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# Responsive contingency planning of capacitated supply networks under disruption risks

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ABSTRACT

This paper prescribes an appropriate risk mitigation model for a capacitated supply chain subject to premeditated attacks on facilities. It presents a unified approach to responsive contingency planning and optimizing protection of supply facilities utilizing a game-theoretic framework of attack and defense which involves multi level optimization. Gradual capacity backups is proposed for the first time in the context of protection under intentional attacks in a capacitated supply system. A recursive tree search algorithm is proposed to solve the tri-level optimization problem. Computational efficiency of the algorithm is demonstrated and managerial insights are presented.


## 1. Introduction

Over the past decade, several natural and man-made disaster events have affected supply chains world-wide. In October 2011, production at several computer manufacturing companies in Asia were halted by catastrophic flooding of hard disk supply facilities located at major cities of Thailand. The 2010 eruption of a volcano in Iceland disrupted millions of air travelers and affected time-sensitive air shipments (Chopra and Sodhi, 2014). The terrorist attacks of September 2001 led Ford to shutdown operations in five of its US assembly plants due to parts shortages. Such incidents of catastrophic events have increased in the recent years, spawning interest towards finding appropriate risk management strategies that help maintain supply chain performance amidst disruptions.

There are several risk management strategies through which disruption risks of supply chains can be managed, such as inventory, backup capacity, routine sourcing from multiple suppliers, contingent rerouting, demand management, facility location, and facility hardening. Tomlin (2006) categorizes inventory and sourcing as proactive mitigation strategies which can be taken ahead of disruption occurrences and rerouting and demand management as contingent or reactive strategies which are taken after disruption occurrences. Facility location is a proactive strategy appropriate while designing new supply chains but it can be very costly to relocate facilities in supply chains that have been operational, for which hardening or protection of existing facilities is a preferred strategy. Combining proactive and reactive strategies improve supply chain

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responsiveness to disaster events and are effective in minimizing both the short term economic impacts and long term losses of market shares from major disruptions.

Responsive contingency planning in supply chain risk management involves identification of appropriate risk management strategies ahead of disruptions, so that such strategies could be implemented in the event of disruptions to improve supply flows in the post disaster situation. It is thus a combination of both proactive and reactive risk management strategies. Holding strategic inventory ahead of disruptions and recovering disrupted flows through these inventories can be considered a responsive contingency approach, as supply chains can react to disruptions faster through such provisions. However, holding inventory for longer periods is cost prohibitive, and therefore is not an appropriate strategy under major disruptions that affect supply chains for longer periods (Hopp et al., 2012). To be of practical relevance, risk management strategies should investigate the trade-off of investments for capability improvements and risk reduction (Nooraie and Parast, 2016).

One of the cost effective and appropriate strategies for managing major disruption risks is contingent capacity adjustment through backup production. It involves utilizing backup capacity for extra production during disruptions so as to recover the lost supply. Unlike strategic inventory which needs to be held even when disasters have not occurred, back up production can be started only when such events occur and the disrupted supplies can be recovered from such backup productions. Risk mitigation through contingent capacity adjustment requires pro-active selection and planning of a backup capacity which improve post-disruption contingency operations. A major challenge in this approach is in having the desired units of backup production available within a short response time so as to improve disruption recovery speeds. Response time is dependent on the manufacturing system structure of a backup production facility. A scalable facility is able to quickly ramp up capacities in small increments, whereas a facility relying on dedicated equipment to reduce production cost will have a slower response time (Nejad et al., 2014). Response speed is related to response time and determines how fast a facility can reach its desired level of production. Response speed and back up capacity volumes together constitute the design parameters of a capacity backup risk mitigation plan. Appropriate selection of these parameters ensure effective contingent re-routing operations during disruptions with adequate protection of supplies and faster recovery from major disruptions.

Contingent capacity adjustments through gradually available capacity has traditionally been used for managing risks under major disruptions from random natural events. However, to the best of our knowledge, this idea has not been applied for managing risks from intentional attacks, which is fundamentally different from managing risks from natural disasters. Intentional attacks, such as the terror attacks are deliberately planned to create maximum damages to the system. In such attacks, the attacker is capable of adjusting attacks to circumvent against protection measures. Unlike intentional attacks, natural disasters do not have the capability of adjusting damage levels. These fundamental differences mean that strategies that are developed for managing disruption risks due to natural disasters are inadequate under intentional attacks. Therefore, it merits to incorporate gradual availability of backup capacities when planning for protection against intentional attacks.

In this paper, we present model for optimizing protection in a capacitated supply network subject to intentional attacks by incorporating gradually available backup capacity for recovering supply flows. The proposed model is a unified framework for responsive contingency planning and protection of critical facilities. Building on a game theoretic modeling framework to capture the elements of dependence between attack and defense (Brown et al., 2006), the mathematical model is formulated as a tri-level mixed integer optimization. This model is used to identify the optimal allocation of protection budget for the necessary levels of backup capacity volumes and response speeds at the different supply facilities prior to attacks. A solution algorithm based on implicit enumeration of defense strategies is proposed to arrive at decisions involving (i) which facilities to protect and back up, (ii) what should be the volume of a backup capacity, and (iii) what should be the response speed of capacity additions.

The remainder of this paper is organized as follows: Section 2 discusses relevant literature in protection planning. Section 3 details the formulation of the mathematical model. Section 4 presents the proposed solution methodology. In Section 5, numerical study is conducted and results are discussed. Section 6 offers some concluding remarks.

## 2. Literature review

Recent literature on supply chain risk management have focused on managing disruption risks through resiliency improvements (Sawik, 2013; Torabi et al., 2015; Fahimnia and Jabbarzadeh, 2016; Lam and Bai, 2016). In resilient systems, the supply chain infrastructures perform cost efficiently both during normal operations and during disruptions. A resilient supply chain can survive, adapt and grow in the face of change and uncertainty (Fiksel, 2006). We focus our literature review on research involving resilient supply chain design for protection against supply flow losses caused due to facility failures. The related literature intersect research domains in supply chain risk management, critical infrastructure protection and location sciences.

The relevant literature can be classified into two major streams of research. The first stream of research deals with protection through strategic locations of facilities to create an intrinsically resilient supply chain network which can perform at low cost both normally and during disruptions. These models rely on contingent rerouting of disrupted demands to the facilities or routine sourcing from multiple facilities for mitigating disruption risks. Readers are referred to Snyder and Daskin (2005), Berman et al. (2007), Cui et al. (2010), Lim et al. (2010), Peng et al. (2011), Aksen and Aras (2012) and references