarantee that flows can only be assigned to active arcs:

$$X_e \leq M . Y_e \quad \text{for all } e \varepsilon A \tag{7}$$

In these inequalities, M is an auxiliary parameter representing a large enough number.

As the presented network design model is based only on lowest possible cost, typically the supply chain reliability is relatively low, too, because the cheapest suppliers are in all likelihood not the most reliable ones. The supply chain performance can be improved by choosing a more reliable supplier in each stage. As these tend not to be the cheapest suppliers, higher costs are incurred which leads to the problem of leveraging reliability and profitability of the chain.

We add a new constraint, which enforces the supply chain reliability to be greater than or equal to the desired target supply chain reliability. We propose a formulation for calculating the supply chain reliability that considers regional reliabilities as well. Let G be the set of all regions. Let r_j denote the reliability of a region j and let p_j be a binary variable indicating if the supply chain has suppliers in the region j. For every $v \in P/\{n\}$, let z_v be a binary variable indicating if a supplier is used or not.

Then, the reliability of the supply chain is,

$$\prod_{v \in P/\{n\}} r_v Z_v \cdot \prod_{j \in G} r_j P_j \geq R \qquad (8)$$

This constraint can be linearised by applying logarithm on both sides.

$$\sum_{v \in P/\{n\}} \log (r_v).\, z_v + \sum_{j \in G} \log (r_j).\, p_j \geq \log R \qquad (9)$$

Since all probabilities are between 0 and 1, and their logarithms are negative, this linearization is equivalent to the expression:

$$\left| \sum_{v \in P/\{n\}} \log (r_v).z_v \right| + \left| \sum_{j \in G} \log (r_j).p_j \right| \leq \left| \log R \right| \qquad (10)$$

The following constraints define zv and pj.

$$Z_v \leq Y(u,v) \quad \text{for all } (u,v) \in A \qquad (11)$$

$$P_j \leq Y(u,v) \quad \text{for all } (u,v) \in A \text{ and } j \in G \qquad (12)$$

This model consists of the objective function (2) constraints (3)-(7) and (10)-(12).

Case study:

Let us consider the following case.

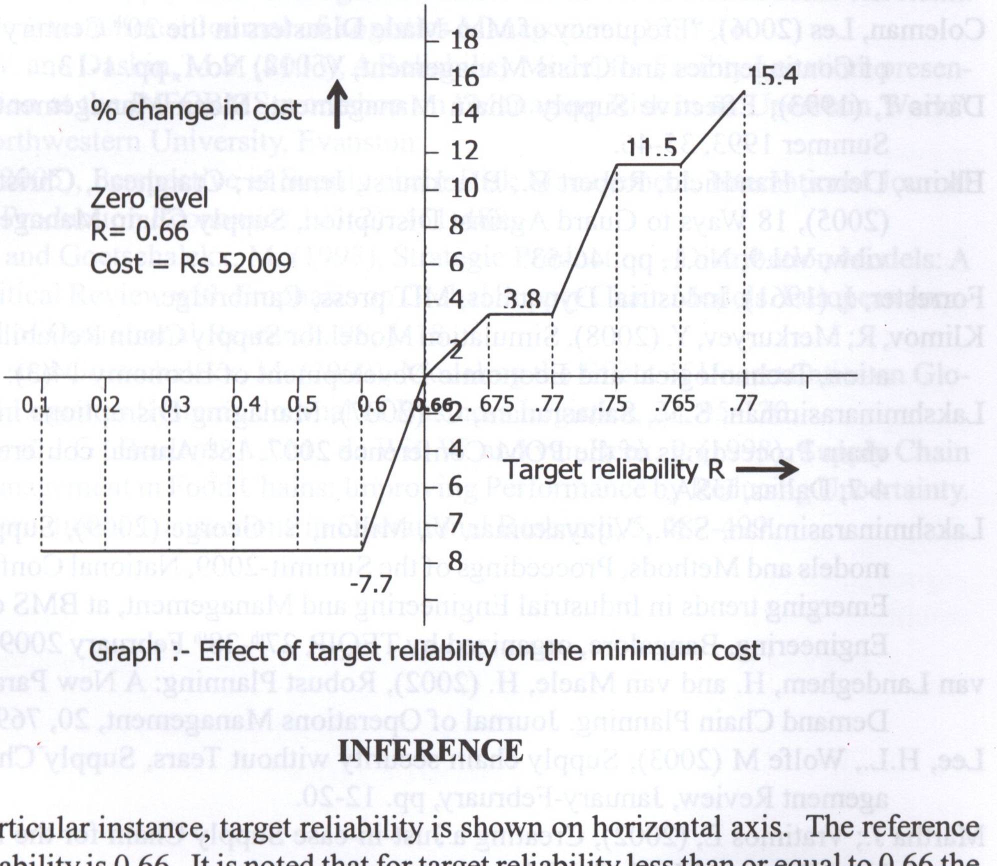
Number of regions, G=3
Number of Stages Ki=4
Number of nodes, P=10
Number of Arcs, A=21
Demand, D=1000 units
Production capacity limit of suppliers, mv=2000 units
Minimum sourcing limit per arc, qe=100
Bill of material parameter for all nodes, αv=1
Fixed cost, fe= Rs. 3/-
M=1500

The total cost (production cost + Transportation cost + Procurement cost) for region 1 is considered as Rs. 20, for region 2 is Rs. 18 and for region 3 is Rs.16.

Each stage consists of one supplier from each region. The assumed reliability values are as follows. Reliability of region 1 is 0.96, of region 2 is 0.94 and of region 3 is 0.90. Reliabilities of different suppliers are as follows: for suppliers 1, 4, 7 and 10, reliability is 0.96. For suppliers 2, 5 and 8, reliability is 0.94: For suppliers 3, 6 and 9, reliability is 0.90.

Suppliers 1, 2 and 3 forms stage 1: Suppliers 4, 5 and 8 forms stage 2: Suppliers 3, 6 and 9 forms stage 3.

The above case is solved using LINDO software. The effect of target reliability on the minimum cost is drawn in the following graph.



Graph :- Effect of target reliability on the minimum cost

INFERENCE

In this particular instance, target reliability is shown on horizontal axis. The reference target reliability is 0.66. It is noted that for target reliability less than or equal to 0.66 the minimum cost remains constant, as the supplier reliability constraints are not binding. From this value up, the minimum cost increases very rapidly and can have large differences for small differences in the target reliability. Therefore achieving target reliabilities close to 1 is very costly or even impossible.

CONCLUSION

The inclusion of a reliability factor in the design of supply chain increases the cost of the supply chain. Hence, it becomes less efficient. But, at the same time the performance level of the network increases because of the reliable suppliers. The risks of disruptions are reduced.

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