Modeling of Inter-Organizational Coordination Dynamics in Resilience Planning: A Multilayer Network Simulation Framework

Qingchun Li[1]; Shangjia Dong[2]; and Ali Mostafavi[3]

[1]Urban Resilience, Networks, and Informatics Lab, Zachry Dept. of Civil Engineering, Texas A&M Univ., 199 Spence St., College Station, TX 77840. E-mail: qingchunlea@tamu.edu
[2]Urban Resilience, Networks, and Informatics Lab, Zachry Dept. of Civil Engineering, Texas A&M Univ., 199 Spence St., College Station, TX 77840. E-mail: shangjia.dong@tamu.edu
[3]Urban Resilience, Networks, and Informatics Lab, Zachry Dept. of Civil Engineering, Texas A&M Univ., 199 Spence St., College Station, TX 77840. E-mail: amostafavi@civil.tamu.edu

ABSTRACT

This paper proposed and tested a multilayer framework for modeling network dynamics of inter-organizational coordination in resilience planning among interdependent infrastructure sectors. Each layer in the network represents one infrastructure sector such as flood control, transportation, and emergency response. Coordination probability was introduced to approximate the inconsistent coordination between organizations, based on which the intra-layer or inter-layer link removal was conducted and inter-organizational coordination efficiency within and across infrastructure sectors was hereby unveiled. To test the proposed framework, a multilayer collaboration network of 35 organizations from five infrastructure sectors in Harris County, Texas, was mapped based on a survey of Hurricane Harvey. The analysis results showed that before Hurricane Harvey, coordination among flood control, transportation, and infrastructure development sectors lacked essential integration to foster robust resilience plans. The proposed framework enables an assessment of coordination efficiency among organizations involving in resilience planning and provides an indicator for urban resilience measurement.

INTRODUCTION

Urban systems are currently facing increasing challenges of disturbance and uncertainty caused by nature, technology and human dynamics (Norris et al. 2008). Natural hazards in particular, e.g., hurricanes, sea-level rise, earthquakes, and flooding have posed great threats to the well-being of our society. For example, Texas was hit by Hurricane Harvey in 2017; California and Mexico City have endured earthquakes and wildfires (Murnane 2006); South Florida and 52 counties along the northern Gulf of Mexico are threatened by the rising sea-level (N. Lam et al. 2016). Urban resilience enhancement under such context requires an integrated hazard mitigation and resilience plan that includes the inter-organizational coordination among interdependent infrastructure sectors (Godschalk 2003).

Infrastructure sectors including flood control, emergency responses, transportation, community development, and environmental conservation are inter-dependent and interacted with each other in complex ways (O'Sullivan et al. 2013). In addition, these infrastructure sectors usually have different goals in infrastructure development, hazard mitigation, and environment conservation (Hughes et al. 2003). For example, transportation agents emphasize on infrastructure development to resolve traffic congestion, while flood control departments and environmental groups focus more on hazard mitigation and environment conservation. Missing coordination between transportation planning and flood control scheme would potentially lead to future development in flood prone area. Such fragmented decision-making processes and lack of inter-organizational coordination would affect the effectiveness and efficiency of the resilience planning, design, and operation process in addressing disturbances (Godschalk 2003).

The aforementioned inconsistent coordination among organization is analogous to the probabilistic link removal in network disruption analysis. Similar approaches have been implemented in robustness and resilience assessment of infrastructure systems. Rasoulkhani and Mostafavi (2018) developed a simulation framework to study the effects of internal dynamics and external stressors on the water distribution network. LaRocca (2014) conducted node removal to simulate random failures in an electric power system caused by operator errors and aging components to evaluate robustness of the electric power system. Mattssonand and Jenelius (2003) concluded that much research on transportation network resilience have been employing node and link removal approaches to simulate the network disruption effect. Meanwhile, multilayer networks were proposed to analyze the interdependencies within infrastructure networks (e.g. underground network and air-flight network) (Cardillo et al. 2013; Cozzo et al. 2015; Zhu and Mostafavi 2017). However, most of the existing network simulation studies about infrastructure sectors used single layer network to study physical attributes of the network structure and did not fully consider the interaction between network entities, i.e., inter-organization coordination in resilience planning among interdependent infrastructure sectors.

To this end, this study proposes a multilayer simulation framework to investigate inter-organizational coordination in interdependent infrastructure sectors. Each layer represents an infrastructure sector. Inter-layer and intra-layer links are removed probabilistically to simulate inconsistent inter-organizational coordination within and across interdependent infrastructure sectors. The proposed framework enables an assessment of coordination efficiency among organizations of interdependent infrastructure sectors and was tested by a case study in Harris County, Texas before Hurricane Harvey.

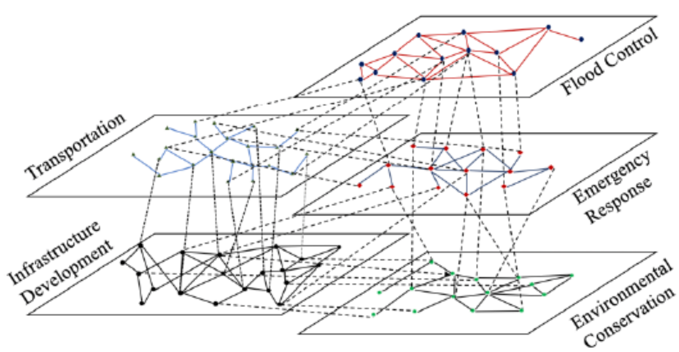


Figure 1. Multilayer Network of Inter-dependent Infrastructure Sectors

MULTILAYER SIMULATION FRAMEWORK

The proposed framework comprises four main steps: (1) conceptualize interdependent infrastructure sectors as a multilayer collaboration network; (2) determine coordination probabilities between organizations; (3) remove links based on assigned coordination probabilities; (4) evaluate the network performance after link removal using indicators such as global efficiency and coefficient of variation.

Conceptualize the multilayer network: To study inter-organizational coordination among interdependent infrastructure sectors, the proposed framework conceptualizes infrastructure sectors as a multilayer network. Figure 1 shows an example of the multilayer collaboration network of five infrastructure sectors. Each layer in the network represents one infrastructure sector in urban systems such as flood control, transportation, emergency response, environmental conservation, and infrastructure development. Intra-layer and inter-layer links of the multilayer network represent inter-organizational coordination within and across inter-dependent infrastructure sectors respectively. Here, coordination was defined as collaboration between organizations in terms of hazard mitigation and was determined by the survey answer.

Determine the daily coordination probability: The daily coordination probability is calculated based on four levels of collaboration frequency (i.e., in the survey question): daily, weekly, monthly and yearly respectively. Table 1 shows calculated probabilities at different collaboration frequency levels.

Table 1. Daily Coordination Probabilities between Organizations

Level of collaboration frequency	Daily coordination probability
Daily	$P=1$
Weekly	$P \sim N\left(\frac{104}{365}, \frac{26}{365}\right)$
Monthly	$P \sim N\left(\frac{24}{365}, \frac{6}{365}\right)$
Yearly	$P \sim N\left(\frac{4}{365}, \frac{1}{365}\right)$

Note: $N\ (\mu,\sigma)$ represents the normal distribution with mean μ and standard deviation σ .

To account for the probabilistic nature of inconsistent inter-organizational coordination, probabilities of different frequencies were approximated as a normal distribution (as seen in Table 1). For example, the yearly coordination frequency is interpreted as 4 times per year on average with a 95% confidence to fall in the range of [2, 6]. Similarly, weekly coordination is considered as average 104 times per year with a 95% confidence that the coordination frequency is in the range of [52, 156]. The daily coordination probabilities will be assigned to each link based on Table 1. Figure 2 shows probability distributions at each collaboration frequency level.

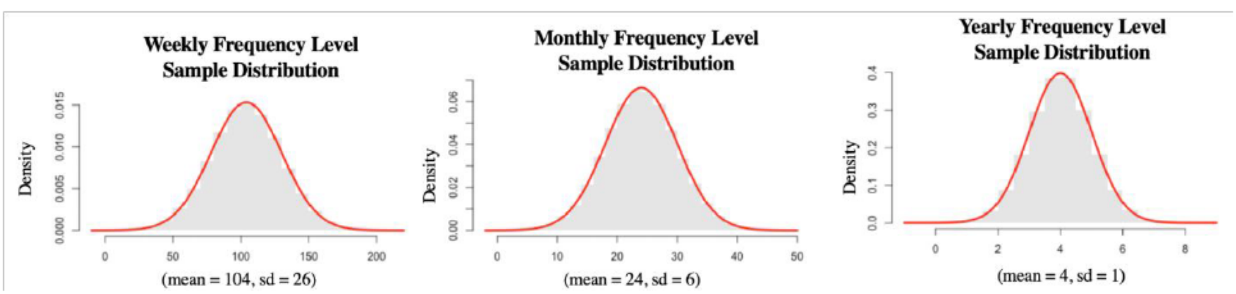


Figure 2. Probability Distribution at Each Frequency Level

Simulate network dynamics of inter-organizational coordination: Each iteration of the simulation process would remove intra-layer and inter-layer links of the multilayer network based on calculated daily coordination probabilities between organizations. The simulation process will iterate 365 times to capture the network performance in a full year cycle. In the case of investigating inter-organizational coordination within specified infrastructure sectors, correspondent intra-layer links will be removed. Accordingly, only inter-layer links would be removed when studying the coordination across infrastructure sectors.

Evaluate network performance after link removal: The network efficiency and its variation after the link removal would be calculated to evaluate the network performance. Network efficiency measures how nodes connect with each other after the disruption (Crucitti et al. 2004; Kinney et al. 2005; Rubinov and Sporns 2010), and therefore was adopted to evaluate the communication efficiency of organizations embedded in interdependent infrastructure sectors. Network efficiency can be calculated as follows (Equation 1) (Latora and Marchiori 2001):

$$E = \frac{1}{N(N-1)} \sum_{i,j} \frac{1}{d_{ij}} \tag{1}$$

where N represents the total number of nodes in the network and d_{ij} is the distance of the shortest path between node i and j. It is worth noting that network efficiency is very sensitive to the total node number of the network (Zanin et al. 2018). That means, it is not desirable for comparing two networks with huge difference in size. Also, the coefficient of variation of the network efficiency of multiple iterations was calculated (Equation 2). Where μ and σ are the mean and standard deviation of the network efficiency after multiple iterations. It is an indicator of network efficiency stability during the simulation process.

$$CV = \frac{\sigma}{\mu} \tag{2}$$

Here we tested two hypotheses: (1) the more frequent of coordination between organizations, the higher network efficiency will be after disruption; (2) the more frequent of coordination between organizations, the lower variation of network efficiency will be. To test the proposed hypotheses, a single layer network including 35 organizations was mapped based on the survey question (Figure 3). The links between organizations represents the existing collaboration and their daily coordination probabilities were uniformly assigned as 15%, 30%, 45%, 60% and 75% respectively. Figure 3 shows the results of two indicators subjected to link removal with different daily coordination probabilities.

It can be concluded from Figure 3 that the increase of the daily coordination probability will lead to the increasement of the mean of the network efficiency and decrease of the variation. The results accept two hypotheses and suggest that the network efficiency and variation are proper measures for the communication efficiency assessment among organizations.

CASE STUDY

The proposed simulation framework is tested by a collaboration network of 35 organizations from five infrastructure sectors in Harris County, Texas. The collaboration relationship is established through one of survey questions: *In the months or years prior to Hurricane Harvey, to the best of your knowledge, did you or any other employee from your organization collaborate or work directly with any of the organizations listed below on flood mitigation efforts? If so, how frequent has been such collaboration (including choices of yearly, monthly, weekly and daily)?*

The surveyed 35 organizations were firstly categorized into five infrastructure sectors: flood control (e.g., Harris County Flood Control District), emergency response (e.g., Harris County Office of Emergency Management), transportation (e.g., Texas Department of Transportation), infrastructure development (e.g., Harris County Community Economic Development Department), and environmental conservation (e.g., Bayou Preservation Association). Then each infrastructure sector was mapped to one layer and links between organizations indicate that they had coordination before Hurricane Harvey. Figure 4 (generated by the software MuxViz (De Domenico et al. 2015) shows the mapped multilayer network structure with descriptive information of each layer. Since the networks have similar sizes, network efficiency can be employed as the indicator of network performance. It should be noted that the total nodes of interdependent sectors are more than 35. This is because some organizations, such as City of Houston, American Planning Association, Houston-Galveston Area Council, would involve in multiple infrastructure sectors and therefore appear in more than one layer.

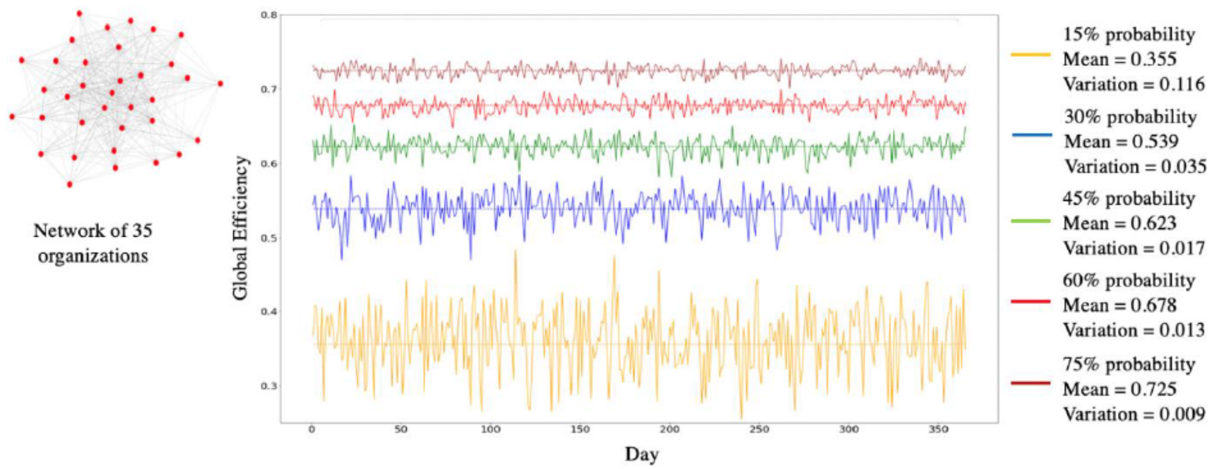


Figure 3. Network Efficiency and Variation after Simulation Process

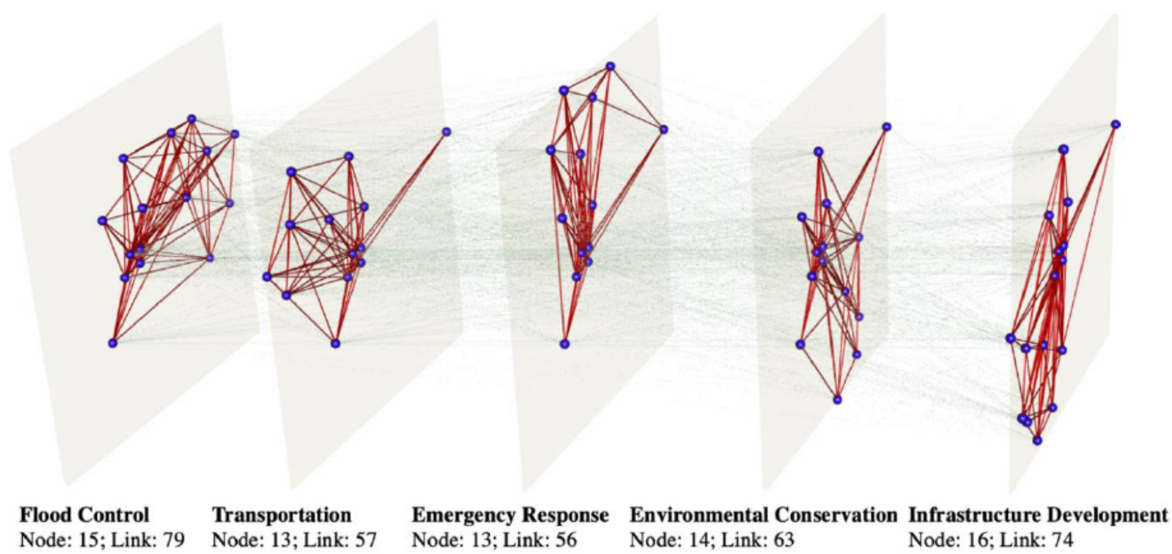
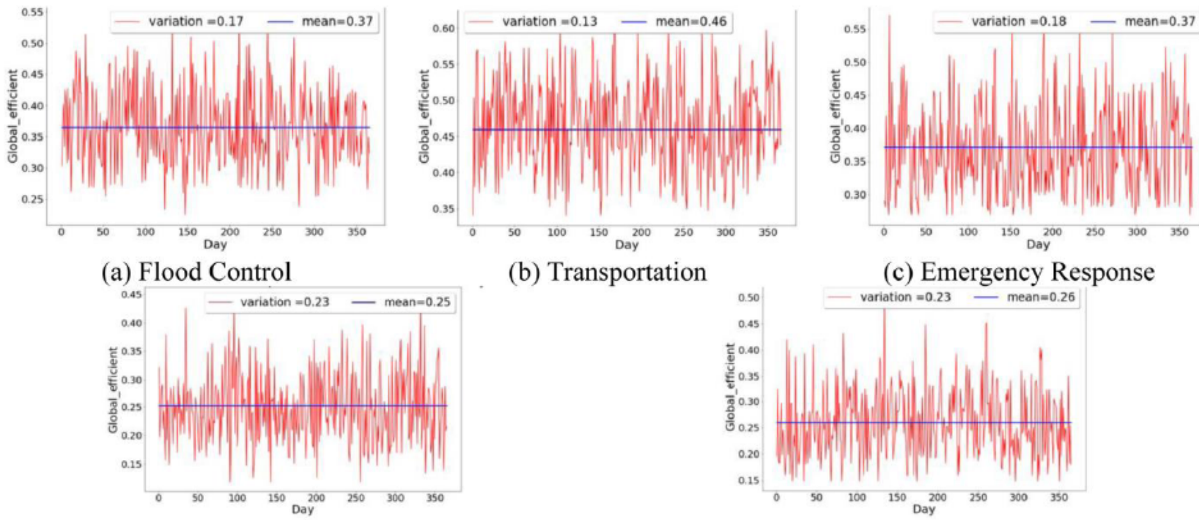


Figure 4. Multilayer Collaboration Network of 35 Organizations

Daily coordination probabilities between organizations was derived and adopted based on surveyed collaboration frequency between organizations and Table 1. Each link probability was assigned according to correspondent distribution of daily coordination. A simulation of 365 iteration is conducted to reflect the coordination fluctuation throughout a year. The mean network efficiency and its variation of both intra-layer and inter-layer disruption scenarios are illustrated by Figure 5 and 6 respectively.

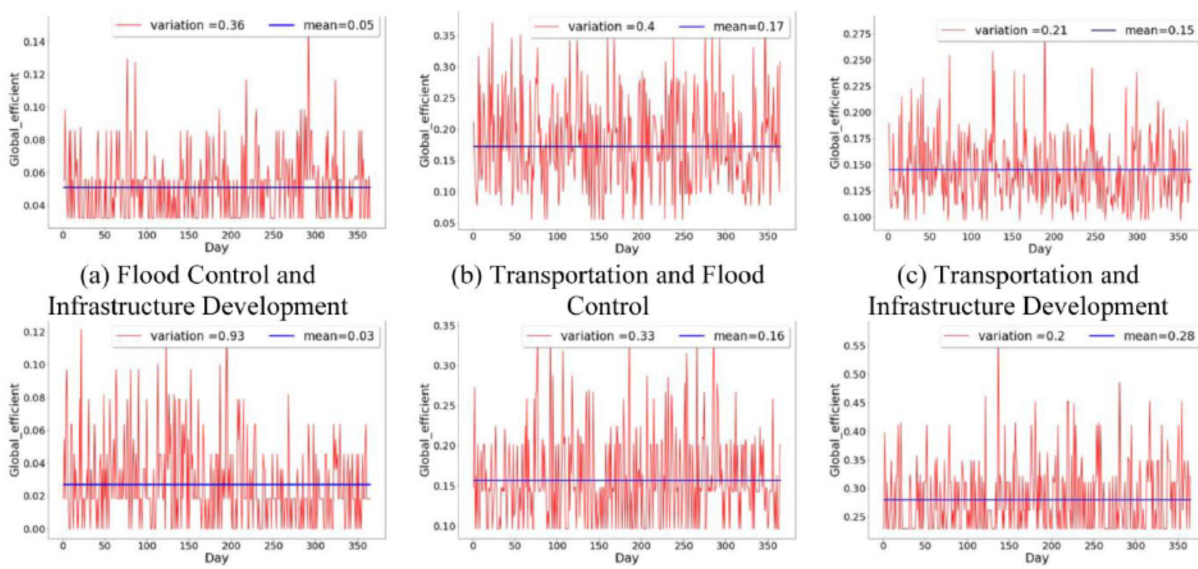
As observed in Figure 5, the transportation sector has the highest mean communication efficiency and lowest variation after the simulation process. This suggests that organizations within the transportation sector have more coordination and more consistent interaction. On the other hand, infrastructure development and environmental conservation sectors have the lowest mean communication efficiency and the highest variation, which indicates that these two infrastructure sectors lack of consistent coordination within their own sectors.



(a) Flood Control (b) Transportation (c) Emergency Response

(d) Infrastructure Development (e) Environmental Conservation

Figure 5. Network Efficiency and Variation under Intra-layer Link Removal



(a) Flood Control and Infrastructure Development (b) Transportation and Flood Control (c) Transportation and Infrastructure Development

(d) Environmental Conservation and Flood Control (e) Emergency Response and Flood Control (f) Emergency Response and Transportation

Figure 6. Network Efficiency and Variation under Inter-layer Link Removal

From Figure 6, it can be observed that, overall, the mean communication efficiency across infrastructure sectors are much lower and the variation are higher than the ones within sectors. In addition, the transportation sector and emergency response sector have the highest mean communication efficiency and the lowest variation. This means transportation and emergency response sectors form a close partnership and continues consistent coordination throughout the year. On the other side, flood control and environmental conservation sectors shows the lowest communication efficiency and highest variation. It is worth noting that the communication efficiency between flood control and infrastructure development sectors is low (almost one-sixth) compared to the communication efficiency between transportation and infrastructure development sectors. The results may suggest that: (1) there lacks sufficient and consistent inter-organizational coordination across interdependent infrastructure sectors; (2) lack of communication efficiency between flood control and infrastructure development sectors could lead to potential conflicts in hazard mitigation, development pattern and resilience planning, which would make urban systems more vulnerable to uncertain disruptions.

CONCLUSION

This paper proposed and tested a multilayer framework for modeling and simulating the network dynamics of inter-organizational coordination in resilience planning among interdependent infrastructure sectors. Probabilistic intra-layer and inter-layer link removal was adopted to approximate the inconsistent coordination between organizations within and across infrastructure sectors. A case study of 35 organizations in Harris County, Texas was then conducted to test the framework. The results show that inter-organizational coordination across infrastructure sectors is much lower compared to the coordination within infrastructure sectors, especially the coordination between flood control and infrastructure development sectors, which could partly explain why Houston suffered huge losses due to Hurricane Harvey. The proposed simulation framework could capture inter-organizational coordination dynamics within and across different infrastructure sectors, and enables an assessment of coordination efficiency among resilience planning organizations.

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