Managing risks in a multi-tier supply chain

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Abstract
Risk management is a crucial challenge for supply chain managers. A firm faces risks from all upstream and downstream supply chain stakeholders. Therefore, an end-to-end risk management approach is needed to fortify the entire supply chain network of any firm. In this paper, we explore the developments in the multi-tier supply chain risk management problem. As a representative case, we present a 4-tier supply chain comprising of suppliers, manufacturers, retailers and consumers. Each supply chain stakeholder is assumed to have two objectives: first to maximize profit, and, second to minimize risks associated with its economic transactions. The resulting individual tier-optimization problems are generally non-linear in nature. The network optimization problem can be derived from these tier-optimizations problems, using variational inequalities. The network optimization problem thus, represent the equilibrium state of the entire supply chain network. A computational procedure that exploits the network structure of the problem is proposed. At equilibrium, production outputs, inventory levels, product prices, risks, and various costs can be calculated and compared over a certain time period. The contribution of this paper is two-fold: First, a comprehensive introduction to the multi-tier supply chain risk management problem is provided. Second, structure of the problem formulation, along with the solution approach is proposed.

Keywords: supply chain risk management, non-linear programming, network equilibrium

Introduction
Supply chain risk management (SCRM) is a nascent area emerging from a growing appreciation for supply chain risk by practitioners and by researchers (Sodhi et al. 2012). On the other hand, the area is still emerging and has rather unclear boundaries at this stage, leading to questions about how to manage risks in a multi-tier supply chain, while considering the objectives of various supply chain stakeholders.

A supply chain is the network of all the individuals, organizations, resources, activities and technology involved in the creation and sale of a product, from the delivery of source materials from the supplier to the manufacturer, through to its eventual delivery to the end user. In the past, when firms manufactured in-house, sourced locally and sold direct to the customer, risk was less uncontrollable and thus, easier to manage. With the increasing complexity, global sourcing and information mismatch, the competition today is among different supply chain networks, rather than few individual firms (Harland et al. 2003). This has resulted in the growing need of fortifying entire supply chain network towards supply chain risks, thus supply chain firms are nowadays using an end-to-end risk management approach covering all the stakeholders.
present in the supply chain (Tang 2006). Following this approach, firms must find a way to protect their supply network by improving material and information flow, while simultaneously mitigating various risks arising due to the ever increasing business uncertainties. This approach requires inherent coordination among the supply chain stakeholders to achieve the common goal of risk mitigation.

In this paper, we explore the developments in the multi-tier supply chain risk management problem. The rest of the paper is organized as follows. In the second section, we classify risks according to their location in the supply chain network. Then, in the third section, we present a representative 4-tier supply chain network comprising of suppliers, manufacturers, retailers and consumers; and define the problem environment. Fourth section proposes a comprehensive approach to fortify the entire supply chain network against operational and opportunism risks. Fifth section concludes the paper.

Supply chain risk classification

Risk in supply chains arises due to several factors, which are generally classified as internal risk factors and external risk factors (Kumar et al. 2010). The internal risk evolves within the supply chain network due to improper coordination among different levels. On the other hand, external risk arises due to the interaction of a supply chain network with its environment. Natural and man-made disasters, terrorist attacks, political disturbances, and exchange rate fluctuations come under this category. These risks may generate inefficiency and disturbances anywhere within the supply chain network. A single risk occurrence at any tier may create ripples at different tiers. This supply chain ripple effect makes it essential to manage the risks in partnership with all other supply chain stakeholders (Norrman and Jansson 2004). Thus, no matter what kind of risk management approach is taken, supply chain risks should be understood and managed as a whole for an end-to-end supply chain (Rao and Goldsby 2009).

Figure 1 depicts the classification of risks depending on the location of risk. The internal

![Figure 1. Supply chain risk classification (adopted from Daultani et al. 2014)](image-url)
risk can further be divided depending upon their location in the supply chain network (Daultani et al. 2014). Firstly, internal risk arise due to a firm’s own operations. Secondly, internal risk arise due to the coordination mismatch with other stakeholders present in the supply chain network of a firm.

As clearly shown in Figure 1, risks are mainly classified in three categories: a. risks internal to the firm; b. risks external to the firm, but internal to its supply network; and c. risks external to the firm’s supply network. Internal risks can be controlled up to some degree by the joint efforts of the stakeholders present in the supply chain network, but the external risks are uncontrollable. Thus, external risks occur independently and not much can be done to avoid these risks prior to their occurrence. Therefore, in this paper, we keep our focus to internal risk only.

Multi-tier supply chain risk management problem

Risk management problem in a multi-tier supply chain network is an increasing area of interest for both the researchers and practitioners. An end-to-end risk management approach in this regard requires all supply chain stakeholders working toward this goal. But, this is rare in reality, as various stakeholders aim to locally optimize their individual goals (profit maximization) first, while ignoring the effect of their decisions on the rest of the network. This local optimization approach is not enough to achieve the objective of risk mitigation in the system (entire supply chain network). The problem can be resolved if all supply chain stakeholders achieve their individual objectives of profit maximization simultaneously, and that state also results in the overall system optimization. Motivation of this research is exploration of such state, which corresponds to the “network equilibrium” problem. A network equilibrium state, as defined by (Nagurney et al. 2002) is one where no stakeholder has any benefit to deviate from his current decisions, and while the entire system also achieves the required optimized state.

Apparently, the first contribution in modeling supply chain risks; specifically the supply and demand side risks, is by Nagurney et al. (2005). Their model consists of three tiers of decision-makers: the manufacturers, the distributors, and the retailers, allowing the physical as well as electronic transactions. Later, Cruz et al. (2006) focused on the financial engineering of integrated global supply chain networks and social networks. They modeled multicriteria decision-making behavior of the various decision-makers (manufacturers, retailers, and consumers), which included the maximization of profit, the maximization of relationship values, and the minimization of risk. But, these models considered single period analysis. We, on the contrary, consider the analysis of supply chain risks over a finite time horizon.

We, in this paper, consider a 4-tier supply chain comprising of suppliers, manufacturers, retailers and consumers, as shown in Figure 2. Each supply chain stakeholder is assumed to have two key objectives: first to maximize profit, and, second to minimize risks associated with its economic transactions. At a particular tier, stakeholders compete with each other in a manner defined by Nash (1950). Thus, individual stakeholders aim towards achieving their local optimum conditions.

Individual stakeholders incur various costs. Supplier and manufacturers incur production costs depending upon the production quantity. Each stakeholder incur certain transaction costs for the economic transactions depending upon the transacted quantity. Inventory costs are associated with respective inventory levels. Further, costs are associated with each risk occurrence. Complete mathematical model along with the notation cannot be provided here due to space constraints, hence we provide general structure of the optimization problems. The general structure of the individual tier optimization problems is as following:
Figure 2. Multi-period supply chain network (adopted from Cruz and Liu 2011)

**Supplier’s optimization problem**
Maximize \([\text{Sales revenues from manufacturers} - \text{Production cost} - \text{Inventory holding cost}] - [\text{Expected cost incurred due to internal risk associated with all manufacturers}] \forall i, j, t\)

Constraints:
1. Production capacity balance
2. Inventory-sales balance
3. Non-negativity constraints

**Manufacturers’ optimization problem**
Maximize \([\text{Sales revenues from retailers} - \text{Inventory holding cost} - \text{Procurement cost paid to suppliers}] - [\text{Expected cost incurred due to internal risk associated with all suppliers}] - [\text{Expected cost incurred due to internal risk associated with all retailers}] \forall i, j, k, t\)

Constraints:
1. Production capacity balance
2. Inventory-sales balance
3. Non-negativity constraints

**Retailers’ optimization problem**
Maximize \([\text{Sales revenues} - \text{Inventory holding cost} - \text{Procurement cost paid to manufacturers}] - [\text{Expected cost incurred due to internal risk associated with all manufacturers}] \forall j, k, t\)
Constraints:
1. Inventory-sales balance
2. Non-negativity constraints

**Consumers’ consumption behavior**
Minimize \[ \text{Unit price} + \text{Unit transaction cost} \times \text{Total quantity purchased} \]

Consumers incur unit transaction costs associated with obtaining the product from a particular retail store. Thus, while making their consumption considerations, they consider the product price, as well as the unit transaction cost incurred while purchasing the product. The demand may be deterministic, random or stochastic depending on the demand market.

**Deriving the network equilibrium state**

Figure 3 depicts the proposed framework for deriving the network equilibrium state. The resulting individual tier optimization problems, as discussed in the previous section are of constrained non-linear optimization nature. Our aim is to find the equilibrium state of the entire supply chain network; as at equilibrium, production outputs, inventory levels, product prices, risks, and various costs can be calculated and compared over a certain time period. Using finite dimensional variational inequalities (cf. Dong et al. 2004), the network optimization problem can be derived from the individual tier-optimizations problems. Variational inequalities help us to obtain the unconstrained optimality conditions for various stakeholders. Next, these optimality conditions, with proper adjustments are used to derive the network equilibrium problem, corresponding to end-to-end supply chain risk mitigation model. A computational procedure that exploits the network structure of the problem is proposed in Nagurney et al. (2002), specifically known as the modified projection method. The problem is coded using MATLAB. Specific results and details will be shared during the presentation at the conference.

![Diagram](image)

*Figure 3. Framework for deriving the network equilibrium state*
Conclusion

This paper addresses an end-to-end risk management problem in a multi-tier supply chain. The key issue is to fortify the entire supply chain network of any firm against risk. Supply chain risks are classified providing a clear picture of the location of various types of risks in the network. As a representative case, 4-tier supply chain comprising of suppliers, manufacturers, retailers and consumers, is presented in presence of internal risks. Individual local optimization problems, which are constrained non-linear in nature, are derived for the stakeholders.

A novel framework to address the given problem from a system optimization perspective (or network equilibrium approach) is proposed. Finite dimensional variational inequalities are proposed to convert the constrained non-linear optimization problems into unconstrained optimality conditions. A comprehensive computation algorithm is proposed to solve the resulting network equilibrium problem. The contribution of this paper is two-fold: First, a comprehensive introduction to the multi-tier supply chain risk management problem is provided. Second, structure of the problem formulation, along with the solution approach is proposed. Instead of detailed mathematical model and method, a general structure is presented due to the space constraints. Details will be shared in the presentation during the conference.

References