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Responsive contingency planning in supply risk management by considering congestion effects

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A B S T R A C T

Contingency rerouting is known as a cost-effective risk management strategy for major disruptions such as earthquakes and natural disasters. The objective of this paper is to develop a decision-making tool to determine the appropriate response speed of a volume-flexible backup supplier to improve the supply chain responsiveness. We propose a mixed integer programming (MIP)-based capacity planning tool which generates the contingency plan of the supply chain subject to random disruptions. In order to make an accurate decision, the impact of critical operational characteristics such as response time and congestion are considered in a disruption scenario. The appropriate response speed is selected through a decision tree analysis by minimizing the expected supply chain costs. The selection is made with respect to three different attitudes of the decision maker towards risk. In order to evaluate the impact of the different failure and recovery probabilities over the selection process, a sensitivity analysis is presented. The results show that considering congestion is especially critical for risk-neutral decision makers in mitigating against disruptions.

1. Introduction

Within the last decade, several supply chains have been affected by natural and manmade disasters, showing their vulnerability in the face of catastrophes. The Japan tsunami in 2011 interrupted Japanese automotive production, as well as automotive production companies all over the world dependent on Japanese suppliers; Toyota, Nissan and Honda closed their plants in Japan and General Motors suspended production in its assembly plant in USA due to the shortage of parts [1]. Ford stopped production in five plants because of the air traffic suspension after the terrorist attacks on 11 September 2001 [2]. With the recent increase in catastrophic disruptions, there has been a growing interest in finding the appropriate risk management strategies which maintain the supply chain performance when such events occur.

Risk management strategies in supply chains are divided into two categories. Mitigation strategies focus on taking precautions in advance of the risk occurrence through strategic inventory and dual sourcing. On the other hand, contingency strategies such as contingency rerouting and revenue management refer to the set of actions that are taken in post-disaster conditions [2,3]. Contingency approach could be appropriate in catastrophic disruptions where holding inventory is cost prohibitive.

Contingency rerouting can be considered as a dual sourcing strategy with volume flexibility to cope with supply uncertainty [4]. The supply chain configuration consists of a main supplier that is cost-effective though prone to disruptions along with a reliable but more expensive volume-flexible backup supplier. In the case of the main supplier breakdowns, the backup supplier could alter its capacity to cover for the disrupted source. For example, Nokia increased the production at the alternative suppliers once its semiconductor supplier was struck by a random lightning bolt. Chiquita reacted to Hurricane Mitch by increasing the production at the alternative location [3]. Contingency rerouting may be especially efficient in recovering from long disruptions. However the drawback of contingency rerouting is the challenge in making the product available within a short response time. Tomlin [3] defines the response time as the time when the firm responds to a supply disruption by placing a capacity increase order with the backup supplier plus the time required for the backup supplier to provide the required capacity.

The response time is a crucial characteristic of contingency rerouting since only a fraction of the required capacity might be available within this period. Ignoring this fact in the supply chain planning stage leads to the overestimation of the available backup capacity, resulting in creating product shortage within the response time. The reduction in the response time can be achieved by selecting scalable suppliers that can quickly ramp up their

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capacities in small increments, whereas a supplier that is relying on dedicated equipment to reduce production cost will have a long response time [5].

While improving the response time can be similar to reducing the mean time to repair (MTTR) [6], it is also critical that the backup supplier provides an appropriate level of capacity during the response time. This is critical mainly due to the loss of market share during this period, creating significant long-term implications for the firm [7,8]. The amount of the available capacity during the response time depends on response speed defined as the speed of the backup supplier to reach the desired capacity level [9]. The layout configuration of the backup supplier is one of the main factors identifying the response speed level [10]. Therefore, a strategy to improve the available capacity within the response time can be achieved through the backup supplier's investment in layout configuration.

The appropriate level of responsiveness of a contingency strategy should be considered in the design phase of the supply chain since the backup supplier's production capability cannot be easily modified. This paper focuses on the optimal selection of the backup supplier's response speed in order to improve the supply chain responsiveness to catastrophic events. The selection is based on the expected cost of the contingency rerouting plan corresponding to each response speed under all plausible future scenarios. Furthermore, an accurate estimate of the backup supplier's capacity is presented in the decision-making stage by considering the impact of the response time and congestion. The rest of the paper is organized as follows: Section 2 reviews the relevant literature; Section 3 presents the problem statements; Section 4 describes the solution methodology, which includes the planning models and the decision analysis; the numerical results are presented in Section 5; and Section 6 states the conclusions and future research areas.

2. Literature review

We focus our literature review on the research that considers the response time and backup facilities to mitigate against the supply disruptions in a supply chain. The seminal work by Tomlin [3] presents the optimal risk management strategies of a supply network which has a backup supplier with volume flexibility. The tradeoff analysis between inventory and backup capacity within a random demand and failure setting reveals that the inventory is appropriate for frequent-short disruptions of the main supplier, and the dual sourcing is optimal for rare and long disruptions. If the backup supplier has flexible capacity, the contingent rerouting might be optimal. In this work, Tomlin [3] assumes that the whole backup capacity would be available only after the response time.

Regarding the availability of the extra capacity within the response time, Hopp and Yin [11] consider a similar premise. The authors try to find the optimal placement of the inventory and/or backup capacity to protect the supply chain in case of a catastrophic failure of supply. Hopp and Yin [11] conclude that the inventory or backup capacity should be provided at most in one node along each path to the customer. Furthermore, it is optimal to locate the backup capacity in upstream nodes of the network as their failure time increases.

Although Tomlin [3] and Hopp and Yin [11] assume that there is no supply from the backup capacity during the response time, Klibi and Martel [12] consider the partial availability of the capacity of a depot during the recovery period. They propose a discrete stepwise function to represent the gradual capacity recovery of the disrupted depot based on the intensity of the disruption and the time to recovery. Gong et al. [13] develop a resilient supply chain design methodology where efficient restoration strategies of the infrastructure are explicitly considered. In addition, Niroomand et al. [9] illustrate partial availability of the capacity within the response time in a strategic capacity planning model. The authors consider a two-echelon supply chain where the production stage includes a dedicated manufacturing system (DMS) and a reconfigurable manufacturing system (RMS) as a volume-flexible backup resource achieved through reconfiguration. The reconfiguration process refers to capacity installation and ramp up/down phases. The model incorporates a partial availability of the RMS capacity during the ramp-up phase to better represent the modular structure of the RMS.

While Jordan and Graves [14] analyze the optimal configuration of the process flexibility among the products and resources in order to cope with demand variations, an RMS provides the required backup through the modular increase of the capacity. This scalable structure allows the RMS to be changeable in a single product setting or based on a part family.

The scalability of the RMS is one of the key enablers of achieving responsiveness in manufacturing systems [5]. Spicer et al. [15] determine the scalable design principles for CNC machine tools. The authors characterize transfer machines with high scalability and long lead time; on the other hand a multi-spindle CNC machine is considered to have better scalability with reduced lead time. An industrial application of scalable systems is presented in Deif and ElMaraghy [16] in electronics industry. Other examples of scalable systems in metal machining and assembly systems can be seen in Koren et al. [17].

The success of contingency rerouting depends on the operational characteristics such as the response speed [18]. A broad body of the literature deals with identifying the optimal response speed through finding the location of the backup facility [19]; but there are a few studies that focus on the manufacturing system structure of the backup facility [10]. Wang and Koren [20] model the scalability of manufacturing systems based on the configuration of machines. In a serial configuration, the added capacity can only become available after completing the reconfiguration process of all stages. Therefore the speed of transition to the required capacity is lower, albeit with low reconfiguration cost due to the use of simpler machine structures. On the other hand, in a pure parallel configuration, each machine could go under a reconfiguration process independently. Therefore the transition speed is faster with smaller increments. This may come at the higher reconfiguration cost since each machine should be capable of performing all the steps in order to create a parallel configuration. The differences in the manufacturing system configuration indicate that the configuration selection of the backup supplier can impact the responsiveness level where the tradeoff is between the cost and the response speed.

In a study using the assumption of investing in equipment to decrease the response time, Schmitt [21] investigates a multi-echelon supply chain where disruption might happen at any stage. The proposed risk management strategies involve safety inventory and backup facilities that could initiate operation after a certain response time. The model's objective is to find the optimal inventory level and the response time such that a certain service level would be satisfied under all plausible future scenarios. While Schmitt's work contributes by representing the partially lost sales as a function of the disruption duration, the model ignores a critical aspect in the supply flow. In a situation where the main supplier is disrupted, its demand would be transferred to the backup supplier under a contingency strategy. This may create an overload of demand at the backup supplier despite the quick ramp-up characteristics. As a result of this overload, queues will build up, degrading performance due to the congestion.

In the contingency planning, ignoring the impact of congestion leads to overestimation of production capacity [22]. In order to