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Measuring the efficacy of inventory with a dynamic input–output model

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ABSTRACT

This paper extends the recently developed dynamic inoperability input–output model (DIIM) for assessing productivity degradations due to disasters. Inventory policies are formulated and incorporated within the DIIM to evaluate the impact of inventories on the resilience of disrupted interdependent systems. The Inventory DIIM can provide practical insights to preparedness decision making through explicit tradeoff analysis of multiple objectives, including inventory costs and economic loss reductions. The model is demonstrated in several illustrative examples to depict various nuances of inventory policies. The paper then culminates in a case study that utilizes input–output and inventory accounts from the Bureau of Economic Analysis.

1. Introduction

The focus of infrastructure risk management and decision making has recently shifted from prevention and protection of infrastructure systems from disruptive events to recovery and response. For example, the US Department of Homeland Security (DHS) through its national infrastructure protection plan (Department of Homeland Security, 2006) has highlighted that the US must prepare for the inevitable occasion when a disruptive event occurs, stressing risk management strategies that “strengthen national preparedness, timely response, and rapid recovery in the event” of an attack or disaster. Furthermore, Department of Homeland Security (2006) underscores the need for instituting preparedness and resilience plans for critical infrastructure and key resources (CI/KR) of the nation.

Discussions of preparedness and resilience appear in Haimes (2006) and Haimes et al. (2008), where the connection is made between preparedness activities prior to a disruptive event to the resilience achieved following the disruptive event. Resilience is defined as the “ability to cushion or mute potential losses” (Rose, 2004) from a disruptive event. In general, economic resilience is defined as the ability or capability of a system to absorb or cushion against damage or loss (Holling, 1973; Perrings, 2001). Increasing the resilience of a sector reduces its recovery time as well as the associated economic losses.

Of particular interest to the discussion of preparedness and resilience are interdependencies among critical infrastructure and economic systems. The operation of such critical systems, or essential services, without interruption is of incredible importance, and failing to prepare can result in “widespread uncertainty about restoration of services, lack of viable economic and social networks, serious loss of public confidence, and even social collapse” (La Porte, 2006). The interdependence of such essential services and the private infrastructure components of supply chains is well documented (e.g., Rinaldi et al., 2001; Little, 2002; Kormos and Bowe, 2006). Due to the interdependencies among production activities in various sectors of the economy, a disruption in production can have far-reaching effects. One significant means of preparedness and resilience in a production environment comes from the availability of inventory. The above motivates this work to strengthen our ability to model

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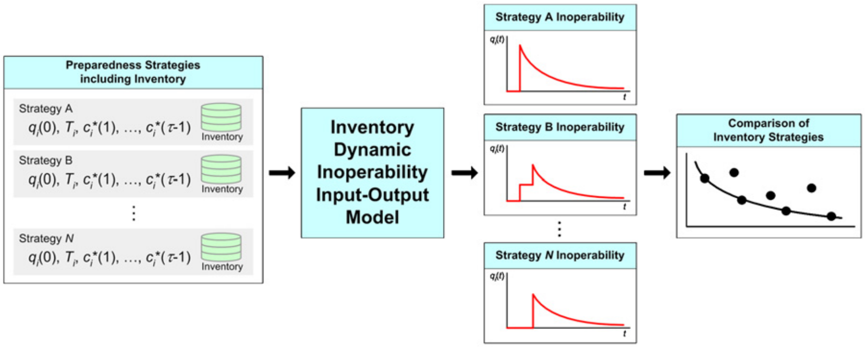

Fig. 1. Depiction of modeling preparedness strategies which involve inventory policies.

the impact of inventory policies on interdependent infrastructure systems.

Several risk-based interdependency modeling schemes have been developed recently, including the inoperability input–output model (IIM) (Haimes and Jiang, 2001; Jiang and Haimes, 2004; Santos and Haimes, 2004). A derivative of the IIM which models the dynamic recovery of interdependent sectors and evaluates the effect of risk management strategies on that recovery is the dynamic IIM (DIIM) (Lian and Haimes, 2006). While the IIM and its derivatives successfully measure the effects of certain risk management strategies, they are unable to account for strategies that add resilience through inventory. This paper integrates the DIIM with an inventory model to quantify the efficacy of inventory strategies employed in interdependent infrastructure sectors and other members of a supply chain.

Ultimately, the model provides a metric quantifying how different risk management strategies involving inventory will affect recovery following a disruption, as depicted in Fig. 1. From left to right, the first component in Fig. 1 depicts various preparedness strategies used to reduce the effects of a disruptive event and the DIIM parameters that vary with each strategy. They serve as inputs to the Inventory DIIM, which quantifies inoperability experienced by different sectors of the economy over time and quantifies the economic losses resulting from a disruptive event. Such inoperability trajectories and economic losses are calculated for each strategy, and the strategies are compared with a multiobjective framework where tradeoffs between costs and benefits are calculated.

2. Methodological background

Discussed in this section are several models of inventory, including previous input–output-based representations of inventory, and the risk-based interdependency model used in this paper, the dynamic inoperability input–output model.

2.1. Inventory philosophies

Presented in this section are discussions of several key inventory control approaches found in practice and in the operations management literature. The philosophies of many of these methods are perhaps contradictory to the concept of preparedness.

Early inventory models include the economic order quantity (EOQ), Wagner–Whitin, base stock, and (Q, r) models, and each calculate a reorder point that attempts to minimize the cost of manufacturing. While each has varying levels of assumptions and data requirements, a basic insight from these models is that there is a tradeoff between customer service and inventory (Hopp and Spearman, 2000). That is, inventory costs are reduced at the cost of meeting customer service levels under conditions of random demand. The previously mentioned inventory models were deemed more appropriate, though highly restrictive, for purchasing environments and not production environments.

A shift to a more supply chain-oriented approach was developed with the just-in-time (JIT) philosophy. The JIT approach is designed around the arrival of required materials to a production workstation precisely when needed (Hopp and Spearman, 2000), thereby reducing the amount of on-hand inventory to nearly zero. Difficulties arising from the "zero inventory" tenet of JIT led companies to adapt the approach, though the desire to maintain small amounts of inventory still remains.

An operations management philosophy that emphasizes minimal inventory has significant implications for participants in an interdependent supply chain. Chittister and Haimes (2004) observe that an information technology-driven shift to JIT has "reduced the operational buffer zone in most infrastructures." Kleindorfer and Saad (2005) note two types of risks to supply chains: risks arising from problems in coordinating supply and demand, and risks arising from disruptions to normal activities. A disruption to a supply chain participant who has no ability to stave off inoperability, either by on-hand inventory or some other means, can have ripple effects throughout its interconnected supply chain. Chopra and Sodhi (2004) remark that while "bare-bones inventory levels decrease the impact of overforecasting demand, they simultaneously increase the impact of a supply chain disruption. Similarly, actions taken by any company in the supply chain can increase risk for any other participating company." Kleindorfer and Saad (2005) observe that implementing a policy of reduced inventory "may result in increasing the level of vulnerability, at both the individual firm level and across the supply chain."