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Resilience assessment of interdependent infrastructure systems: With a focus on joint restoration modeling and analysis

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ABSTRACT

As infrastructure systems are highly interconnected, it is crucial to analyze their resilience with the consideration of their interdependencies. This paper adapts an existing resilience assessment framework for single systems to interdependent systems and mainly focuses on modeling and resilience contribution analysis of multi-systems' joint restoration processes, which are seldom addressed in the literature. Taking interdependent power and gas systems in Houston, Texas, USA under hurricane hazards as an illustrative exmaple, five types of joint restoration stategies are proposed, including random restoration strategy RS_1, independent restoration strategy RS_2, power first and gas second restoration strategy RS_3, gas aimed restoration strategy RS_4, and power and gas compromised restoration strategy RS_5. Results show that under limited restoration resources, RS_1 produces the least resilience for both systems, RS_2 and RS_3 both generates the largest power system resilience while RS_4 is the best for the gas system; and if quantifying the total resilience as the evenly weighted sum of two systems' individual resilience, RS_5 produces the largest total resilience. The proposed method can help decision makers search optimum joint restoration strategy, which can significantly enhance both systems' resilience.

1. Introduction

Scholars and governments in the field of disaster mitigation have paid many efforts to make communities and cities more "disaster-resilient" [1–4]. To improve the overall resilience of a community or a city, it is crucial to analyze resilience by focusing on infrastructure systems, which form the backbone for its functioning and provide essential services to support the well-being of its citizens in the aftermath of disruptive events. These critical facilities include electric power, water supply, telecommunication, emergence service systems and so on. However, these systems are not isolated but highly interconnected and mutually interdependent [5–7]. Interdependencies can improve infrastructure operational efficiency, but they can also increase system vulnerability, i.e., small failures in one infrastructure system can result in cascading failures within it and across other systems, largely impacting the regional or national economic systems as well as people's life. Hence, it is necessary to study infrastructure resilience with the consideration of their interdependencies, which is seldom addressed in the literature and will be then discussed in this work. As this paper is based on an existing resilience framework for single systems, this paper will next briefly review this framework and then introduce additional requirements for interdependent systems' resilience assessment as well as pertinent literature review.

In previous work [22], it defined resilience of an infrastructure system as its joint ability to *resist* (prevent and withstand) any possible hazards, *absorb* the initial damage, and *recover* to normal operation. Compared with other definitions in the literature [8–12], this definition can reflect systems' ability to reduce some events' frequencies. Based on this definition, the authors further introduced a time-dependent infrastructure resilience metric and its assessment framework, which not only adequate for both single and multiple hazards [22,23], but also adequate for quantifying potential future resilience with the consideration of system evolution [24]. This metric is based on two curves during a time period: one is the real performance curve, recording system performance change under disruptive events and under restoration efforts, while the other is the targeted performance curve, giving system performance levels in the case of no disruptive event. The resilience value is then quantified as the ratio of the area between the real performance curve and the time axis during the period to the area between the target performance curve and the time axis during the period. The difference between this metric and other resilience metrics in the literature, such as the loss of resilience quantified as the area between the targeted performance curve and the real performance curve within the restoration period [13,14], a normalized shaded

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area underneath the performance curve of systems in a disruptive event [16,17], and some others [15,18–21], is that the proposed metric is defined during a given period while others are defined for specific events during a specific restoration period without incorporating the event frequency. This paper will still use this time-dependent metric to assess the resilience of interdependent systems.

When applying that time-dependent resilience concept to interdependent systems, it requires system performance curves during a time period T with possible disruptive events, which means that it needs modeling and simulation of cascading failures across multiple systems and multi-systems' joint restoration processes under disruptive events. There exist many approaches to address these issues in the literature [25], such as empirical approaches, agent based approaches, system dynamics based approaches, economic theory based approaches, network based approaches, and others. However, most of existing interdependency-related studies by these approaches mainly focused on the cascading failures within and across multiple systems to estimate system-level damage or vulnerability, with only a few addressing the restoration processes.

Some economic theory based studies modeled each infrastructure system by its industry sector in an economy system, and adapted the Leontief dynamic input–output model for economic systems to describe the recoveries of infrastructure systems (or industry sectors) following a disruptive event. Based on the initial perturbations of sectors caused by the event and on the estimated recovery times, the adapted model could calculate the inoperabilities and economic losses of interdependent sectors during the recovery period [26,27]. However, this system-level model cannot model decision makings at infrastructure component level, such as restoration sequence of damaged components, and mobilization of restoration resources during the restoration period. To model these restoration details, Wallace and Lee [28,29] modeled different infrastructure functionality by a uniform network flows mathematical representation and then analyzed the multi-systems' restoration processes by solving a flow optimization problem. However, different types of infrastructure systems are all modeled by a maximum network flow model is unrealistic; for some systems, taking power systems as examples, if modeled by a maximum network flow model, it could produce large different vulnerability results under disruptive events from those realistic models [30,31], such as direct current power flow model. Recently Coffrin et al. addressed the restoration problem of interdependent power and gas system by modeling the former by a direct current power flow model and the latter by a maximum network flow model, and then analyzed multi-systems' restoration processes by solving a Mix integer programming model to maximize the weighted sum of interdependent demand during the whole restoration period [32]. However, this model did not consider various repair times for damage components and different quantities of restoration resources. This paper will address these features and propose a multi-systems' joint restoration model to support interdependent systems' resilience assessment.

The rest of this paper is organized as follows: Section 2 introduces the resilience assessment framework for interdependent systems, with a focus on modeling of multi-systems' joint restoration processes. Section 3 takes the interdependent power and gas systems in Harris County, Texas, USA under hurricane hazards as an example to illustrate the proposed resilience method and mainly discusses resilience contribution of various restoration strategies. The last Section 4 provides the discussions and conclusions of this study and includes directions for future research.

2. Resilience assessment framework of interdependent infrastructure systems

The resilience metric is built upon the system performance process during a time period from 0 to T [22–24], which may include none or several disruptive events, as shown in Fig. 1. Each event covers a disaster prevention stage ($t_0 \le t \le t_1$), a damage propagation stage ($t_1 < t \le t_2$) and an assessment and recovery stage ($t_2 < t \le t_3$). These three stages can respectively reflect resistant, absorptive and restorative capacities of the system under that event, and these capacities reflected from 0 to T together determine system resilience over that time horizon. Resilience is then quantified according to the targeted performance curve $P_T(t)$ and the real performance curve $P_R(t)$:

$$R(T) = \int_0^T P_R(t)dt \Big/ \int_0^T P_T(t)dt \tag{1}$$

Note that different periods T yield different forms of resilience: *previous resilience*, *current potential resilience* and *future potential resilience* [24]. This paper mainly investigates the current potential resilience, where system parameters are fixed during 0 to T and equal to those at the current time. For the case in which the current potential resilience $P_T(t)$ is a constant value 1.0, and when a hazard of interest has its occurrence governed by a Poisson process [22], the expected resilience $E[R(T)]$ is:

$$E[R(T)] = E\left[\frac{\int_0^T P_R(t)dt}{T}\right] = E\left[\frac{T - \sum_{n=1}^{N(T)} \mathrm{IA}_n(t_n)}{T}\right] = 1 - E\left[\frac{1}{T}\sum_{n=1}^{N(T)} \mathrm{IA}_n(t_n)\right]$$
$$= 1 - \frac{1}{T}\sum_{N=0}^{\infty} N \times E[\mathrm{IA}]\frac{(\lambda T)^N e^{-\lambda T}}{N!} = 1 - \lambda E[\mathrm{IA}] \tag{2}$$

where $E[\bullet]$ is the expected value; n is the event occurrence number; $N(T)$ is the total number of event occurrences during T;

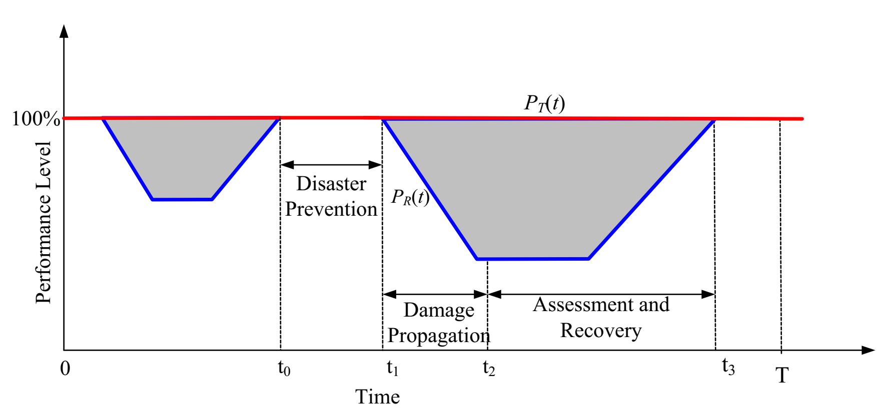

Fig. 1. Typical performance process of an infrastructure system during a time period T with several disruptive events (adapted from the reference [22]).