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Restoration resource allocation model for enhancing resilience of interdependent infrastructure systems

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ABSTRACT

Enhancing the resilience of infrastructure systems is critical to the sustainability of the society against multiple disruptive events. This paper develops an approach for allocating restoration resources to enhance resilience of interdependent infrastructure systems. According to Inoperability Input–Output Model, a resilience metric for infrastructure systems is developed, in which the performance loss of infrastructure systems resulting from a disruptive event is measured in economic loss and inoperability. Model for determining the optimal infrastructure restoration resources allocation is proposed with the objective of maximizing resilience. Infrastructure interdependence is modeled by the Dynamic Inoperability Input-Output Model (DIIM), which is an accepted economic model for describing the interconnected relationship of industry sectors. To investigate the utility of the restoration resource allocation model, numerical analysis is conducted with an example derived from the data provided by the US Bureau of Economic Analysis. The results show that: (1) the optimal restoration resource allocation varies with the resource budget; (2) for a specific disruptive event, there exists an optimal resource budget which can minimize the sum of restoration cost and the performance loss of infrastructure system; and (3) the significance of factors such as initial inoperability of infrastructure systems on the optimal allocation. The proposed model can assist the decision makers in (i) better understand the effects of resource allocation, and (ii) deciding which allocation strategies should be used following a disruptive event.

1. Introduction

Modern society relies on the continuing services of infrastructure systems, e.g. transportation system, power grid, water supply system, as the backbone of national economy, security, and health. Critical infrastructure systems are complex with interconnected structural elements and functions. Interdependency is the basic operational characteristic of infrastructure systems. However, the infrastructure systems are becoming more vulnerable due to failure propagation across systems through the interconnected elements (Buldyrev et al., 2010). Large-scale disruptive events affecting infrastructure, though infrequent, are extremely costly to a society (Fang et al., 2015). Typical examples include 2003 power outage in North America, 2005 Hurricane Katrina in the USA (Leavitt and Kiefer, 2006), and the 2008 snow disaster in South China (Hou et al., 2008). The economic loss induced by these events can be very high (up to billions of dollars). For example, the 2003 power outage in North America generated almost US $6 billion loss. The resilience is an important characteristic of real-world systems affected by disruptive events, which are (i) related to systems' abilities to perform their functions, (b) reduce the magnitude of impacts of disruptive events through their adaptive capacity (National Infrastructure Advisory Council, 2009), and (iii) recover to normal functions (Ouyang and Wang, 2015). Given the increasing impact of natural and man-made disasters on infrastructure systems, improving resilience of interdependent infrastructure system is of growing importance. This requires quantifying the resilience of interconnected systems and developing approaches for enhancing resilience.

Some studies have developed resilience metrics for single infrastructure systems based on two system performance curves during a specific time period: one is the real performance curve, recording system performance change under a disruptive event and restoration activities, and the other is the expected performance curve, giving system performance level without a disruptive event. The resilience is then quantified as the area between the two curves within a restoration period (Bruneau et al., 2003; Bruneau and Reinhorn, 2007), or the area between the two curves during a given time period during which

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multiple disruptive events may happen (Ouyang and Dueñas-Osorio, 2012), or a normalized area under the performance curve of a system during a disruptive event (Chang and Shinozuka, 2004). These metrics quantify the resilience of an infrastructure system to a disruptive event or a sequence of disruptive events based on their performance losses. The basic idea of the aforementioned resilience metrics has been extended in a number of ways, for example, applying the ratio of recovery at a given time to the loss in performance (Henry and Ramirez-Marquez, 2012), or a stochastic metric by taking uncertainty into account (Pant et al., 2014a, 2014b). A dynamic resilience metric was proposed based on the adaptive capacity of an infrastructure system and the level of system performance, which can provide more insight into system performance evolution from the beginning of a disruptive event until the full performance recovery (Simonovic and Peck, 2013; Simonovic, 2016). However, since it is difficult to quantify the performance of different infrastructure systems into one formulation, the literature on resilience metrics concentrates on the capacity of a single system. Since the protection and recovery from infrastructure system failures are complex practical problems, the resilience of infrastructure systems becomes a focus point for policy making. There is a need for study of resilience of interdependent infrastructure systems and enhancement strategies.

Restoration activities are essential for enhancing resilience of infrastructure systems (Heath et al., 2016). Under large scale disruptive events, through supply of physical and/or financial restoration resources to infrastructure managers, central or local governments will help restore performance of damaged infrastructure systems and mitigate the disastrous impacts (MacKenzie and Zobel, 2016). Optimal resource allocation among infrastructures at the system level is critical for resilience enhancement due to the budget limitations. In the literature, resource allocation models seek to answer the question of how to satisfy specific goals with limited resources within a given constraints (MacKenzie et al., 2016), and have been applied to analyze many policy-related problems (Petrovic et al., 2012; Shan and Zhuang, 2013a, 2013b). The objective of restoration resources allocation is to help expedite the recovery of infrastructure systems, with consideration of their damage magnitudes and interdependencies. This problem has not been addressed in the available literature and will be investigated in this research.

Interdependencies among infrastructure systems should be considered in the restoration resource allocation problems. The effects of interdependencies include propagation of effects from one infrastructure system to another (Rinaldi et al., 2001). Therefore, a disruptive event that directly impacts one infrastructure system can trigger indirect impacts to other systems. Further, the performance recovery processes of impacted infrastructure systems are also affected by interdependencies (Baroud et al., 2015). A variety of models have been proposed to analyze the interconnected relationships among infrastructure systems (Ouyang, 2014). Network based models and economic theory based models are most commonly used. Interdependent infrastructure systems are described as multilayer networks in network based models. The interdependencies between systems can be quantified and analyzed at component level (Wang et al., 2013; Ouyang and Wang, 2015). In comparison, economic theory based models usually use infrastructure system, or subsystem, as the smallest analysis unit, and analyze the interdependencies at system level (Haimes et al., 2005a, 2005b). In this study, Dynamic Inoperability Input-Output Model (DIIM), one of the economic theory based models, proposed by Haimes et al. (2005a, 2005b), is chosen to capture the recovery dynamics of interdependent infrastructure systems. Based on the interdependency matrix and initial disturbances caused by a disruptive event, the DIIM can calculate the economic losses and inoperabilities of interdependent infrastructure systems during the recovery process (Lian and Haimes, 2006).

The main contributions of the present research include: (i) development of an optimization model for determining the optimal allocation of restoration resources to interdependent infrastructure systems. As interdependencies among infrastructure systems are of great importance in system recovery process, the effects of interdependencies are embedded into the model by the application of DIIM. (ii) Application of the model to an example derived from the data provided by the BEA (the US Bureau of Economic Analysis). The example demonstrates the utility of the model in decision making. The results show (i) how to allocate limited resources to interdependent infrastructure systems, (ii) what is the optimal level of recovery budget for a specific disruptive event, and (iii) the significance of various factors on the level of resource budget for a specific infrastructure system.

The paper is organized as follows. Section 2 develops a resilience metric for interdependent infrastructure systems. With the objective of maximizing resilience, Section 3 proposes a restoration resources allocation model for enhancing resilience of interdependent infrastructure systems. Section 4 provides a numerical method for solving the resource allocation model. Section 5 investigates the utility of the model through numerical analysis. Section 6 concludes.

2. Resilience of infrastructure systems

2.1. Resilience metric for single infrastructure system

From engineering-based point of view, infrastructure system resilience is derived from the change in system performance over time (MacKenzie and Zobel, 2016). The resilience model derived by MCEER (Multidisciplinary Center for Earthquake Engineering Research, Bruneau and Reinhorn, 2007) quantifies the resilience as the area under the system performance curve (describing system performance from the beginning of system disturbance until full system recovery shown as the area under system performance with restoration strategy from t_{DO} to t_{RE} in Fig. 1). In order for easy comparison among diverse systems, system resilience is measured as the ratio of the area under system performance with restoration strategy to the area under expected system performance from t_{DO} to t_{RE} (Zobel, 2011; Simonovic and Peck, 2013). Then the resilience of infrastructure ϕ under a disruptive event is expressed as

$$\gamma_\phi = \frac{\int_{t_{DO}}^{t_{RE}} SP_\phi(t)dt}{\int_{t_{DO}}^{t_{RE}} SP_\phi^E(t)dt} = \frac{\int_{t_{DO}}^{t_{RE}} (SP_\phi^E(t) - SL_\phi(t))dt}{\int_{t_{DO}}^{t_{RE}} SP_\phi^E(t)dt} = 1 - \frac{\int_{Rapidity_\phi} SL_\phi(t)dt}{\int_{Rapidity_\phi} SP_\phi^E(t)dt} \tag{1}$$

where t_{DO} is the occurrence time of a disruptive event, t_{RE} is the full recovery time of infrastructure system ϕ, $SP_\phi^E(t)$ is the expected system performance level, $SP_\phi(t)$ is the actual system performance, $SL_\phi(t)$ is the difference between $SP_\phi^E(t)$ and $SP_\phi(t)$. Rapidity refers to the capacity to meet priorities and achieve goals in a timely manner, which is measured by the duration of system performance recovery and expressed as $Rapidity_\phi = t_{RE} - t_{DO}$. Robustness refers to the ability of a system to withstand a given level of stress without suffering further degradation or loss of function. It is usually quantified as the minimum system performance under recovery process.

According to Eq. (1), system resilience is the proportion of the shaded area to the area under expected system performance. The level of robustness indicates that the infrastructure system is not totally damaged by a disruptive event but, without self-repairing capability, it could not recover to normal performance level. Since the robustness of an infrastructure system under a specific disruptive event is fixed (property of the system structure), the system resilience is determined by the restoration activities. In Fig. 1, the result of a restoration strategy i is illustrated as the shaded area. The different contributions of restoration strategy i and j to resilience could be measured by the difference in shaded area between system performance curves with the two restoration strategies.