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Robust supply chain network design with service level against disruptions and demand uncertainties: A real-life case

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ABSTRACT

We have developed a stochastic mathematical formulation for designing a network of multi-product supply chains comprising several capacitated production facilities, distribution centres and retailers in markets under uncertainty. This model considers demand-side and supply-side uncertainties simultaneously, which makes it more realistic in comparison to models in the existing literature. In this model, we consider a discrete set as potential locations of distribution centres and retailing outlets and investigate the impact of strategic facility location decisions on the operational inventory and shipment decisions of the supply chain. We use a path-based formulation that helps us to consider supply-side uncertainties that are possible disruptions in manufacturers, distribution centres and their connecting links. The resultant model, which incorporates the cut-set concept in reliability theory and also the robust optimisation concept, is a mixed integer nonlinear problem. To solve the model to attain global optimality, we have created a transformation based on the piecewise linearisation method. Finally, we illustrate the model outputs and discuss the results through several numerical examples, including a real-life case study from the agri-food industry.

1. Introduction

The fierce competition in today's markets and the swift changing of customers' preferences, together with the rapid development of technology and globalisation, have forced organisations to operate as members of a supply chain (SC) instead of acting as individual enterprises. The success of an SC depends on the integration and coordination of its all entities to form an efficient network structure; an efficient network leads to cost-effective operations throughout the chain and helps it to react quickly in response to customers' needs. According to Simchi-Levi and Kaminsky (2004), SC network design is the most basic decision of SC management, which influences all other decisions concerning an SC and has the most extensive effect on the chain's return on investment and its overall performance. Lin and Wang (2011) define SC network design as an integrated configuration of supply, manufacturing and demand side sub-systems. SC network design deals with strategic decisions of the chain, such as the number, location and capacity of entities in each echelon of the chain. However, the network structure of the chain strongly influences the later operational decisions of flow management throughout the chain, so in addition to strategic locating and capacity setting costs, the resulting operational inventory holding and transportation costs should be considered at the network design stage. Ignoring operational costs at this stage leads to sub-optimality of the network structure.

As mentioned earlier, SC network design mainly deals with strategic decisions that are usually long-term. Considering changes over time also has an important role in making suitable strategic decisions. This fact necessitates considering uncertainties of the environment at the strategic decision making stage, as uncertainty is an undeniable part of today's business environment. SCs are important entities of today's markets and also their decentralised nature makes them vulnerable against these uncertainties. Thus, SC risk management is a major part of SC management that involves designing a robust SC network structure and managing the product flow throughout this network in a manner which enables them to be able to predict, cope with and recover from disruptions. Today, many experts believe that numerous risk sources are involved in an SC, and these chains remain ill-equipped to handle them. There are many examples of disruption in real-world SC problems.

According to Sarkar et al. (2002), during the labour strike in 2002, 29 ports on the West coast of the United States were shut down, which led to the closure of the New United Motor Manufacturing production factory. During the recent destructive earthquake of Japan in 2011, the Toyota Motor Company had to

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cease manufacture at its twelve assembly plants, leading to a production loss of 140,000 vehicles. The main cause of this problem was disruption of its chain's manufacturing subsystem. In addition to the impairment of production facilities and factories throughout Japan, many Japanese companies had problems with the supply of required materials, fuel and power. In these kinds of catastrophes, supply and manufacturing disruptions are huge problems for companies. As mentioned by Norrman and Jansson (2004), a fire at one of the major suppliers of the Ericsson Company resulted in several serious problems for this company and the shutdown of its manufacturing plants for several days.

There are many other examples, for instance: Dole suffered revenue declines after their banana plantations were destroyed by Hurricane Mitch in 1998; Ford was forced to close five plants for several days after the terrorist attacks of September 11 caused a suspension in air traffic in 2001; the 1999 earthquake in Taiwan displaced power lines to the semiconductor fabrication facilities responsible for more than 50% of world wide supplies of memory chips, circuit boards, flat-panel displays and other computer components and many hardware manufacturers including HP, Dell, Apple, IBM, Gateway and Compaq suffered as a consequence; and a Motorola cell phone factory in Singapore closed after an employee became infected with the SARS disease. For more details, see Martha and Subbakrishna (2002) and Monahan et al. (2003). Further examples include Ericsson's loss of 400 million Euros after their supplier's semiconductor plant caught fire in 2000, and Apple losing many customer orders during a supply shortage of DRAM chips after an earthquake hit Taiwan in 1999;. The 2002 longshoremen's union strike at a US West Coast port interrupted trans-shipments and deliveries to many US-based firms, with port operations and schedules not returning to normal until 6 months after the strike had ended: for more detail see Cavinato (2004). Network-related risk sources arise from interactions between organisations within a supply chain, and interested readers should refer to Juttner et al. (2003) for a discussion of the relationships between categories of risk sources in a network.

Hendricks and Singhal (2005) quantified the negative effects of supply chain disruption through empirical analysis, which is useful for modelling purposes. They found 33–40% lower stock returns relative to their benchmarks over a 3-year time period that started 1 year before and ended 2 years after a disruption, large negative effects on profitability, a 107% drop in operating income, 7% lower sales growth and an 11% growth in costs, 2 years at a lower performance level after a disruption and a negative effect on stock prices, profitability, and share price volatility.

Chopra and Sodhi (2004) categorised potential supply chain risks into nine categories: (a) Disruptions (e.g. natural disasters, terrorism, war, etc.), (b) Delays (e.g. inflexibility of supply source), (c) Systems (e.g. information infrastructure breakdown), (d) Forecast (e.g. inaccurate forecast, bullwhip effect, etc.), (d) Intellectual property (e.g. vertical integration), (e) Procurement (e.g. exchange rate risk), (f) Receivables (e.g. number of customers), (g) Inventory (e.g. inventory holding cost, demand and supply uncertainty, etc.), and (h) Capacity (e.g. cost of capacity). They also discussed the mitigation strategy against each kind of risk.

Tang (2006) considers two types of risks: (a) ***operational risks*** which are inherent uncertainties such as uncertain customer demands, uncertain supply, and uncertain costs, and (b) ***disruption risks*** which are major disruptions caused by natural and man-made disasters such as earthquakes, floods, hurricanes, terrorist attacks, or economic crises such as currency fluctuations or strikes.

Waters (2007) divides SC risk sources into ***internal risks*** (which can be controlled) and ***external risks*** (which cannot be controlled). Internal risks appear in normal operations, such as late deliveries, excess stock, poor forecasts, human errors, and faults in IT systems. External risks come from outside of an SC, such as earthquakes, hurricanes, industrial action, wars, terrorist attacks, price rises, problems with trading partners, shortages of raw materials and crime.

Moreover, Waters (2007) introduces a further three categories of risk sources: (a) Environmental risk sources, which comprise any uncertainties arising from the interaction of the SC with the environment and these may be the result of accidents (e.g. fire), socio-political actions (e.g. fuel protests or terrorist attacks) or acts of God (e.g. extreme weather or earthquakes); (b) Organisational risk sources which lie within the boundaries of SC parties and range from labour (e.g. strikes) or production uncertainties (e.g. machine failure) to IT-system uncertainties; and (c) Network-related risk sources which arise from interactions between organisations within an SC.

Kar (2010) believed the risks of a chain can also be categorised into two groups:

Systematic risks: This risk is related to environmental factors which are unavoidable. Companies do not have any control over factors such as: demand-side uncertainty; supply-side disruption; regulatory, legal, and bureaucratic changes; the occurrence of catastrophic events; and infrastructure disruption.

Non-systematic risks: This risk is related to factors that can be controlled to a large extent by a company, such as facility disruption of a manufacturing subsystem.

There are several ways to mitigate, model, quantify and solve uncertainty problems. Uncertainties can be demonstrated using concepts of fuzzy theory and also distribution function in stochastic models and this paper considers that supply and demand are probabilistic with known distribution functions. Another uncertainty we aim to cover is related to disruption and consequently closure of our manufacturing facilities due to disasters. From a modelling and solution point of view there are different strategies to cope with these problems. One of these is robust optimisation and here we try to use its concepts within the solution section.

We consider both demand and supply uncertainties in our model. Demand uncertainty will be demonstrated in the form of a demand distribution function and supply uncertainty will be modelled in terms of the probability of the occurrence of disruptions in manufacturers, distribution centres, and the connecting links of an SC network.

A real-life case study motivated the development of the model presented in this paper. The case was the designing of a network structure for a chain in the rice industry of a Middle Eastern country. Rice is one of the most important essential goods within Asia and especially in the Middle East. Most of the rice in the world is produced and consumed in this area and rice has an important role in the food basket of local people. Since the service level has an important role in the competitive rice markets in this country, so we have to consider the related costs of providing an appropriate service level in our modelling and propose a creative and straightforward solving method to dominate the computational difficulties of this model.

2. Literature review

We summarise the detailed specifications of some of the recent research in the field of stochastic SC network design in Table 1. As can be seen, most of the research that has been undertaken in the field of probabilistic SC network design only considers