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Resilience-based network design under uncertainty

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ABSTRACT

This paper introduces an approach to quantify resilience for the design of systems that can be described as a network. A key characteristic of resilience is the ability of restoring functionality and performance in response to a disruptive event. Therefore, the restoration behavior is encapsulated via a non-linear function that provides the ability to model at the component level more refined attributes of restoration. In particular, it considers the remaining capacity (absorptive ability), the degree to which capability can be recovered (restoration ability) and the recovery speed. The component restoration functions can then be used to impose a resilience target at a given time as a design constraint.

The resilience-based design optimization is then formulated for both deterministic and stochastic cases of a network system. The objective is to have as the design solution a network that incurs the least cost while meeting system resilience constraints. Maximum flow through the network is used as a measure of system performance. Several possible links are examined with regards to flow performance from origin node to a destination node. A probabilistic solution discovery algorithm is combined with stochastic ranking to approach this problem. Two numerical examples are used to illustrate the procedure and the effectiveness of the proposed method.

1. Introduction

Considering the ubiquitous nature of multiple infrastructure networks in our daily life, there is an ever-increasing demand for ensuring their regular function by minimizing the adverse effects of disruptive events. A common strategy is to reduce the likelihood of system malfunctions by increasing system redundancy, which is often the focus of reliability engineering [1,2]. Nevertheless, strategies are also needed to mitigate the consequences of undesirable events, because recent natural disasters demonstrate that not all undesirable random events are preventable. For example, in 2008, a deadly earthquake with a magnitude of 8.0 hit the county Wenchuan in Sichuan province, China, causing 69,197 confirmed deaths, 374,176 injured, and 18,222 missing [3]. Several infrastructure systems, e.g., power network, telecommunication network, were heavily undermined by this earthquake, which severely impeded on the subsequent rescue activities. The 14 August 2003 blackout cost between US $4 billion and $6 billion according to the U.S. Department of Energy [4]. In 2016, heavy rains devastated the transportation system of Beijing, and hundreds of flights and trains were cancelled after the capital was hit by persistent rain [5].

The above large-scale disruptive events highlight the need for innovative design of infrastructure systems, whose performance can be restored in a timely manner after the disruption. As a result, recent efforts have expanded from reliability engineering to a new paradigm – resilience engineering [6,7]. In general, while reliability engineering focuses on enhancing the ability of a system (or component) to work properly for a specified period of time by reducing its probability of failure through testing and simulation, resilience engineering emphasizes improving the system's capability to bounce back from disruptive events quickly to offer a desired level of performance (perhaps not the original level of performance) after the disruption. Three types of strategies have been advocated for resilience, namely, preparedness, timely response, and rapid recovery [8].

Since Holling [9] first introduced the concept of resilience and demonstrated its significant role in maintaining the stability of ecological systems, this research topic has received increasing attention in other domains [10,11]. Subsequently, much effort has been dedicated to defining and to measuring system resilience. For example, Haimes [12] defined system resilience as the ability of a system to withstand and to recover from a major disruption, and compared it with reliability, robustness, vulnerability, and risk. In 2009, Attoh-Okine et al. [13] formulated a resilience index for urban infrastructure using Dempster–Shafer theory. In 2012, Henry and Ramirez-Marquez [14] identified several important parameters associated with system resilience quantification, e.g., disruptive events and component restoration, in which they mea-

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sured system resilience as a time dependent function. In 2012, Ouyang et al. [15] assessed the resilience of the power transmission grid in Harris County, Texas USA under hurricane and other hazards. In 2013, Barker et al. [16] developed an indicator to measure the component importance by quantifying its adverse impact on system resilience when the disruption affected that component. Likewise, Fang et al. [17] utilized two metrics, i.e., optimal repair time and resilience reduction worth, to measure the importance of the components in a network system from the perspective of their contribution to system resilience. In 2016, Adjetey-Bahun et al. [18] proposed a simulation-based model to quantify the resilience in mass railway systems by using passenger delay and passenger load as system performance indicators. In 2016, Zhen and Mahadevan [19] modeled system resilience as a function of time-dependent system reliability, system failure paths and recovery probability, and utilized sensitivity analysis to measure the component importance. In 2017, Fotouhi et al. [20] developed a bi-level, mixed-integer, stochastic program to quantify the resilience of a coupled traffic-power network under a host of potential natural hazard-impact scenarios. Recently, Hosseini et al. [21] presented a comprehensive review focusing on qualitative and quantitative modelling of system resilience in engineering systems.

Many different definitions of resilience are available [22], depending on the specific subject area. All of the definitions have one common goal: to understand the system resilience in different contexts so as to design and to deploy resilient infrastructure systems. However, methods for resilient infrastructure system design are yet to be explored. To the best of the authors' knowledge, only a few research studies have investigated this issue. For example, Youn et al. [23] proposed a conceptual resilience definition for engineered systems by incorporating system reliability and restoration, developed a Resilience-Driven System Design (RDSD) framework, and demonstrated its usefulness in a simplified aircraft control actuator optimization problem. In order to achieve the target system resilience, Yodo and Wang [24] presented a three-step framework to allocate resilience optimally for the early stage design of complex engineering systems: quantification of system resilience through a Bayesian network, identification of critical components by utilizing sensitivity analysis, and allocation of resilience to critical components. Christopher and Peck [25] explored resilience in supply chains, and identified a number of discernible general principles that underpin resilience in supply chains.

However, most of these studies focus on resilient design in engineering systems. Whereas, in reality, many infrastructure systems, e.g., transportation networks, power grids, and telecommunication networks, are organized in the form of networks. By enabling resilience in these infrastructure systems, these systems can be equipped with the capability to return to the original performance level or some other desired state in the presence of disruptive events, which has the potential to reduce the economic losses.

Unfortunately, the design of resilient infrastructure systems is still a largely unexplored topic. Only a few studies have investigated resilient design [26–28] and communication systems [29,30]. For example, in 2012, Chen and Miller-Hooks [31] identified an optimal post-event course of actions for an intermodal freight model transport network in the immediate aftermath of the disruptive event so as to fulfill target operational levels while adhering to a fixed budget. In 2014, Faturechi et al. [32] modeled the airport resilience as the expected fraction of total pre-event demand in terms of arrival and departure flows that can be met post-repair within limited repair time and budget, formulated the problem as stochastic integer program, and identified the optimal allocation of limited resources to maximize the system resilience. Later, Faturechi and Miller-Hooks [33] formulated a bi-level, three-stage Stochastic Mathematical Program to characterize and optimize the travel time resilience in road networks. In 2015, Fang et al. [34] considered the problem of optimizing the power transmission network under the objective of maximizing system resilience to cascading failures and minimizing investment costs. In the same year, Bhatia et al. [35] quantified several different recovery strategies in restoring the critical functionality of the Indian Railways Network by considering three disruptive events, namely the 2004 Indian Ocean Tsunami, 2012 North Indian blackout, and a cyber-physical attack. However, how to carry out *a priori* analysis during the design phase to optimize the topology of the current network to strengthen its resilience against these disruptions has not been addressed yet. In 2017, Fang and Sansavini [36] adopted a planner-attacker-defender model to optimize power system investments and resilience against attacks through capacity expansion and switch installation. Asadabadi and Miller-Hooks [37] modelled the impact of climate change in terms of sea level rise (SLR) on roadway performance as a multi-stage, stochastic, bi-level, mixed integer program and developed a to identify a recursive noisy genetic algorithm optimal investment location, timing and extent.

However, there are some common shortcomings in the above studies. First, they do not characterize the significant features of a system or a component (e.g., link in traffic network) in the aftermath of a disruptive event, such as, absorptive ability (the remaining capacity), restorative ability (the restoration magnitude), and restoration speed. Such characteristics are important considerations in designing resilient infrastructure system. In addition, when a disruptive event happens, the system restoration and recovery usually consumes a certain amount of time to bounce back to the original performance. From this perspective, system resilience is a time-varying variable, whereas, most current studies do not model the system resilience in this manner.

In this paper, we are motivated to fill the above gaps by mathematically formulating the resilience-based network design problem and developing an effective approach to identify solution to this problem. With respect to system resilience, we adopt the definition proposed by Henry and Ramirez-Marquez [14] because their definition helps to model the system resilience quantitatively as an attribute of a system's delivery function. Compared to the current state of the art, we make the following contributions:

- To design a resilient network system, the first step is to understand how each system component recovers over time after the disruption. In this paper, we introduce a flexible nonlinear function to characterize the component restoration process after the disruption.
- We formulate the resilience-based network design optimization problem. Our goal is to design a system with minimal cost while satisfying a resilience constraint. The resilience constraint requires that the system performance spring back to a desired level after the disruptive event.
- Since uncertainty arises in modeling the component restoration, we consider two cases: deterministic and stochastic. The system resilience constraint varies from case to case. In the first case, it is a deterministic constraint. While in the latter, the system resilience is a probabilistic constraint.
- To solve the resilience-based network design optimization problem, we develop a probabilistic solution discovery algorithm and integrate it with a stochastic ranking approach to identify the optimal solution.

The rest of this paper is organized as follows. In Section 2, we introduce system resilience and the system performance metric used in this paper. In Section 3, we define the resilience-based network design problem and develop an algorithm to solve this problem. In Section 4, two numerical examples are used to illustrate the proposed method and demonstrate its efficiency. In Section 5, we conclude this paper with a brief summary and suggest possible directions for future research.

2. Background

In this section, we review the definition of system (network) resilience, which is originally discussed in Refs [14,38], and the modelling of network performance.