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Complex interdependent supply chain networks: Cascading failure and robustness

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HIGHLIGHTS

- We construct a theoretical model of interdependent supply chain network.
- A time-varied cascading failure model of failed loads propagation is developed.
- We present a priority redistribution strategy for failed loads propagation.
- The robustness of supply chain network is assessed in three node removal ways.
- The simulation results show a sudden collapse of interdependent supply chain network.

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ABSTRACT

A supply chain network is a typical interdependent network composed of an undirected cyber-layer network and a directed physical-layer network. To analyze the robustness of this complex interdependent supply chain network when it suffers from disruption events that can cause nodes to fail, we use a cascading failure process that focuses on load propagation. We consider load propagation via connectivity links as node failure spreads through one layer of an interdependent network, and we develop a priority redistribution strategy for failed loads subject to flow constraint. Using a giant component function and a one-to-one directed interdependence relation between nodes in a cyber-layer network and physical-layer network, we construct time-varied functional equations to quantify the dynamic process of failed loads propagation in an interdependent network. Finally, we conduct a numerical simulation for two cases, i.e., single node removal and multiple node removal at the initial disruption. The simulation results show that when we increase the number of removed nodes in an interdependent supply chain network its robustness undergoes a first-order discontinuous phase transition, and that even removing a small number of nodes will cause it to crash.

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1. Introduction

In recent years we have begun to understand the behavior of such phenomena as natural disasters, the breakdown of technological systems, epidemic propagation, and spreading social unrest in terms of their complex network structure. During these events, supply chain systems often collapse, e.g., during the 2011 earthquake in Japan the Toyota Motor Company was forced to stop operations in twelve assembly plants and absorb a production loss of 140,000 vehicles. The main cause of this problem was the disruption of the supply chain supporting the manufacturing subsystem. During disruptive events, supply chains are particularly vulnerable to propagating failure. A major cause of this is the connectivity and interdependent relationships between supply chain partners. Dependence relationships can cause the transmission of disruptions to "snowball" through a supply chain network or through a portion of it [1].

In order to develop effective countermeasures to these disruptions, we must understand the conditions that allow them to occur and the mechanisms that drive risk propagation. Linked relations are one precondition for cascading failures that collapse a supply chain system, but there are others. As information and network technology becomes increasingly sophisticated, supply chain systems increase in complexity and become ever more dependent on a collaborative network structure. Most real-world supply chain collaborative networks consist of two networks: an undirected cyber-layer network and a directed physical-layer network. As the two layers interact they guarantee the function of the supply chain system, but they also become less robust to attack and breakdown and more likely to facilitate global collapse. A significant amount of empirical and quantitative research has been done on supply chain risk management, including measuring global supply chain risk, planning for catastrophic events in supply chains, and increasing chain agility and risk mitigation [2]. These research have been of limited usefulness because they have been focused on the risk of cascading failure in single isolated networks and, in contrast, most real-world supply chain networks are geographically dispersed across regions and countries [3–5].

Most current studies of cascading failures in complex networks have focused on single networks [6–12]. Because it is difficult to depict real-world network systems using a single network model, e.g., a supply chain network with multiple attributes and multiple functions, some researchers have proposed a "super network" concept [13–16], and interdependent network models have also been proposed. A notable case is the work by Buldyrev et al. [17] in which they describe a one-to-one correspondence model for studying the ramifications of interdependence between two networks. Their analytical framework is based on a generating-function formalism widely used for studies of percolation and structure within a single network [7]. This framework for interdependent networks enables us to follow the dynamics of the cascading failures and derive analytic solutions for the final steady state. Inspired by the work of Buldyrev [17], many researchers have studied interdependent networks from different angles [18–26].

Most of the above researches especially those related to interdependent networks, do not consider the spreading of failed loads, and thus their determining whether neighbor nodes connecting with failed nodes will fail depends on the connectivity links and dependence links, and not on the capacity of the neighbor nodes. Unlike most of these previous works, which focuses on interdependent networks formed from undirected networks, we analyze the cascading failure process and the robustness of interdependent networks that are composed of both undirected and directed networks. We also take into account the flow constraints present when failed loads propagate through a directed layer network, which is an important factor in a supply chain network. We examine the cascading failure mechanism of an interdependent supply chain network subject to a one-to-one interdependence relation in order to measure its robustness against disruption when it is composed of an undirected cyber-layer network and a directed physical-layer network. Our results can provide a scientific basis for the structural optimization of an interdependent supply chain network and for the development of a robustness control Q2 strategy.

2. Theoretical model of interdependent supply chain networks

As described above, an interdependent supply chain network is composed of a physical-layer network G^P and a cyber-layer network G^L. We assume all suppliers, production centers, distribution centers, and customers to be network nodes. Because the cyber-layer and the physical-layer of a supply chain network are interactive, failed nodes in one layer can propagate their failure through dependence links to nodes in both layers. The links between nodes in the same layer are connectivity links, and they can transfer failed loads. The links between nodes in different layers are dependence links. In this two-layered interdependent supply chain network, failures caused by disruption are redistributed.

Here both networks have N nodes. Without loss of generality, we assume the nodes in network G^P are connected with directed links using a degree distribution function $P_P(k)$, which contains an in-degree distribution $P_P(k_{in})$ and an out-degree distribution $P_P(k_{out})$. The nodes in network G^L are similarly connected with undirected links using a degree distribution $P_L(k)$.

2.1. Supply chain physical-layer network

A supply chain physical-layer network is composed of suppliers, manufacturers, distributors, retailers, and customers, all of which can be denoted as nodes, and the connecting relationship between entities can be denoted as edges. A model of a physical-layer network can therefore be represented as

$$R^P = (V^P, E^P, W^P, L^P, C^P), \tag{1}$$