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A supporting station model for reliable infrastructure location design under interdependent disruptions ☆

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ABSTRACT

This paper proposes a new modeling method that equivalently transforms interdependent and correlated facility failures in an infrastructure system into only i.i.d. disruptions in a supporting structure. The properties of this structure are examined and a mathematical model is created to solve reliable facility location design problems under correlated facility failure risks. This model is formulated into a compact integer linear program and can be efficiently solved by state-of-the-art solvers. A set of experiments and case studies are conducted to demonstrate the applicability of the proposed model and to draw managerial insights into the optimal system design.

1. Introduction

Infrastructures, such as those for transportation, energy, communications, are critical to the welfare and sustainability of a modern economy. Complex connections from increasing physical, resource, information, and social interactions have tied these critical infrastructures into highly coupled and interdependent network systems. Such interdependent infrastructures, however, are particularly vulnerable to natural and human-induced disasters, as evidenced by the series of recent catastrophic events and their associated costs for response and recovery. Well-known examples include the 2002 west-coast port lockout that strangled US freight supply chains (D'Amico, 2002), the massive power outage in 2003 that disabled major transportation systems in the Northeast (Schewe, 2004), and the 2005 Hurricane Katrina that idled all production and transportation facilities in the Gulf Coast region (Godoy, 2007). Japan's Fukushima Daiichi nuclear reactor failure in March 2011, in particular, was not due to direct impact of the 8.9-magnitude earthquake or the tsunami that followed, but rather due to the loss of regular electricity power supply (from outside power stations) for its emergency cooling system (World Health Organization, 2011). This highlights the pressing need to address the potential risk of correlated (or even cascading) failures while planning and designing interdependent infrastructure networks.

Network location design has been intensively studied for several decades. Most early efforts focused on systems with deterministic settings, and numerous models have been developed using discrete (see Daskin, 1995; Drezner, 1995 for reviews) and continuous (see Langevin et al., 1996; Daganzo, 2005 for reviews) formulations. Later, researchers started to investigate facility congestion that arises from stochastic demand and attempted to enhance system availability by providing redundancy (Daskin, 1982, 1983; Revelle and Hogan, 1989; Batta et al., 1989; Ball and Lin, 1993). Recently, adversary

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impacts from stochastic facility failures have been recognized, and reliable facility location models were proposed to design facility locations and customer assignment plans under probabilistic facility failure risks (Snyder and Daskin, 2005; Cui et al., 2010; Qi et al., 2010; Chen et al., 2011; Li and Ouyang, 2011, 2012). These efforts have produced a number of mathematical models to design infrastructure systems where operations at different facilities are isolated and facility failures are completely independent. However, to our best knowledge, only a very few studies ever considered correlated failure mechanisms. Li and Ouyang (2010) addressed correlations among network facility failures in the context of reliable facility location design, but the developed continuum approximation model is only suitable for macroscopic problems with a smooth and continuous setting. Berman and Krass (2011) studied a reliable *p*-median problem considering correlated disruptions, but the analysis is only limited to problems in a one-dimensional space. In the infrastructure protection context, Liberatore et al. (2012) considered facility failure propagations by a two-dimensional correlation matrix, which however only captures deterministic capacity losses under pair-wise failure correlations rather than stochastic failures or their higher-order correlations. Few discrete models have been developed in the form of a compact mathematical program (i.e., the numbers of variables and constraints are polynomial functions of the problem size) for a highly heterogeneous two-dimensional space with stochastic correlated facility failures. Even evaluating the expected performance of a given design is quite challenging, which is probably because no efficient modeling method was found to describe correlated facility failures (e.g., without enumerating the large number of probabilistic failure scenarios).

To bridge these gaps in the existing literature, this paper explored succinct representation schemes of interdependent facility failures and successfully created a compact modeling framework that efficiently solves the reliable facility location design problem under failure correlations. We propose an explicit supporting structure framework to equivalently represent a range of correlated facility failure patterns, e.g., those due to shared fallible resource suppliers or common disastrous hazards. This framework transforms convoluted and complex failure correlation patterns observed at service facilities into a set of explicitly connected supporting stations that are subject to only independent and identically distributed (i.i.d.) disruptions. With proper settings (e.g., connection relationships and station disruption probabilities), such a supporting structure can be used to emulate a general class of correlated facility failure patterns. Besides, it is actually consistent with many real-world infrastructure interdependence relationships (e.g., electricity grids experiencing power plant disruptions, and bridge networks exposed to earthquakes), and thus it can be directly used to model a range of realistic infrastructure system design problems.

Building upon the proposed supporting structure model, we further propose a mathematical programming model that determines the optimal network location design for an infrastructure system under correlated facility failure risks. The optimal design shall minimize the total expected system cost throughout the planning horizon, including both the initial infrastructure investment to construct supporting stations and service facilities and the expected day-to-day operational costs due to customer traveling or loss of service. This problem is formulated into a compact integer linear program and can be solved efficiently by state-of-the-art commercial solvers. Numerical experiments and case studies are conducted to illustrate the applicability of the proposed model framework and to show interesting insights on how various system parameters (e.g., correlation pattern, failure probability, spatial heterogeneity) impact the optimal network design.

The exposition of the remainder of this paper is as follows. Section 2 introduces the notation of a supporting structure and associated cost components. Key properties of the supporting structure are identified. Building upon this structure, Section 3 proposes a reliable facility location design model that has a compact formulation and can be efficiently solved with state-of-the-art solvers. Section 4 conducts numerical and case studies and analyzes their results. Section 5 concludes this paper and discusses possible future research.

2. Supporting structure analysis

The core system of our interest includes a set of spatially distributed customers and a set of facilities that provide certain service to the nearby customers. We assume these facilities may fail (and thus stop providing the service) from time to time, and we allow their failures to be site-dependent and spatially-correlated. Such a model can represent many real-world systems where infrastructures are subject to disruptions due to various internal or external hazards. However, efficiently and accurately quantifying the performance of such a system is quite challenging, primarily due to the difficulty in modeling complex facility failures in an efficient and compact form (e.g., without enumerating all possible combinatorial failure scenarios). Nevertheless, many complex failure patterns in a real-world system are caused by certain underlying mechanisms shared by individual facilities (e.g., a common disaster, shared resource suppliers). Thus, instead of directly enumerating all failure scenarios, we propose to represent failure mechanisms of the service facilities equivalently by attaching a properly-defined supporting station structure. Basically, the supporting structure includes a set of vulnerable supporting stations, each of which is connected to certain service facilities. We require that a facility is operational if at least one of its connected supporting stations is functioning. This way, this paper shows that facility failures with general site-dependent and positively-correlated patterns can be equivalently "transferred" to independent and homogeneous disruptions in the supporting structure.

In the remainder of this section, Section 2.1 introduces the notation of a supporting structure representation of an infrastructure system and the related cost components. Section 2.2 discusses several key properties of this structure and shows how to use it to represent a range of heterogeneous and correlated facility failure patterns.