Integrating effective flexibility measures and resilience to mitigate supply chain risk

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Abstract - In today’s highly globalized and interconnected world, an end-to-end view of supply chain is vital to understand and manage supply chain risks. These risks are classified broadly into two categories: operational risk and disruptive risks. The firms have to plan their strategy in a way in which they can overcome these risks and fulfill the customers demand. In order to maintain the supply chain operations under the loss of some structures against these mentioned disruptions, supply chain network needs to be resilient. Thus, to mitigate the supply chain risk, the present study improves the supply chain resilience by strategically incorporating supply chain flexibility. The objective of the model is to maximize resilience and the upstream supplier flexibility, internal manufacturing flexibility and logistics flexibility are formulated in the constraints. The model is a non-linear model. Leading companies are looking into higher supply chain flexibility so as to compete in the dynamic customer oriented market. Our problem considers multiple suppliers, multiple plants, multiple distribution centres and multiple retailers.

Keywords - Supply Chain Management, Multi-objective Optimization, Resilience, Supply chain flexibility

1. Introduction

In today’s highly competitive business environment, satisfying customer demand is the most important challenge otherwise there would be customer loss. Customers demand better quality, better services, more variety and low cost. To compete in market many companies have switched their overall strategy from low cost standardized production to flexible production. In today’s unpredictable and highly interdependent system, even the planned and organized companies are being caught by the events that are beyond their control or which are the results of plans and designs not working as expected. An end-to-end view of supply chain is important to understand and manage supply chain risks. Supply chain risks are broadly classified into two categories that are operational risks and disruptive risks (Kleindorfer and Saad, 2005). Operational risks are those risks arising from the problems of coordinating from upstream supplier, internal manufacturing and downstream demand and can be seen due to unforeseen discontinuities in supply, manufacturing equipment malfunctions, human centered issues from strikes to fraud and due customer demand change. And the disruptive risks are those which may arise from natural disasters like earthquake or fire attack or tsunami or hurricanes, economic recessions, terrorist attacks or unacceptable accidents. The firms have to plan their strategy in a way in which they can overcome these risks and fulfill the customers demand. This can be achieved by making the supply chain network resilient. “Supply chain resilience” is the ability of a system to cope with the consequences of unavoidable disruptions or risk and to return to a stable state either its original state or move to a more desirable state, following strong perturbation from failure or disruption or attack. (Christopher and Peck, 2004). Ponomarov and Holcomb, 2009 in their paper argued that resilience is more than just recovery and in its definition there is an implicit notion of level of flexibility.
and also, summarized that important aspects of resilience include adaptability, flexibility, maintenance and recovery. Upton (1994) defined flexibility generally as “the ability to respond to variations with little penalty in time, effort, cost or performance” and the concept of supply chain flexibility is stated as flexibility dimensions required by all the supply chain participants to successfully meet volatile customer demands (Duclos et al., 2003). Flexibility has been classified depending on its different functions. Some authors have used flexibility as a key success factor or competitive priority, as a strategically or operational decision, as a performance indicator and as a proactive or reactive measure. In this paper, flexibility is considered as the ability of the system to cope with internal and external variation by maximizing the overall resilience of the supply chain.

Although the current literature on flexibility is quite rich and vast, there exist few drawbacks. The current literature has mainly focused on manufacturing flexibility and not on the entire supply chain flexibility. Most of the authors have considered manufacturing firms as a single entity and not considered the partners attached to the firm thus ignoring the supply chain partners linked to the firm. Gunasekran et al. (2001) pointed that in supply chain system as the products or services subsequently move from one channel partner to another, firms have recognized that to respond to the end customer demand, all the channel partners must be flexible. Thus the requirement of understanding supply chain flexibility arose. The various reasons to understand the supply chain flexibility is explained. Firstly, the paradigm shift of mass production to mass customization has made customers to play a key role during product manufacturing. Firms start the product development taking into consideration the customer requirements for the product. This kind of requirement can be accomplished either by hiring new plants or developing new products as per the requirements in a way that would not affect the performance of the supply chain much in terms of cost, time and effort. This would also bring the fact that partners supplying the raw material should be able to provide the demanded raw material. Secondly, the demand is not deterministic, it is completely uncertain. In order to quickly cater to the changing demand in all parts of the world and avoid the uncertainty, the firms need to have responsive supply chain and the ability to increase or decrease the production output with minimal penalty to supply chain performance. Thus, Das, 2011 clearly states that inclusion of effective flexibility measures resolves most of the SC uncertainty issues. Thirdly, there is uncertainty in the environmental conditions which means a disruption could be caused at any facility or path in terms of fire, breakdown, earthquake, traffic on the path, etc. So it is important to built resilient supply chain to overcome the consequences of disruptions. Despite its importance, till date there is limited literature addressing supply chain flexibility and resilient supply chain. There is a dearth of knowledge in modeling the supply chain flexibility and resilience.

Thus, to mitigate the supply chain risk, the present study improves the supply chain resilience by strategically incorporating supply chain flexibility. The objective of the model is to maximize resilience and the upstream supplier flexibility, internal manufacturing flexibility and logistics flexibility are formulated in the constraints. The model is a non-linear model. The problem considers suppliers (s), plants (p), distribution centres (d) and retailers (r).

The section below highlights the work done in each area of flexibility and resilience.

2. Literature Review:

Supply chain resilience concepts have been discussed by many researchers such as Christopher and Peck, 2004 conceptualized resilient supply chain and Lakovou et al., 2007 addressed an analytical methodological framework for the optimal design of resilient supply chain. In literature, measurement of supply chain resilience doesn’t exist widely, but there are some studies which report its quantification. To quantify the resilience of network edges and nodes Rosenkrantz et al., 2005 presented the concept of ‘Structure based
Resilience Metrics’, to analyze logistic network resilience Wang and Ip, 2009 used the resilience evaluation approach and in Intermodal Freight Transport Chen and Hooks, 2011 quantified resilience. By modifying and using the existing studies, our research formulates a model which can be used to maximize resilience. The formulation addresses the ability of the network to absorb the disruption with its internal operational capability and also with the capability of recovery activities that may be implemented in the aftermath of a disaster. Wang and Ip, 2009 have given the formula for evaluating resilience in case of multiple resources which depends on the source reliability, the path reliability between the sources and quantity of demand, supply or link capacity. It is noticed that multiple and redundant reliable supplies bring higher resilience to a demand node. Rose, 2004 classified this type of resilience as inherent resilience and defined it as the ability in normal conditions to reallocate resources in response to market signals. The author also suggested second type of resilience called adaptive resilience which is defined as the ability in crisis situations due to ingenuity or extra effort. Chen and Hooks, 2011 quantified this type of resilience as the ability to satisfy the proportion of demand in case of occurrence of a disruptive event. In both of these works it is seen that authors have considered one tier system but our network is a three tier system. So we have modified and used the given formulae to build our model. Ponomarov and Holcomb, 2009 in their paper argued that resilience is more than just recovery and in its definition there is an implicit notion of level of flexibility and also, summarized that important aspects of resilience include adaptability, flexibility, maintenance and recovery. Flexibility has been a research topic since decades and researchers have discussed it in economic and organizational perspectives. These days the trend is to analyze the firm’s flexibility along with its attached partner’s flexibility and thus our work focuses on supply chain flexibility and supply chain resilience. The concept of supply chain flexibility is stated as flexibility dimensions required by all the supply chain participants to successfully meet volatile customer demands (Duclos et al., 2003). The definition and review presented by authors Steven and Spring (2007) have argued that empirical research in future designed from a network prospective, in which supply chain should be treated as a single entity and this would to explore complete understanding of the effects of flexibility across whole supply chain. They suggest that supply chain flexibility encapsulates components of flexibility that are inherent to the firm level called inter-firm level flexibility and those which are external to the firm called intra-firm level flexibility. The detailed review discusses the different studies done in the area of supply chain flexibility related to building concept models of supply chain flexibility (Duclos et al., 2003; Lummus et al., 2003 and Kumar et al. 2006), supply chain flexibility empirical analysis (Suarez et al., 1995; Golden and Powell, 1999; Young et al., 2003; Sanchez and Perez, 2005; Fredriksson and Gadde, 2005 and Swafford et al., 2006), measuring of supply chain flexibility (Beamon, 1999; Gupta and Nehra, 2002 and Pujawan, 2004) and considering supply chain flexibility in the design and simulation model (Barad and Sapir, 2003; Wadhwa and Rao, 2003; Aprile, et al., 2005 and Shen, 2006). After 2006, some authors worked on the flexibility modeling based papers that are similar to our approach. Like Wang et al., 2007 discussed about the outsourcing and vertical integration concept, Ahlert et al., 2009 suggested creating long-term capacity pools, Schutz and Tomasmgard, 2010 discussed extra capacity/extra inventory related approaches and Das, 2011 integrated capacity, product mix, distribution and input supply flexibility in mixed integer supply chain planning model to mitigate supply and demand uncertainty and improve market responsiveness. The idea of our proposed work is in line with the existing work of creating network partners for extra capacity where demand dictates. This study proposes a supply chain flexibility model that takes care of most of the relevant issues related to supply and demand variation and disruption. The model considers supplier flexibility, plant and product flexibility which come under the concept of internal manufacturing flexibility and logistic flexibility thus catering to upstream, internal and downstream flexibility. This would help the managers to plan their strategic process and create the flexibility that will allow them to face the evolving market. Das, 2011 paper is a seminal paper for our problem but there are few drawbacks existing in the model. We will explain each of the modeled flexibility. Firstly, the author has formulated the capacity flexibility by adding a new or extra capacity depending on the anticipated increase in demand for a product which is computed considering
mean demand and estimated percentage increase in demand for that product. This modeled capacity flexibility did not address demand decrease cases. To eliminate this drawback we modeled plant flexibility to cater to increase and decrease in demand of a particular product. The plant can be added to or removed from the supply chain system depending on the demand. Secondly, in the product mix flexibility formulation the total number of product types in an organization’s product portfolio is compared with the minimum base level of that product types. They have divided the products into two ranges – fast moving product range and extended product range. To satisfy the targeted customer demand an organization selects the product types from appropriate ranges, to make sure that the right product mix in their portfolio. Our formulation captures this since the plants produce multiple products and thus demand of any new product can be either satisfied with existing plant which produces products that are similar to new demanded product or add new plant which can produce the demanded product. Thirdly, the supplier flexibility was formulated by creating two pools of suppliers, one pool of high quality supplier which was the existing supplier pool and the other pool for affiliated supplier which was the extended supplier pool. When the high quality suppliers failed to accommodate the entire supply input requirements, only the quantity of increase in demand or product mix change for the input supply is fulfilled by the affiliated suppliers. Our formulation doesn’t consider adding the entire pool of affiliated suppliers, instead adds a relevant supplier one at a time in the system when the demand cannot be met by the existing system. Duclos, et al. 2003 and Steven and Spring, 2007 in their literature review have clearly said that there is a need for development of more sophisticated models and need to explore the relationship between supply chain design and flexibility across larger network. Thus, our proposed model enhances the supply chain flexibility literature and is useful to mitigate supply chain risk. We will discuss the previous literature regarding supplier flexibility, manufacturing flexibility and logistic flexibility.

Supplier flexibility:

Supplier flexibility is considered as an important tool to respond to environmental uncertainties. Lummus et al., 2003 defined supplier flexibility as the availability of qualified materials and services and the ability to reconfigure the supply chain, altering the supply of product in response to unanticipated demand. It facilitates a faster response when there is uncertainty; therefore it has a positive impact on supply chain flexibility. Flexible suppliers are capable of supplying/processing other jobs in addition to the one for which they are the original supplier. In a cluster of flexible suppliers, it is expected that flexibility of suppliers be utilized more expressively through better control of the supply chain. The model formulated by Tomlin, 2003 considered a reliable supplier and an unreliable supplier supplying a single product to a firm that influence’s optimal disruption management strategy of a firm. They have involved both risk-neutral and risk-averse decision making but not considered contingency actions. In context of flexible procurement contracts, Milner and Kouvelis, 2005 presented flexibility in order quantity and timing in a single period inventory model. The order could be placed twice, first opportunity was forecast driven order and second opportunity was orders updated with demand information. The authors suggest that order quantity and timing flexibility reduces supply chain cost. As mentioned earlier Das, 2011 formulated supplier flexibility in a way such that the pool of affiliated suppliers is added to the system to fulfill the increased in supply order which could not be accommodated by the pool of high quality suppliers. The supplier flexibility formulated in our study also strategically mitigates the supply side risk, but is different than the above mentioned ones. The constraints consider the ability to ramp up or down size the production, the ability to add or remove a supplier and the ability to change the portfolio of the inbound material supplied by suppliers. The supplier is added or deleted one at a time and not together as a pool when the quantity or product mix change demanded cannot be met by the existing supplier system. In this area, Narasimhan and Das, 1999; Narasimhan and Das, 2000 and Scannell et al., 2000 have done empirical analysis by conducting
survey using a questionnaire. Thus we can see that supplier flexibility is extensively studied empirically and there is need to model the supplier flexibility to bridge the gap.

**Manufacturing flexibility:**

The term flexibility was first used for manufacturing firms, to describe the manufacturing ability to cope with the unexpected environmental variations (Sethi and Sethi, 1990; Gupta and Goyal, 1989). Mascarenhas (1981) defined flexibility as the ability of a production system to maintain its performance against the variation caused by the environment. Cox (1989) defined manufacturing flexibility as ability of plant to respond to market variations. Koste et al., 2004 defined it as the ability to provide products with a wide range of features and volumes according to customer specifications. Manufacturing strategy treats manufacturing flexibility as one of its important attribute/entity and helps the manufacturing firms to remain unaffected by environmental uncertainty. In literature, there exist many dimensions of manufacturing flexibility. As we are modeling supply chain flexibility we need not go into the intricacy of each dimension and so we have considered Plant flexibility and Product flexibility dimensions which are important and suitable to our study. It is seen that volume flexibility, has also been handled in the model as a resource can temporarily alter its capacity to meet the demand and incase the capacity can’t be increased then plant flexibility helps to cater the demand. There exists vast empirical research that addresses to manufacturing flexibility; Jack and Raturi, 2002; Zhang et al., 2003 and Claycomb et al., 2005 have explored and collected data through questionnaire for understanding the manufacturing flexibility. There are very few papers on mathematically modeling manufacturing flexibility. Fine and Freund, 1990 is regarded as a seminal work on product flexibility and they have optimized the capacity level(s) of one flexible resource that can manufacture all n products and n dedicated resources producing n products. The investment done in flexible system is based on the cost differential between the flexible and dedicated technologies as well as demand uncertainty and demand correlation. There are few mathematical model formulated in this area. Graves, 1988 analyzed the interaction between process, safety stock and volume flexibility and he also studied that this model could be for inventory and flexibility optimization. But our model is different than the existing model in terms we have considered only two types of manufacturing flexibility which mainly is important in terms of supply chain flexibility. Considering all the parts of manufacturing flexibility will make the model very cumbersome to understand and solve. So we limit ourselves to plant and product flexibility.

1) **Plant flexibility:** At the strategic level during the planning phase, the supply chain managers have a provision to acquire or rent new plant in addition to using the existing capacity to offset the anticipated increase in demand. The idea of renting or acquiring a plant can be done for a shorter period or longer period of time depending on the demand increase history. Our model adds or removes plants to cater to the changing demand.

2) **Product flexibility:** whereby a resource can produce multiple products, has been widely studied in the literature, including in Fine and Freund (1990), Jordan and Graves (1995), Van Mieghem (1998), and Tomlin and Wang (2005). There is a very slight difference between Product flexibility and mix flexibility. Our study’s interest lies in the fact that manufacturing plant are capable to accept the orders of new products called the extended product which are similar to the existing products produced in the plants. It clearly suggests that product portfolio can be changed from the existing one to a new portfolio in which some products are added or removed. Our model addresses this fact.
Logistics flexibility:

Logistic flexibility or Distribution flexibility is defined as firm’s ability to control the movement and storage of products or items under constantly changing marketplace conditions (Duclos et al., 2003; Swafford et al., 2006). Mohamed, et al., (2006) clearly mentions in his study that there exist very few studies relevant to logistics flexibility or transportation flexibility or distribution flexibility and thus there is a need for studies that consider this flexibility. Most often it is seen that firms take precautionary measures and proper security against equipment failure, terrorist attack, fire attacks, earthquakes, etc. but it is beyond the firms control to prevent the delivery routes from any disruption or traffic congestion. Thus, logistic flexibility proves to be important aspect to make the supply chain system resilient. Logistic flexibility consists of many components but our model focus only on Link, Mode and Node flexibility Mohamed, et al., 2006. Link flexibility caters to establishing new paths between the nodes or resources Feitelson and Salomon, 2000. Mode flexibility is defined as the ability to provide different modes of transport but in our model by giving different modes we can consider different vehicle types also which depends on the quantity to be shipped. Node flexibility reflects the fact to add any node which implies to add a resource in the system Feitelson and Salomon, 2000. Zhu and Levinson studied the impact of network disruption on human behavior and described the various options opted by the travelers immediately after the network is disrupted. Travelers may change their normal route because of traffic congestion or road and ramp closure, adjust travel time to avoid congestion or switch to alternative travel modes. The main purpose of having logistics flexibility firstly, is that if a path/route is disrupted or damaged then an alternative path/route can be used to deliver the items between the sources. Secondly, depending on the quantity to be shipped the relevant mode and vehicle type will be selected. Thirdly, when there is some disruption or demand change then the ability to connect the new resources or facilities in the system.

3. Formulation:

![SUPPLY CHAIN SYSTEM Diagram]
Our problem considers the above shown system having multiple suppliers (s), multiple plants (p), multiple distribution centres (d) and multiple retailers (r). A supplier supplies multiple inbound materials to plants and a plant produces multiple products. Each distribution centre consists of certain products and all retailers have all the products.

Formulation will be presented in the conference itself.

4. Solution Procedure:

This study proposes a solution algorithm to solve the above multi objective problem which integrates flexibility the constraints. The solution involves Stochastic Optimization Technique called Particle Swarm Optimization (PSO) which is a naturally evolutionary process. It was developed in 1995 by James Kennedy and Russ Eberhart. The algorithm adopted uses a set of particles flying over a search space to locate a global optimum. In PSO, a swarm of n particles (individuals) communicate either directly or indirectly with one another using search directions (gradients). The algorithm adopted uses a set of particles flying over a search space to locate a global optimum. During an iteration of PSO, each particle updates its position according to its previous experience and the experience of its neighbors. A particle (individual) is composed of three vectors: the x-vector records the current position (location) of the particle in the search space, the p-vector (pbest) records the location of the best solution found so far by the particle, and the v-vector contains a gradient (direction) for which particle will travel in if undisturbed. The basic concept of PSO lies in accelerating each particle toward the best position found by it so far (pbest) and the global best position (gbest) obtained so far by any particle, with a random weighted acceleration at each time step. This is done by simply adding the v-vector to the x-vector to get another x-vector \( X_{i+1} = X_i + V_i \). Once the particle computes the new \( X_i \) it then evaluates its new location. If x-fitness is better than p-fitness, then pbest = \( X_i \) and p-fitness = x-fitness. PSO does not implement survival of the fittest strategy and all individuals are kept as members of the population throughout the course like the other Genetic Algorithm.

\[
v_{t+1} = W \times v_t + c_1 \times rand(0,1) \times (p_{best} - x_t) + c_2 \times rand(0,1) \times (g_{best} - x_t)
\]

Parameters \( W = \) Inertial Weight and \( c_1 \) and \( c_2 = \) Acceleration Coefficients
5. Conclusion

We successfully built the supply chain resilience and flexibility model to mitigate the supply chain risks. This model reconfigures itself to satisfy the changing demand and also avoids the supply chain failure against disruptions from either supply side or internal manufacturing or from the logistics perspective. This work is different from the previous work as it integrates all three supply chain flexibility measures. The nonlinear model is solved using Particle Swarm Optimization.

References


