UNRAVELING THE DYNAMICS OF COUPLED HUMAN-INFRASTRUCTURE NETWORKS FOR URBAN RESILIENCE

A Dissertation

by

QINGCHUN LI

Submitted to the Graduate and Professional School of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Chair of Committee,	Ali Mostafavi
Committee Members,	Arnold Vedlitz
	Ivan Damnjonvic
	Maria Koliou
	Philip R Berke
Head of Department,	Robin Autenrieth

August 2021

Major Subject: Civil Engineering

ABSTRACT

The objective of this study is to enhance the fundamental understanding of the dynamics of coupled human-infrastructure networks for urban resilience. Natural hazards are natural phenomenon, while the consequent disasters are the outcomes of human-infrastructure interactions related to social behavior (e.g., collaboration), urban planning and the governance of infrastructure systems. Therefore, urban resilience needs to account for the human-infrastructure interactions, instead of merely focusing on the resilience of infrastructure systems. In this study, we focus on three synergistic areas embedded in human systems affecting infrastructure systems: actor networks, networks of plans and actor values, norms and cognition. The study proposes an institutional connectedness framework to investigate the extent to which the interdependencies among these areas would affect urban resilience. We mainly use the data extracted from a stakeholder survey that aims to, among other targets, collect collaborations among actors for resilience planning and actor preferences to flood risk reduction policy actions. The study includes five research studies to investigate (1) the network positions of actors from diverse urban sectors in the collaboration network for resilience planning management of infrastructure systems, (2) the coordination dynamics among actors from diverse urban sectors, (3) the extent to which networks of plans incorporate and reflect diverse stakeholder values, (4) the extent of actor coordination, plan and task consistencies in terms of infrastructure interdependencies, and (5) the local interactions and homophily effects for collective actions in resilience planning and management of infrastructure systems. The results show the lack of coordination among actors across diverse urban sectors, and strong local interactions within sectors, especially in the transportation sector. The results also show that transportation plans fail to incorporate and reflect diverse stakeholder values in resilience planning and there lacks consistency among networks of plans. The study demonstrates the necessity to involve diverse actors in resilience planning and improve the collaboration among the actors, especially the across-sector coordination.

DEDICATION

I dedicate my dissertation work to my family, for their unconditional love and support.

ACKNOWLEDGEMENTS

I would like to thank my advisor and my committee chair, Dr. Mostafavi, for his always support, guidance and positive energy and feedback throughout the journey of this study.

I would also like to thank my committee members, Dr. Berke and Dr. Vedlitz. It is a great honor to work with them in two NSF funded projects. Their viewpoints and visions are my inspirations in the journey of this study.

I would also like to thank my committee members, Dr. Damnjanovic and Dr. Koliou, for their time and great help in the journey of this study.

Finally, I would like to thank my friends, Ivan Fuentes, who takes cares of me all the time, and colleagues and the department faculty and staff (special thanks go to our department graduate assistant, Laura Byrd) and my dear lab mates for their help and making my time at Texas A&M University a great experience.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a dissertation committee consisting of Professor Ali Mostafavi, Professor Ivan Damnjanovic, and Professor Maria Koliou of the Department of Civil and Environmental Engineering and Professor Arnold Vedlitz of the Department of Government and Public Policy at Texas A&M University and Professor Philip Berker of Department of City and Regional Planning at the University of North Carolina – Chapel Hill.

The plan evaluation part for Chapter 4 was supported by Professor Philip Berke and Graduate Research Assistant Malini Roy.

All other work conducted for the dissertation was completed by the student independently.

Funding Sources

The graduate study was made possible in part by NSF RAPID project under Grant Number:1760258, NSF CRISP project under Grant Number: 1832662 . Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the NSF.

This work was also partly support by an Institutional Grant (NA18OAR4170088) to the Texas Sea Grant College Program from the National Sea Grant Office, National Oceanic and Atmospheric Administration, US Department of Commerce.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Page

CHAPTER I

INTRODUCTION*

Urban infrastructure systems face increasing challenges due to the natural hazards which are taking an increasing toll. For example, Texas was hit by Hurricane Harvey in 2017; California and Mexico City endured earthquakes and wildfires (Murnane 2006; Siegel 2000); South Florida and 52 United States counties along the northern Gulf of Mexico faced the challenges of rising sea-levels (N. Lam et al. 2016; Sallenger et al. 2012). The increasing frequency of natural hazards requires urban resilience that is defined as "the capacity of human and infrastructure systems (including both physical infrastructure and green infrastructure systems) to anticipate, absorb, recover from, or more successfully adapt to actual or potential adverse events (National Research Council 2012)." This definition of resilience highlights the inclusion of human systems instead of only account for infrastructure systems. Natural hazards (e.g., flooding, wildfire, earthquake, tsunami) are natural phenomenon while the caused disasters are the outcomes of human interactions and decisions related to social behavior, urban planning and the governance of infrastructure systems (Clark-Ginsberg 2020; Masterson et al. 2014a). For example, the topology (i.e., the structural pattern) of social networks have huge impacts on the natural resource governance (Bodin and Crona

---

* Parts of the content in this chapter was submitted to and published in "Journal of Management in Engineering" as a collaborative paper (Dong, S., Li, Q., Farahmand, H., Mostafavi, A., Berke, P.R. and Vedlitz, A., 2020. Institutional connectedness in resilience planning and management of interdependent infrastructure systems. Journal of Management in Engineering, 36(6), p.04020075.) Reprint with permission from ASCE.

2009). Interdependent infrastructure systems, including power, transportation, information technology and ecosystems, require collaborative governance by diverse stakeholders with comprehensive understanding of interdependencies within and across infrastructure and social systems (Bodin 2017). Communication and collaboration among stakeholders from different urban sectors (e.g., transportation, flood control, emergency response) in the planning process will greatly affect the quality of plans (Woodruff and Regan 2019). Inconsistency and contradictions among networks of plans and policies, such as land use, transportation, hazard mitigation and capital improvement, will increase both physical and social vulnerabilities in targeted areas (Berke et al. 2015, 2019). Hence, the dissertation focuses on unraveling the dynamics of coupled human-infrastructure networks for urban resilience based on the investigation of interdependencies among three synergistic areas in human systems: actor networks, network of plans and actor values, norms and cognition (illustrated in Figure1). I elaborate these three synergistic areas in the following sections.

Actor Networks

Human interactions (e.g., communication, coordination, collaboration, and support) in social activities such as planning form actor networks (Dong et al. 2020; Li et al. 2020c). In this proposal, actors refer to all possible stakeholders involved in the planning and management of interdependent infrastructure systems, including organizations, agencies, and groups within and outside the government. Norris (2008) and Goodman (1998) believe that the presence of actor networks representing human interactions is one dimension of the community capacity. On one hand, the structural characteristics of actor networks can partly explain the resilience of the human system. For example, if there are only several hubs converging most of the ties in the network representing communication among actors, the system would be highly vulnerable when these hubs are compromised (Albert et al. 2000; Allenby and Fink 2005). Longstaff (2005) and Walker (2012) believe that loosely connected systems maybe more resilient to local disruptions because they would not affect the whole system. On the other hand, increasing studies showed that actor networks have great impacts on community resilience in terms of preparing for, responding to and recovering from disturbances by affecting the flood disaster risk assessment (Aerts et al. 2018), planning (Godschalk 2003; Mills et al. 2014; Woodruff and Regan 2019), natural resource governance (Bodin and Crona 2009; Olsson et al. 2006) and social capital (Aldrich and Meyer 2015; Sadri et al. 2018). Aerts et al. (2018) integrated the human behavior dynamics into flood disaster risk assessment and found that interactions between stakeholders (e.g., government, business and households) would affect risk and risk components (e.g., hazard, exposure and vulnerability).). Godschalk (2003) pointed out that actor networks embedded in urban systems representing formal and informal, stable and ad hoc social and institutional interactions that plays an important role in urban resilience. Actor networks are formed when plan for future uncertainties, respond to current needs and learn from the past experience (Godschalk 2003; Olsson et al. 2006). Aldrich and Meyer (2015) highlighted that social capital would greatly affect the disaster recovery process. The social capital includes social ties within communities (e.g., bonding social capital), ties across communities (e.g., bridging social capital) and ties across power and authority gradients (e.g., linking social capital). In summary, actor networks represent human interactions, which turns resilience into network properties. The key characteristics of actor networks affecting community resilience fall into network properties such as number of ties in the network (including bonding ties and bridging ties), level of network cohesion and network position (Bodin and Crona 2009).

Networks of Plans

Cities are increasingly guided by networks of plans such as transportation, land use, hazard mitigation, capital improvement, parks and recreation, housing and environmental conservation plans (Berke et al. 2019). Planning is the formal approach for institutions to develop plans to guide collective actions and identify general principles (Afroz et al. 2016). A community's capability to coordinate networks of plans that guide its development is critical to gain and maintain resilience (Malecha et al. 2018). Plans can also show the capability of responsible parties to properly deal with the disaster risks because they are able to account for associated issues and contingencies (Berke and Campanella 2006). Plans reflect values in the form of visions/goals and values/cognition of actors involved in planning process. The network of plans are usually developed and implemented by stakeholders from different urban sectors with different perspectives and goals (Hopkins and Knaap 2018). For example, the transportation plan may focus on improving the transportation system, while hazard mitigation plan pays attention to flood control through restricting infrastructure development in hazard-prone areas (Li et al. 2019, 2020a). The contradictions and inconsistencies among the network plans would arise if the diverse stakeholders involving in the planning process fail to integrate different plans (Finn et al. 2007). A good example is the contradictions and inconsistencies between land use approaches and hazard mitigation plans (Berke et al. 2015).

Land use planning plays an important role to increase urban resilience to natural hazards (Burby et al. 1999). Land use planning could guide urban development and expansion to hazard-free areas and eliminate the probability of exposing to natural hazards (Burby et al. 1999). Also, when the development is inevitable in the hazard areas, land use planning could steer the inevitable development to the least hazardous areas (Godschalk 2003). Furthermore, land use planning could not only reduce physical vulnerability but also reduce social vulnerability to natural hazards in targeted areas by helping create a knowledgeable constituency of citizens (Berke et al. 2015; Burby et al. 1999). On the other hand, planning for hazard mitigation includes activities to identify urban vulnerability to hazards, adopt sustainable urban growth, develop hazard mitigation plans before disasters, build codes for engineering design to strengthen structures (e.g., codes for flood-proofing), and avoid development in hazard areas. These activities require the integration with land use planning such as leading new growth away from hazard-prone areas, relocating existing structures and land uses to hazard-free areas and limiting development to protect natural resources (e.g., wetlands, forests, dunes and prairies) that can reduce hazard impacts (Godschalk 2003). However, planning for hazard mitigation is often weakly integrated with land use planning, leading urban development and expansion in hazard-prone areas (Berke et al. 2015). This has caused huge amounts of loss in natural hazards for the past century. To this end, resilience planning of interdependent infrastructure systems requires integration of hazard mitigation across various types of plans (Berke et al. 2019).

Actor Values, Norms and Cognition

Urban and Perry (1927) define values in terms of interest, and interest is an essential condition for anything to be valuable. For many years, there have been two main streams of studies regarding value systems: economy and psycho-sociology (Macedo et al. 2006). The economy stream assumed that value is purely objective and represents merely monetary value of an object. The psycho-sociology stream, on the other hand, assumes that value is subjective and defines value as shared beliefs on moral or ethical principles (Macedo et al. 2006). Value, however, is not merely objective nor merely subjective, but the link between the object and the subject (Echeverría 2003). Studies have proposed value systems and applied the value systems in different domains, such as organizational management and sustainable infrastructure development. Camarinha-Matos and Macedo (2010) used value systems to help reach shared values among different types of stakeholders in organizational collaborative networks. El-Gohary and Qari (2010) proposed an value-based model to develop joint understanding about diverse stakeholder values involved in collaborative sustainable infrastructure development.

In the context of resilience planning and management of interdependent infrastructure systems, values represent those policies, institutions, and services diverse stakeholders from different urban sectors regard as of importance and worth (El-Gohary and Qari 2010; Ros et al. 1999). “Planning is a value-laden activity” (Forester 2013) that caters to diverse needs and capacities (Sandercock 2017). Each stakeholder involved in the planning process may have diverse values (sometimes even conflicted values) with different degrees of importance (Jahani and El-Gohary 2012; Schwartz 2012). Also, values could motivate and explain decision-making among the stakeholders (Cheng and Fleischmann 2010; Zhang and El-Gohary 2016). On the other side, norms are defined as traditional manner to pursue the activities and form the practices (Scott 2013). Accounting for shared norms of actors in policy making process will facilitate the formation and implementation of policy options (Ford et al. 2019). Furthermore, cognition is regarded as the comprehension of a problem (Dong et al. 2020; Farahmand et al. 2020). Congruent values, norms and cognition would enhance the coordination among diverse stakeholders from different urban sectors involved in the planning and management of interdependent infrastructure systems.

Interdependencies among Actor Networks, Networks of Plans and Actor Values, Norms, and Cognition

The three aforementioned areas are not independent but interact with each other. Figure 2 illustrates the interdependencies among three areas in human systems. The structure patterns of actor networks would greatly affect the collaboration and information dissemination among actors (Bodin and Crona 2009). For example, the information is difficult to disseminate across different urban sectors through an actor network with a low level of cohesion/coordination. Actor networks with insufficient coordination will lead to a failure of the formation of congruent values of diverse stakeholders involved in planning and management of infrastructure systems. As a result, contradictions and inconsistencies will be expected in the networks of plans (Berke et al. 2015; Finn et al. 2007; Woodruff and Regan 2019). Not only could coordinated network help form congruent values, but also facilitate the comprehension of infrastructure interdependencies among actors. Infrastructures governed by different actors are interdependent with each other. Replacing the natural green land (e.g., wetlands, forests and prairies) that can store water with pavements will increase the burden of the reservoirs (e.g., the Addicks and Barkers). Breach of the reservoirs will have huge impacts on nearby infrastructures (e.g., residential buildings and road networks). A lack of comprehension of infrastructure interdependencies will also lead to contradictions and inconsistencies among networks of plans such as urban growth in hazard-prone areas (Berke et al. 2019; Bodin 2017).

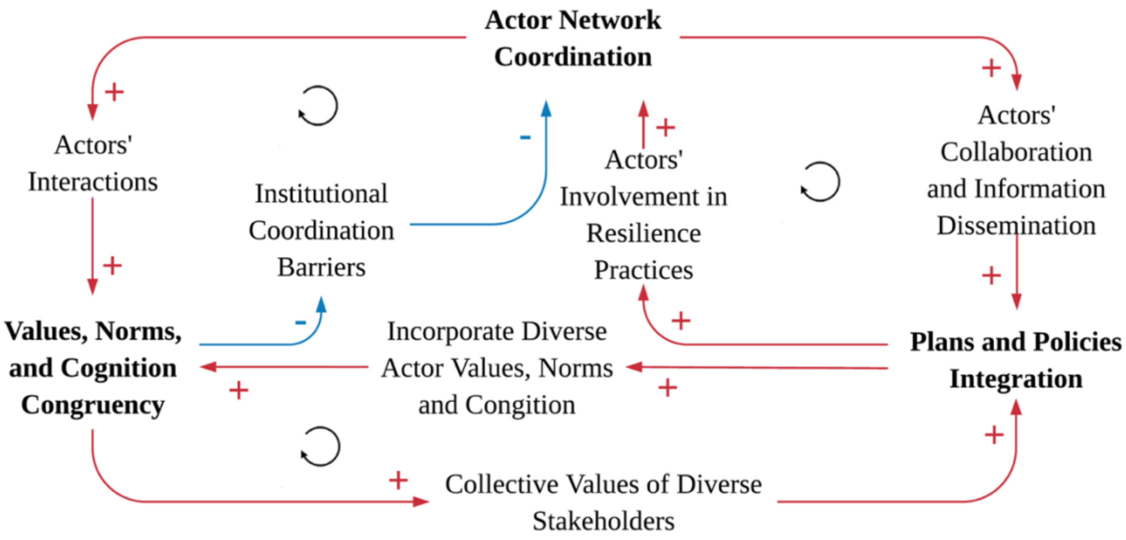


Figure 1 Interdependencies among three areas in human systems.

On the other hand, actors' values, norms and cognition shape the actor networks and affect the development of plans and policies. El-Gohary and Qari (2010) pointed out that conflicted values of key stakeholders would hinder collaborative decision-making in sustainable infrastructure development. Matinheikki et al. (2016) found that stakeholders with shared values tend to establish ties, communicate more frequently, and collaborate more effectively in the inter-organizational network of projects. "Planning is a value-laden activity" (Forester 2013) that caters to diverse needs and capacities (Sandercock 2017). Consequently, validity of plans are rooted by the degree to which they facilitate the dialogue on complex problems (Rittel and Webber 1973) and navigate pluralistic opinions and incorporate them into strategic policy framework (Baer 1997). Substantial planning literature has theorized on different ways to deliberate on value conflicts (Habib 1979) and improve communication gaps (Forester 2013; Healey 1992; Innes and Booher 2004; Sandercock 2017). Therefore, well-integrated plans will improve actor coordination and help reach congruent actor values in the planning and management process.

Existing studies highlighted the interdependencies among these three areas in human systems. To what extent the interdependencies among the areas will affect the resilience of infrastructure systems, however, did not fully discuss. Therefore, in this proposal, I focus on to what extent the human systems would affect the resilience of infrastructure systems. I propose a framework for characterizing and analyzing institutional connectedness as the emerging property of human systems that reflects and accounts for the interdependencies among three areas: actor networks, networks of plans and actor values, norms and cognition.

Research Objectives

The overarching objective of this study is to enhance the fundamental understanding of the dynamics of coupled human-infrastructure systems for urban resilience to natural hazards. In particular, this study aims to investigate the interdependencies among three areas in human systems: actor networks, networks plans and actor values, norms and cognition, and to what extent the interdependencies will affect the infrastructure systems and urban resilience. In this dissertation, the overarching objective could be achieved by accomplishing following objectives:

Objective 1: Understand network positions of actors in the networks of hazard mitigation and resilience planning.

Objective 2: Understand coordination dynamics of actors from different urban sectors in resilience planning and management of interdependent infrastructure systems.

Objective 3: Establish a framework to quantitatively measure to what extent plans incorporate diverse stakeholder values in resilience planning and management of interdependent infrastructure systems.

Objective 4: Establish a framework to model interdependencies among actors, plans, tasks and infrastructures and propose measures to examine the extent of actor coordination, plan and task consistencies in terms of infrastructure interdependencies.

Objective 5: Understand the mechanisms of local interactions and homophily affecting collective action in resilience planning and management of interdependent infrastructure systems.

Research Questions

To accomplish the research objectives, the proposal aims to answer and discuss following research questions:

Question 1: To what extent would the types of actors (e.g., from different urban sectors, within and outside government) affect their positions in the networks of hazard mitigation and resilience planning?

Question 2: To what extent would the types of actors (e.g., from different urban sectors, within and outside government) would affect the coordination among actors in resilience planning and management of interdependent infrastructure systems?

Question 3: To what extent do different plan incorporate diverse stakeholder values in resilience planning and management of interdependent infrastructure systems?

Question 4: To what extent are actors coordinated, plans integrated, and tasks consistent in terms of infrastructure interdependencies?

Questions 5: To what extent do local interactions and the homophily effects affect collective action in resilience planning and management of interdependent infrastructure systems?

Research Framework

This study proposes a framework for characterizing and analyzing institutional connectedness as a property of human systems that affecting infrastructure systems for urban resilience. As illustrated in Figure 2, institutional connectedness is an indicator that represents the overall institutional capital for resilience planning and management of interdependent infrastructure systems. Institutional connectedness measures the extent of coordination of actor networks, integration and consistency of plans and congruency of actor values. The actor networks are more coordinated, the networks of plans are more integrated and consistent, and the actor values are more congruent, the stronger institutional connectedness will be, representing more institutional capital for resilience planning and management of interdependent infrastructure systems.

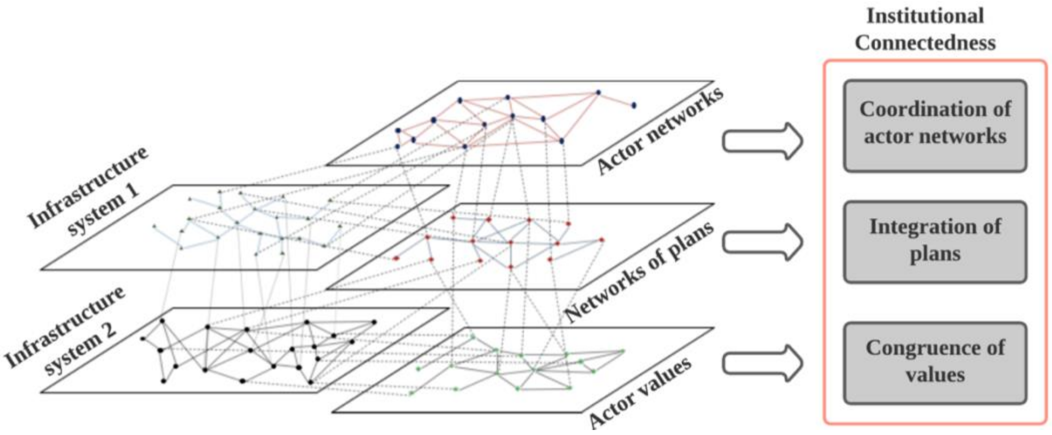


Figure 2 The Institutional Connectedness Framework.

It is worth noting that the proposed framework measures the level of coordination of actor networks, integration of networks of plans, and congruence of actor values in a networks of networks perspective. There are existing methods to measure the level of cohesion of the actor networks (e.g., number of ties, modularity) (Bodin and Crona 2009), the integration and consistency of networks of plans (e.g., plan resilience scorecard) (Berke et al. 2015, 2019), and the congruence of actor values (e.g., axiology-based value evaluation systems) (El-Gohary and Qari 2010; Jahani and El-Gohary 2012; Taeby and Zhang 2018). However, the existing measures did not consider the interdependencies with other areas in human systems and infrastructure systems. As we highlighted before, actor networks, networks of plans and actor values are interacted with each other and interacted with the infrastructure systems. Therefore, the proposed framework accounts for the interdependencies among human and infrastructure systems.

Research Methodology

The study mainly adopts the network analysis (i.e., graph theory) to investigate the interdependencies among actor networks, networks of plans and infrastructure systems. Network analysis conceptualizes the studied objectives (e.g., actors, plans, infrastructures) as nodes and the relationships (e.g., interdependencies, collaborations) among them as edges or links to map the networks. Therefore, in the context of resilience planning and management of infrastructure systems, interdependencies among actors, plans and infrastructures turn resilience into network properties such as the network position and network efficiency. Network analysis could also help focus on the studied attributes of nodes (e.g., organization types, urban sectors, policy action preferences), and ignore the irrelevant information of nodes such as the sizes, geolocations and profit or non-profit types of organizations. Many extant studies used network analysis to investigate the extent to which the interdependencies among actors would affect the effectiveness of planning, emergency response and recovery before, during and after natural disasters (Abbasi 2014; Fan and Mostafavi 2019; Kapucu 2005;

Kapucu and Van Wart 2006; Kotani and Yokomatsu 2016; Therrien et al. 2019; Zhu and Mostafavi 2016). Network analysis was also used to map and investigate the resilience of physical infrastructure network when facing disruptions (such as the transportation network, power network, pipeline network) (Dey et al. 2019a; Ip and Wang 2011; Koetse and Rietveld 2009; Nowell et al. 2015; Van Vliet et al. 2012).

Network analysis involves different kinds of network measures and methods. For example, there are network measures at the node level such as the centrality measures including degree centrality, betweenness centrality and closeness centrality, network measures at the whole network level such as density, connectivity, global efficiency, community structure and core-periphery structure, and network measures at the sub-graph level such as network motifs, local efficiency, and clustering (Jackson 2010; Milo et al. 2002; Newman 2003a). Also, existing studies used network simulations (e.g., network percolation) to measure the resilience and robustness of networks when facing disruptions (Albert et al. 2000; Callaway et al. 2000; Hackett et al. 2016). In this study, to answer the first research question, we examine the network positions of actors in the collaboration network for hazard mitigation and resilience planning using three network measures: degree centrality, betweenness centrality and core-periphery structure. To answer the second research question, we propose a multi-layer network simulation framework that conceptualizes actors from different urban sectors as nodes in different network layers. The proposed network simulation framework perturbates the within-sector and across-sector links to investigate the within-sector and across-sector coordination dynamics. To answer the fourth research question, we propose the meta-network framework for modeling the interdependent actor-plan-task-infrastructure network. We also propose new network measures to quantify the level of actor coordination, plan integrity and task consistency based on the mapped actual network and potential network. To answer the fifth research question, we adopt network motif analysis and Exponential Random Graph Models (ERGMs) to examine the local interactions and homophily effects in the actor collaboration network for resilience planning of interdependent infrastructure systems. Detailed discussion of adopted methodology for each research question, please refer to the methodology part in the following chapters.

Main Data in the Research

In this study, we mainly use the data collected in a stakeholder survey administered after Hurricane Harvey in Harris County, Texas to map the actor collaboration network for resilience planning. One of the targets of the stakeholder survey is to collect the essential information regarding collaboration among actors from diverse urban sectors for resilience planning. Therefore, we complied information from various plans and organizational websites and identified 95 important and influential actors involved in resilience planning across different urban sectors (e.g., community development, flood control, transportation, environmental conservation and emergency response). These actors were included in the survey roster as the potential actors with whom the survey participants collaborated. We also developed a list risk reduction policy actions to capture actors’ preference to different types of policy actions.

Survey Administration

We finished the first draft of survey instruments on January 18, 2018, and tested the online survey system in the following several days. Then we started a pilot test of the stakeholder survey on January 31, 2018, in order to get feedback from participants on the first draft of developed survey instrument. We randomly invited 15 individuals as a group from the existing sample pool of selected organizations. We concluded the pilot test on February 12, 2018 with four individuals completed the pilot test. We refined the survey instruments based on the feedback obtained in the pilot test. The stakeholder survey officially started on February 15, 2018. We sent out total 795 invitations, and we invited survey respondents from both governmental and non-governmental organizations at different scales (e.g., state, regional, county and local) that involved in resilience planning from different urban sectors. We invited respondents who were in positions of management and planning (e.g., CEO, chair and department head) in organizations. Thus, the invited survey respondents had a clear picture about involved work and planning for hazard mitigation. We concluded the survey on April 10, 2018 and received total 198 individual responses representing 160 distinctive departments of 109 organizations (around 30% response rate). Detailed discussion regarding mapping the actor collaboration networks based on the survey data will be presented in the following research studies.

Flood Risk Reduction Policy Actions in the Survey

We would like to note that the flood risk reduction policy actions in the survey are used in two ways in this study. First, the policy actions are used to examine the extent to which networks of plans capture and reflect diverse stakeholder values in resilience planning. In this way, planning and plans are our focuses and the use of risk reduction policy actions is to elaborate the plan evaluation frameworks. Second, we use actors' preferences to risk reduction policy actions as a node attribute in the actor collaboration network. In this way, we only focus on the homophily effects for collective action in resilience planning (i.e., whether the actors have same preferences to the risk reduction policy actions tend to establish the collaboration.). In this study, the discussion of the policy actions themselves and the reason why the specific policy action will contribute to the homophily effect is out of the scope.

Research Overview

The study highlights the importance of accounting for the interdependencies with and across human and infrastructure systems for urban resilience. The research proposes a framework for characterizing and analyzing institutional connectedness as a property of human systems that affecting infrastructure systems for urban resilience. The institutional connectedness includes three synergistic areas in human systems: actor networks, networks of plans and actor values, norms and cognition. Institutional connectedness is proposed as an indicator to institutional capital in resilience planning and management of interdependent infrastructure systems. The research aims to enhance the fundamental understanding of the dynamics of coupled human-infrastructure systems for urban resilience to natural hazards. To this end, quantitative measures were proposed to measure the level of actor coordination, plan integration and value congruence accounting for interdependencies among human and infrastructure systems.

To reach research objectives and answer the research questions, the study defined five research studies. Each research study looks over a specific topic related to human networks in resilience planning and management of interdependent infrastructure systems. The study includes seven chapters. The current chapter (Chapter I) provided an introduction to the research problem statement, research objectives, research questions, the research framework and adopted research methodologies. Chapter II includes Research Study A of this research, which aims to answer the first research question. Research Studies B, C, D and E aim to answer the second to fifth research questions and the research studies are presented in detail in Chapters III, IV, V, and VI respectively. Chapter VII provides a conclusion of five research studies.

CHAPTER II

STUDY A: EXAMINING OF THE ACTOR COLLABORATION NETWORKS AROUND HAZARD MITIGATION: A HURRICANE HARVEY STUDY [†]

The objective of this study is to examine the properties of actor collaboration networks and to analyze how they influence the coordination of hazard mitigation in resilience planning in Harris County, Texas. Effective resilience planning can only be achieved through the collective actions of various actors and the network structures unfold the collaboration among the actors. Understanding the structural properties of actor collaboration networks for hazard mitigation may hold the key to understanding and improving the resilience planning process. To this end, after Hurricane Harvey, we administered a stakeholder survey to actors in various urban sectors involved in hazard mitigation (e.g., flood control, transportation, and emergency response). The survey aimed to capture actor collaboration networks for hazard mitigation in Harris County, Texas prior to Harvey. The collaboration represents that the survey respondents worked with the actors in the survey roster for hazard mitigation. We asked the respondents the frequency of the collaboration in the survey (e.g., yearly, monthly, weekly and daily). We examined three network structural properties to study actor positions in the network: degree centrality, boundary spanners, and core-periphery structure, because degree

---

[†] This chapter is submitted to and published in "Natural Hazards" as an individual paper (Li, Q., Hannibal, B., Mostafavi, A., Berke, P., Woodruff, S. and Vedlitz, A., 2020. Examining of the actor collaboration networks around hazard mitigation: a hurricane Harvey study. Natural Hazards, 103(3), pp.3541-3562.). Reprint with permission from Springer Nature.

centrality could indicate what actors had more collaborations; boundary spanners could reveal what actors were in strategic positions to connect otherwise separate actors; and core-periphery structure could identify what actors formed the core of actor collaboration network for hazard mitigation and whether the core was composed of actors from diverse sectors. The results showed: 1) governmental actors from different sectors had high degree centrality and betweenness centrality, which indicated that governmental actors had a more influential role in coordination and information dissemination in hazard mitigation planning and implementation; and 2) fewer flood control and non-governmental actors were at the core of the actor collaboration networks, which reduced the extent of hazard mitigation coordination. The results identify potential influential actors (such as City of Houston, Harris County, and Houston-Galveston Area Council) in coordination of hazard mitigation and yield recommendations for increased actor network cohesion for better coordination of hazard mitigation across diverse sectors in resilience planning.

Introduction

Natural hazards and disasters have posed a great threat to the well-being of society (Berz et al. 2001; Matyas and Silva 2013). As National Research Council defined, resilience is the "ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events" (National Research Council 2012). Hence, resilience planning across the diverse sectors of infrastructure and urban development plays an important role in dealing with the increased risk of disasters (Berke et al. 2015; Malecha et al. 2018). The planning process, however, requires collective actions involving different actors (e.g., organizations, agencies, and groups) with different perspectives and goals. Resilience planning, in particular, involves multi-actor processes that require essential coordination across different infrastructure sectors (e.g., transportation, community development, flood control, emergency response, and environmental conservation) and scales (e.g., local, county, regional and state) (Woodruff and Regan 2019). Woodruff and Regan (2019) found that involving diverse actors from various urban sectors in the planning process will greatly improve the quality of resilience planning.

A lack of essential coordination among different actors cannot only lead to fragmented resilience planning, but also can affect infrastructure systems through faulty decision making, delayed investments, and lengthy response and recovery procedures during and after disasters (Bodin 2017; Godschalk 2003; Opdyke et al. 2017; Sadri et al. 2018). Furthermore, Opdyke et al. (2017) noted that coordination among various actors (e.g. intergovernmental agencies) may face many barriers due to 'poor census, low level of trust, and contested authority among actors'. Hence, the structure of actor networks on which the coordination behavior among various infrastructure sectors unfolds is a key aspect for understanding and assessing of the extent to which resilience planning integrates hazard mitigation across diverse sectors of urban development (Doreian and Conti 2012). Although much research has studied how actor networks affect community resilience to disasters (Abbasi 2014; Fan et al. 2018; Kapucu and Van Wart 2006; Kotani and Yokomatsu 2016; Zhu and Mostafavi 2016), most of the existing works of literature have focused on the role of actor networks in emergency response and recovery processes during and after disasters and did not fully consider structural properties of actor networks unfolding coordination of hazard mitigation for resilience planning. In this paper, we mapped the actor collaboration network for hazard mitigation in Harris County, Texas area and examined three network properties (e.g., degree centrality, boundary spanner, and core-periphery structure) to study the actors' network positions that would affect coordination of hazard mitigation across diverse actors in resilience planning. The study attempts to answer the following research questions based on the network positions of actors: 1) What actors in collaboration networks would have a greater influence on coordination in hazard mitigation (measured based on higher degree centrality)? 2) What actors in collaboration networks played an important role in information dissemination and coordination improvement in terms of hazard mitigation (boundary spanners identified based on betweenness centrality measures)? 3)What actors in collaboration networks are densely connected with each other (based on examining the core of the actor networks)? 4) What is the composition of the sectors (e.g., transportation, community development, flood control, emergency response) in the cores and how would the composition of the sectors affect the coordination of hazard mitigation across diverse sectors?

Properties of Social Networks in Hazard Mitigation

In this study, we conducted social network analysis (SNA) to examine the actors' network positions (e.g., degree centrality, boundary spanner and core-periphery properties) in the collaboration network. Also, we classified actors into governmental and non-governmental actors across five infrastructure sectors involved in resilience planning (e.g., community development, flood control, emergency response, transportation and environmental conservation), in order to study network positions of actors of different types and from different sectors. Various structural properties of actor networks can provide insights into the roles and importance of actors in hazard mitigation integration aspect of resilience planning. Research regarding social networks suggests that there are empirical benefits to specific structural locations and the underlying structural properties of the network will influence the flow of information (Borgatti 2005; Phelps et al. 2012). For example, a network actor that has a higher degree centrality than other actors may have more resources and be of more prestige, prominence, importance, and power (Borgatti 1995). A network actor that occupies a boundary spanning location may control information flow because of its strategic positions (Lazega and Burt 1995a). Actors in the core position of the network may represent specialized information (Bastos et al. 2017), power elites (Larsen and Ellersgaard 2017), more social solidarity (Bourgeois and Friedkin 2001), and stronger connections that allow more complex and thorough information to be transmitted between the network actors (Aral, Sinan, Van Alstyne 2011). However, there is still a lack of empirical evidence that specific types of actors (e.g., governmental or non-governmental, at different government levels or from different infrastructure sectors) would occupy distinct structural locations according to theorized benefits of the network structure. In particular, in this study, we examine degree centrality (connectivity), boundary spanners, and core-periphery properties in actor coordination networks. These three network properties are explained in the following sections.

Degree Centrality

A network is made up of nodes connected by edges (also called links or ties) (Newman 2018). We use degree centrality to measure an actors' connectivity to other actors in the network. Degree centrality in network theory measures the number of links connected to the studied nodes (Freeman 1978a) (Figure 3). Because nodes with a higher degree centrality connect to more nodes in the network, actors with higher degree centrality have been interpreted to have access to more resources, be more popular, or be of more prestige, importance, and power (Borgatti 1995). Gibbons (2004) also found that nodes with a higher degree centrality can increase overall network connectivity and facilitate the flow of information dissemination.

In this study, the mapped collaboration networks are directed because the edges were associated with directions (Newman 2018). The directions of an edge represent that one actor collaborated with the other actor. Based on directed network data, actors with a higher in-degree centrality are those with whom a greater number of other actors coordinate. This means that actors with high in-degree centrality may have increased access to resources that other actors need for hazard mitigation. Actors with higher out-degree centrality are in greater communication with other actors in the network. This can mean that these actors are more active in coordination for hazard mitigation. Considering these points, we defined the actors with a higher degree centrality (either in-degree or out-degree centrality) as influential actors in the collaboration network. The influential actors would potentially have a greater influence on the coordination for hazard mitigation among diverse actors within and across different urban sectors. Identifying the influential actors will increase understanding of the basic structure of the collaboration network and increase the ability to make future recommendation and policies for improving coordination of hazard mitigation among the actors.

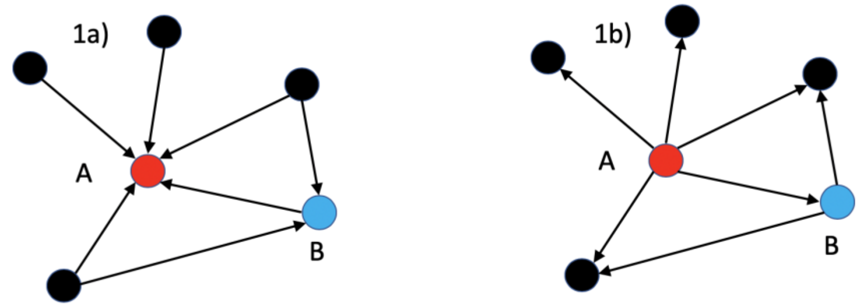


Figure 3 A Graphical Depiction of Degree Centrality.

One limitation of relying solely on degree centrality to capture the network property is that degree centrality cannot reflect positions of given nodes in the global structure of the network (Opsahl et al. 2010). In other words, the degree centrality measure does not capture information beyond the focal actor's immediate connections. For example, although nodes with higher degree centrality connect many other nodes, they still may not be the shortest path to the information source or be in a critical position to control the information flow (Borgatti 2005). This entails the examination of next two network properties: boundary spanner and core-periphery structure.

Boundary Spanner

The boundary spanner, as illustrated in Figure 4, bridges or closes the gap between otherwise disconnected actors in the network. Boundary spanners are important in facilitating information dissemination and communication among disparate groups because they are in a unique structural position that allows them access to diverse bodies of information and knowledge (Granovetter 1983; Hannibal and Ono 2017; Long et al. 2013). Therefore, boundary spanners have a potentially great impact on coordination improvement in hazard mitigation integration across diverse sets of actors. As many actors in urban systems come from different infrastructure sectors (e.g., flood control, transportation, emergency response, community development and environmental conservation), boundary spanners may play a critical role in information dissemination and coordination improvement across infrastructure sectors. To illustrate, actors from different urban sectors may have various operation strategies and goals in urban growth, flood control, and environmental preservation (Hughes et al. 2003). Actors in transportation sectors may focus on improving transportation system to avoid traffic congestion, while actors in flood control sectors and environmental conservation sectors would pay more attention to hazard mitigation and environmental preservation (Li et al. 2020a). The problem is that hazard mitigation are multi-actor processes that need the involvement of actors across different infrastructure sectors. If actors representing different infrastructure sectors lack essential coordination, the mitigation strategies developed by actors in different sectors could be conflicted, resulting in a reduction in effectiveness and efficiency of planning, design, and the operation process for hazard mitigation (Malecha et al. 2018). Boundary spanners may offer useful solutions by connecting actors of dissimilar sectors and improving information dissemination and coordination across different sectors. Identifying potential boundary spanners in the actor collaboration network further our understanding about which actors play important roles in information dissemination and improve coordination of hazard mitigation across different infrastructure sectors.

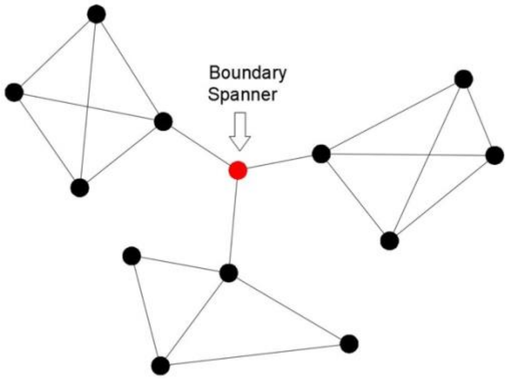


Figure 4 An example of a Boundary Spanner.

Although boundary spanners provide a unique function for information flow that is crucial for information dissemination and coordination improvement across diverse infrastructure sectors, this function may relate to an overall fragmented network (Feiock 2013; Scholz et al. 2008). On the other side, a densely connected group can allow complex and thorough information to be transmitted between the network actors (Milallos 2013; Uzzi 1997). These findings necessitate the discussion of the next network property: core-periphery structure.

Core-Periphery Structure

Nodes in a core location in the overall structure are usually a densely connected group, while nodes are loosely connected with each other in the periphery (Holme 2005). Rombach et al. (2014) also noted that the core nodes need to well connect with the nodes in periphery. Core-periphery structure is ubiquitous in real networks (Rajput et al. 2020;

Zhang et al. 2015). Figure 5 illustrates an example of core-periphery structure in the network. Due to the dense structure of core actors, a diverse core composed of actors from different infrastructure sectors would assist in providing essential coordination among core actors in hazard mitigation. Meanwhile, because distances between the core and the periphery are short in the network, a diverse core could also help information disseminate to periphery nodes of various sectors (Schilling and Phelps 2007; Uzzi and Spiro 2005). Woodruff and Regan (2019) found that multi-actor involvement would greatly improve the quality of resilience plans. This suggests that a diverse core is desirable for coordination of hazard mitigation across diverse actors in resilience planning. If the core is composed of actors from a single infrastructure sector, and because the periphery nodes are generally not well connected with each other, the communication and coordination across different infrastructure sectors may be inhibited. This inhibition will highly affect the efficiency of coordination among actors in hazard mitigation. Examining the core-periphery structure of the actor collaboration network would inform the characteristics of the core and periphery nodes (e.g., what actors are in the core and what actors are in the periphery), helping planners understand the extent of coordination of hazard mitigation among actors.

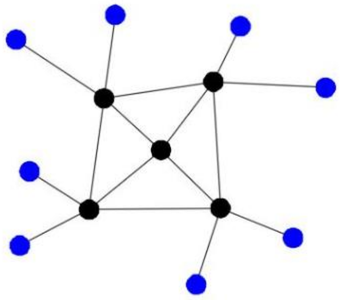


Figure 5 An Example of a core-periphery structure in the network.

Examining aforementioned three network properties–degree centrality, boundary spanners, and core-periphery structure of the actor network--would improve the understanding of roles and levels of coordination of organizations in the pre-Hurricane Harvey actor collaboration network. Such information could help provide recommendations to strengthen essential coordination between diverse actors, consequently improving hazard mitigation across the diverse sectors of urban development. Overall connectivity and degree centrality would inform the actors in collaboration networks that have a greater influence on coordination in hazard mitigation. Potential boundary spanners would inform the actors in collaboration networks that play an important role in information dissemination and coordination improvement in terms of hazard mitigation. An analysis of the core-periphery structure would inform densely connected actors (e.g., the core) in collaboration networks and the composition of the sectors in cores, thus helping planners understand how the composition of the sectors would affect the hazard mitigation integration across diverse sectors.

To this end, we mapped collaboration actor networks of 109 organizations, with 160 distinctive departments responsible for different infrastructure sectors in Harris County, Texas, based on information collected through a stakeholder survey. We studied and discussed the three network properties of the mapped actor collaboration network in order to understand roles and structural positions of organizations in the actor network and how these roles and positions affected coordination of hazard mitigation across different sectors in resilience planning.

Background: Houston and Hurricane Harvey

In 2017, Hurricane Harvey hit Houston, the fourth largest city of United States. Houston suffered an estimated $125 billion loss, mainly from the flooding triggered by the rainfall and the release of the Addicks and Barker reservoirs (NOAA & NHC 2018). Hurricane Harvey and its devastation, however, is only the latest hurricane in the long history of hurricane events in the Houston area. The Houston area has been flooded ten times from 1935 to 2017 (Wiki 2019). Just before Hurricane Harvey, two floods hit Houston in 2015 and 2016, and caused 16 casualties and over $1 billion financial loss (Berke 2019).

The reason why Huston is a flood-prone city may lie in the conflict between urban growth and the negligence of appropriate urban planning on flood control infrastructure systems. As the biggest city in Texas, Houston has witnessed a huge population growth over the past ten years, aligned with a laissez-faire development pattern of Texas. Houston is known for its lack of formal zoning policy, with economic development being the driving force (Masterson et al. 2014a). Houston's metropolitan area is one of the fastest growing in the nation and the population is projected to 10 million by 2040 (METRO 1969). Yet, officials in Houston failed to integrate the rapid urban growth with land use regulations, incentives, and infrastructure investments considering hazard mitigation (Berke et al. 2019). This implies that, to some extent, there is a lack of essential coordination in hazard mitigation across infrastructure sectors (e.g., flood control and transportation), which has caused poor integration of hazard mitigation in resilience planning at the county and city.

Data and Methods

We gathered the data to map collaboration among actors in hazard mitigation through a stakeholder survey. After Hurricane Harvey, we administered a stakeholder survey in Harris County, Texas, aimed at collecting, among other things, essential data regarding collaboration for hazard mitigation among actors from different infrastructure sectors. We sought to map a network of actors involved in hazard mitigation planning and implementation across different urban sectors. A research team, including researchers from civil engineering, urban planning, and sociology, complied information from various plans and organizational websites and identified 95 important and influential actors involved in hazard mitigation across different urban sectors (e.g., community development, flood control, transportation, environmental conservation and emergency response). These actors were in the survey roster as the potential actors with whom the survey participants collaborated. The survey question to collect the collaboration data is stated as follows: ‘*This question focuses on understanding the collaborations and relationships among key organizations and how they work together* *in dealing with catastrophic events such as Hurricane Harvey. 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? Note: You may leave a row blank if you have not had any interaction with an organization*.' The survey participants need to select an answer from following options or leave a row blank: '*1 Daily, 2 Weekly, 3 Monthly, 4 Several times per year, and 5 Not at all.*'

To understand the collaboration between different infrastructure sectors, we categorized actors into five sectors, including flood control, emergency response, transportation, community development, and environmental conservation (Farahmand et al. 2020; Li et al. 2019). Some actors (e.g., Harris County, City of Houston, Houston-Galveston Area Council) were regarded as regional governance, because they or their departments may have been involved in different infrastructure sectors. Table 1 lists examples of actors in each category. Meanwhile, we wanted to see whether the governmental and non-governmental attributes affected the network property. These two attributes (i.e., governmental and non-governmental) were also included as node attributes.

Table 1 Examples of Actors in Each Category

Category	**Examples**
Flood control	Harris County Flood Control District, City of Houston Floodplain Management Office, The Texas Floodplain Management Association, City of Pearland Floodplain Administration
Emergency response	City of Houston Fire Department, FEMA Emergency Corps, Texas Department of Public Safety, Harris County Office of Emergency Management
Transportation	HGAC Transportation Policy Council, Houston Transtar, METRO, Port of Houston Authority
Community development	H-GAC Community and Environmental Planning, City of Houston Parks Board, U.S. Army Corps of Engineers (USACE) Research and Development, Bay Area Houston Economic Partnership
Environmental conservation	Texas Water Development Board, Bayou Land Conservancy, Conservation Fund, The Nature Conservancy
Regional governance	City of Houston, Harris County, Houston-Galveston Area Council, American Planning Association

The network components of the survey provide information to create a two-mode (respondent-organization) directed networks, where the tie represents the frequency of collaboration (weekly, monthly, and yearly). The network represents collaboration among actors (e.g., organizations, agencies and groups) from different infrastructure sectors in terms of hazard mitigation. Here, we focused on two frequencies of collaboration, monthly and weekly. The monthly collaboration actor network includes all the ties in the weekly network, with additional ties at only monthly collaboration level.

Degree Centrality: In this paper, degree centrality was calculated according to Freeman’s (1978b) definition (Equation 1).

$$d_i = \sum_j^n x_{ij} \tag{1}$$

In Equation 1, i is the studied node, j are other nodes in the network, n represent all the nodes in the network, and x_{ij} is defined as 1 if node i and j are linked, and 0 otherwise.

Boundary Spanner: In this paper, potential boundary spanners in a network were identified by betweenness centrality extended for the two-mode network (Scott et al. 2015) (Equation 2).

$$g(v) = \sum_{s \neq v \neq t} \frac{\delta_{st}(v)}{\delta_{st}} \tag{2}$$

Where δ_{st} represents all the shortest paths in the pair of nodes s and t and $\delta_{st}(v)$ represents number of paths including node v. In bipartite networks, betweenness centrality would be normalized by dividing the denominator in Equations 3 and 4 corresponding to its node set. In Equations 3 and 4, n is the node number in node set U and m represents the node number in another node set V. Then node betweenness centrality of U is normalized by dividing U_{max} and node betweenness centrality of V is normalized by dividing V_{max} (Scott et al. 2015).

$$U_{max} = \frac{1}{2}[m^2(s+1)^2 + m(s+1)(2t-s-1) - t(2s-t+3)] \tag{3}$$

$$V_{max} = \frac{1}{2}[n^2(p+1)^2 + n(p+1)(2r-p-1) - r(2p-r+3)] \tag{4}$$

Where $s = \frac{n-1}{m}, t = (n-1)\ mod\ m, p = \frac{m-1}{n}, r = (m-1)\ mod\ n$

Node betweenness centrality could indicate the importance of a node connecting other nodes in the network, because betweenness centrality calculates how many times the node is included in the shortest paths of other node pairs (Zambrano Leal 2012). Boundary spanners usually have a higher betweenness centrality in a network as they are in a strategic position that connects to potentially dissimilar actors or groups from various walks of life or backgrounds. Creswick (2010), Di (2012), and Hawe (2008) adopted betweenness centrality to identify potential boundary spanners in their research.

Although different studies adopted betweenness centrality to identify boundary spanners, there is no specific threshold for betweenness centrality with which to determine a boundary spanner (i.e., for what value of betweenness centrality indicator we can determine the node is a boundary spanner). Therefore, in this analysis, we assumed that greater betweenness centrality implies potential boundary spanners in the actor collaboration network.

Core-periphery Structure: There are several methods available to identify core-periphery structure, including block model (Borgatti and Everett 2000), k-core decomposition (Holme 2005), spectral methods and geodesic paths (Cucuringu et al. 2016), modularity identification (Da Silva et al. 2008), random walker (Rossa et al. 2013) and structural equivalence (Doreian 1985). In this paper, we adopted k-core decomposition to examine the core-periphery structure in the collaboration actor networks. Because the mapped networks are bipartite networks, other methods for identifying core-periphery structure cannot be directly applied without the network projection. K-core decomposition, however, only relies on the node degree centrality and can be directly applied to the bipartite network, as k-core is “the maximal sub-graph with the minimal degree k” (Holme 2005).

We also calculated the density of the core. For the bipartite network, because there are only edges between two node sets, the maximum possible undirected ordinary density should be calculated according to Equation 5 (Scott et al. 2015).

$$\frac{m \times n}{(m+n)(m+n-1)} \tag{5}$$

Where n and m have the same definitions for Equations 3 and 4.

Results

Collaboration actor networks at the departmental level were mapped based on the data collected from the stakeholder survey. Figure 6 and Figure 7 show the monthly and weekly collaboration actor networks respectively. The mapped networks are directed networks, meaning that the direction of a tie (or edge) is from survey respondents dictating the level of collaboration with actors listed in the survey. The blue nodes represent actors listed in the survey, while the red nodes represent survey respondents representing actor departments who took part in the survey. Isolates are not presented in the figures below. Sizes of nodes are proportional to their degree centrality in Figure 6 and Figure 7. The following analyses focus on weekly and monthly frequency levels because they are the most representative answers in the survey.

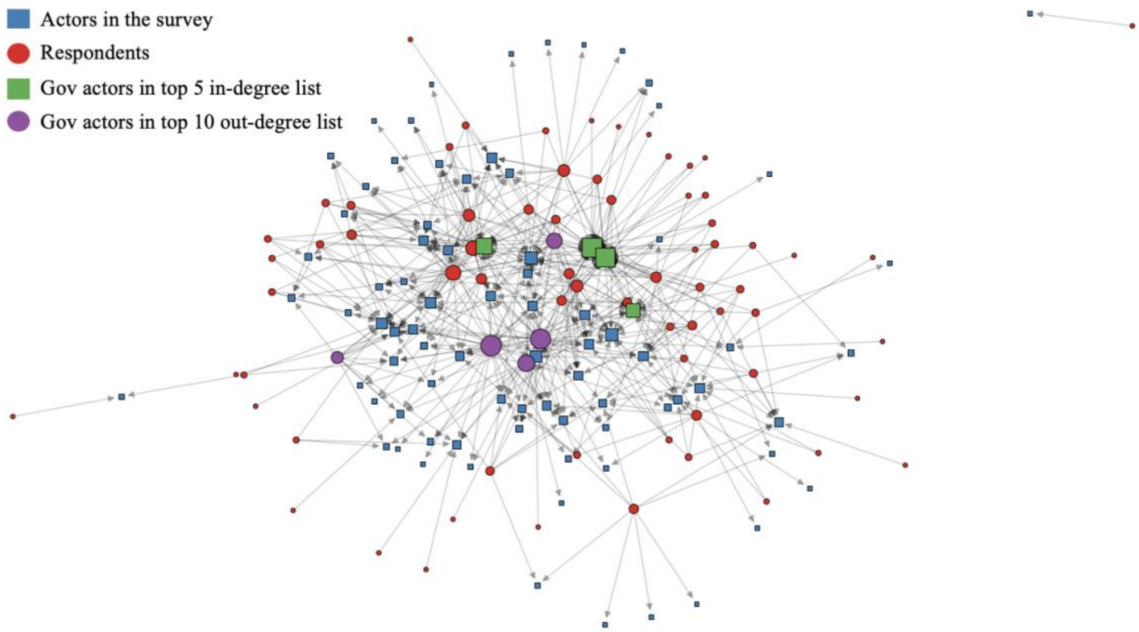


Figure 6 Weekly collaboration actor network: 160 nodes; 478 ties; 95 isolates were removed; four Gov actors in top 5 in-degree list; five Gov actors in top out-degree list.

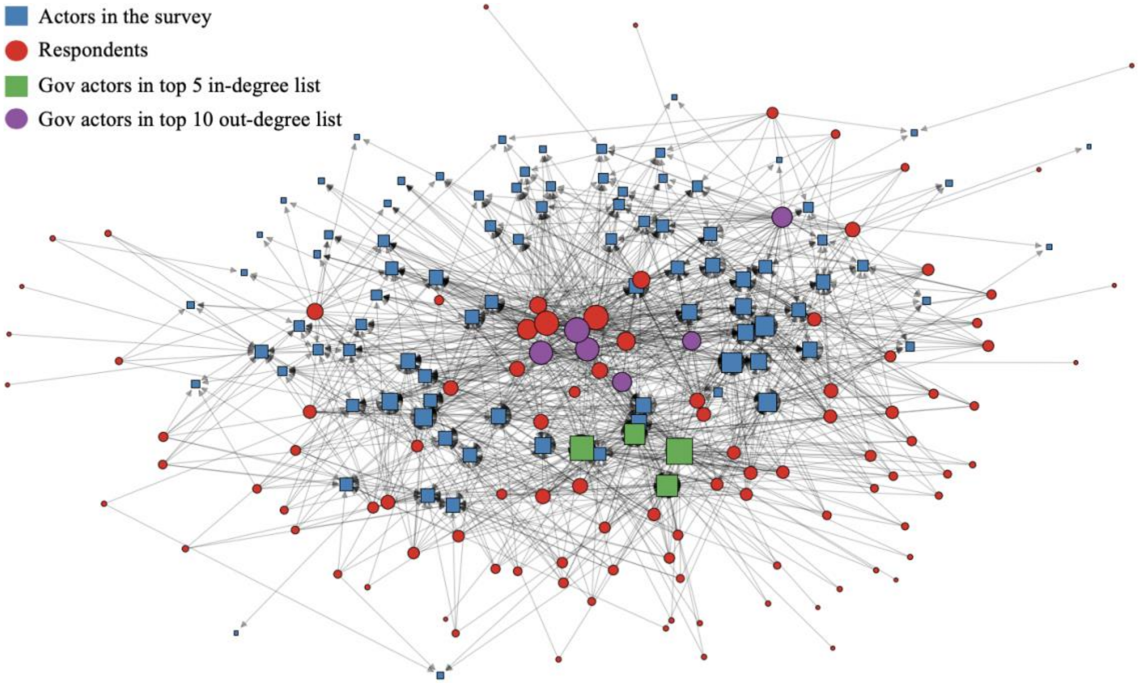


Figure 7 Monthly collaboration actor network: 200 nodes; 1171 ties; 55 isolates were removed; four Gov actors in top 5 in-degree list; six Gov actors in top out-degree list.

Degree Centrality

We calculated degree centrality of each node according to Equation 1. Table A1 and Table A2 in Appendix A list actors in the survey with top 5 in-degree centrality and survey respondents with top 10 out-degree centrality at weekly and monthly collaboration respectively.

The degree centrality of actors at weekly and monthly collaboration are quite similar. Among five infrastructure sectors, actors of regional governance have higher degree centrality, particularly for actors with multiple departments involved in different infrastructure sectors, such as Harris County, City of Houston and Houston-Galveston Area Council. Actors from the community development infrastructure sector also have higher degree centrality, especially among respondents. This suggests that actors from the community development sector are more active in the network. Transportation actors (e.g., Texas Department of Transportation) have a higher degree centrality at the weekly level than monthly level. This suggests that transportation actors have more weekly coordination than other actors. However, when other actors include more coordination at the monthly collaboration level, transportation actors do not have more coordination. These results clearly indicate that transportation actors have more programs that need daily and weekly coordination with other actors.

On the other hand, we can see that governmental actors such as Harris County, City of Houston. and their departments (e.g., City of Houston Department of Public Work and Engineering and Harris County Engineering Department) have a relatively high degree centrality. Houston-Galveston Area Council, although not a governmental actor per se, is a regional organization with multiple departments that have close collaborations with local governments to solve problems and issues in Houston-Galveston area. This indicates that governmental actors, especially actors with multiple departments involving different infrastructures, may have increased access to resources and have more influence on collaboration of hazard mitigation in resilience planning.

Furthermore, Harris County Flood Control District (HCFCD) had a relatively high degree centrality, both as the actor in the survey and the survey respondent. This indicates that HCFCD not only has resources for collaboration but also is active in seeking collaboration with other actors. Actors in the survey roster with high in-degree centrality do not necessarily also have high out-degree centrality as a survey respondent. For example, the City of Houston has high in-degree centrality as the actor in the survey roster. However, departments of the City of Houston do not have high out-degree centrality compared to departments of Harris County and the Houston-Galveston Area Council. This may reveal that although the City of Houston has enough resources that other actors need to collaborate with, itself is not active in collaboration with other agencies.

The analysis of degree centrality could answer the first research question. The results indicate that governmental actors, especially actors with multiple departments involved in different infrastructure sectors (e.g., Harris County, City of Houston) play an important role in collaboration for hazard mitigation. Likewise, regional actors, through which local government consider and solve issues (e.g., Houston-Galveston Area Council) also have huge impacts on collaboration in terms of hazard mitigation. These actors have high in-degree centrality, which may imply that they have a more potential influence on improving collaboration and information dissemination in hazard mitigation.

Potential Boundary Spanners

To identify the potential boundary spanners in the collaboration actor network, we calculated betweenness centrality of each node. Table A3 and Table A4 in Appendix A show the results of betweenness centrality at different collaboration frequency levels.

The potential boundary spanners in the actor networks at weekly and monthly collaboration are similar. Although betweenness centrality does not necessarily have a high correlation with degree centrality, in this case, actors with higher betweenness centrality have higher degree centrality. Similar to degree centrality, actors of regional governance with multiple departments involving various infrastructure sectors, such as Harris County, the City of Houston, and the Houston-Galveston Area Council, have higher betweenness centrality and are more likely to be boundary spanners. Actors from community development sectors also have higher betweenness centrality and transportation actors have higher betweenness centrality at the weekly collaboration level rather than the monthly level. Governmental actors, likewise, have a relatively high betweenness centrality and are potential boundary spanners.

However, there are some actors with relatively low degree centrality that we identified as potential boundary spanners because of their relatively high betweenness centrality. These actors including Federal Emergency Management Agency (FEMA) and Center for Houston's Future at weekly collaboration, and United Way of Greater

Houston, Houston Wilderness and Bayou Preservation Association at monthly collaboration. FEMA is reasonable to be the potential boundary spanner as they have a high likelihood of collaborating with actors from various infrastructure sectors in terms of hazard mitigation. Center for Houston's Future, Houston Wilderness, United Way of Greater Houston and Bayou Preservation, on the other hand, are in the strategic positions to connect actors that do not have coordination with other actors (Figure 8 and Figure 9). These actors, except for FEMA, are non-governmental actors. This result suggests that non-governmental actors also play an important role in information dissemination and coordination improvement in hazard mitigation in resilience planning. Woodruff (2019) finds that non-governmental actors may offer unique and important insight into hazard mitigation and resilience planning efforts.

Harris County Flood Control District (HCFCD) is the only potential boundary spanner from the flood control infrastructure sector, while most of the potential boundary spanners come from the community development infrastructure sector or governmental actors with multiple divisions. This implies that HCFCD plays an important role in disseminating potentially important information about hazard mitigation. Figure 8 and Figure 9 show the potential boundary spanners (green and purple dots) at weekly and monthly collaboration.

The results of potential boundary spanners could answer the second research question by indicating that the governmental actors involved in multiple infrastructure sectors are the potential boundary spanners to connect otherwise separated actors. The result is highly correlated to their high in-degree centrality. This means many other actors would rely on the collaboration with these high in-degree centrality actors in disseminating and exchanging information. Actors with high in-degree centrality in the survey roster have more influence on improving coordination and information dissemination across different infrastructure sectors, as well as for hazard mitigation integration across diverse sectors.

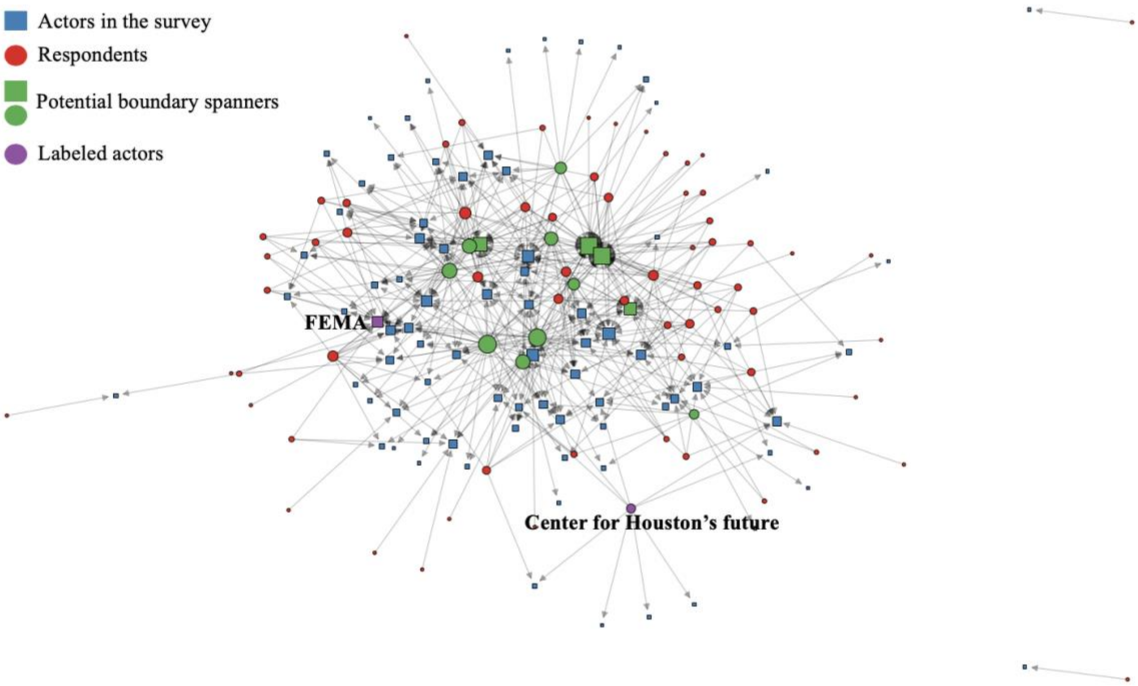


Figure 8 Potential boundary spanners at weekly collaboration; labeled actors are potential spanners with relatively low degree centrality.

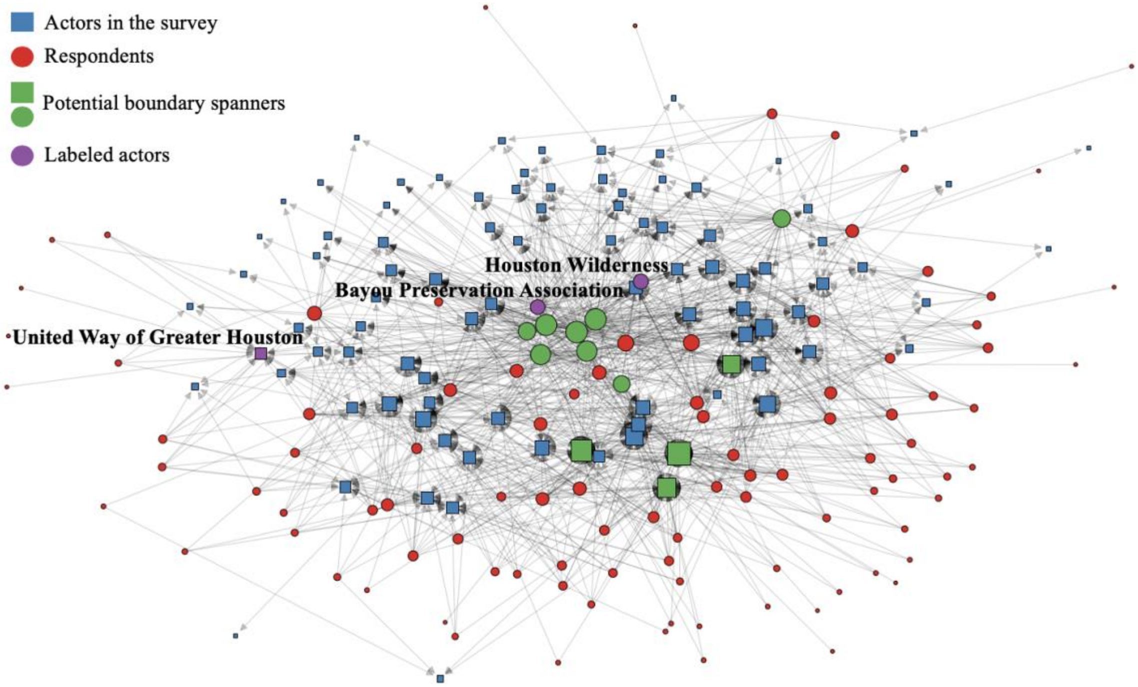


Figure 9 Potential boundary spanners at monthly collaboration; labeled actors are potential spanners with relatively low degree centrality.

Core and Periphery

The K-core decomposition method was adopted to identify the core and periphery of the actor collaboration network. The method outputs the densest and smallest core (number of actors in the core) by default. Figure 10 and Figure 11 show the results of core and periphery nodes in actor networks at weekly and monthly collaboration, designated by the blue and red nodes in the core, representing actors in the survey and survey respondents respectively. The darker edges show the links within the cores. Furthermore, to identify the makeup of infrastructure sectors in the core, the number of actors from each infrastructure sector are shown in Table A5 and Table A6 in

Appendix A. Table 2 illustrates the number of governmental and non-governmental actors in the cores.

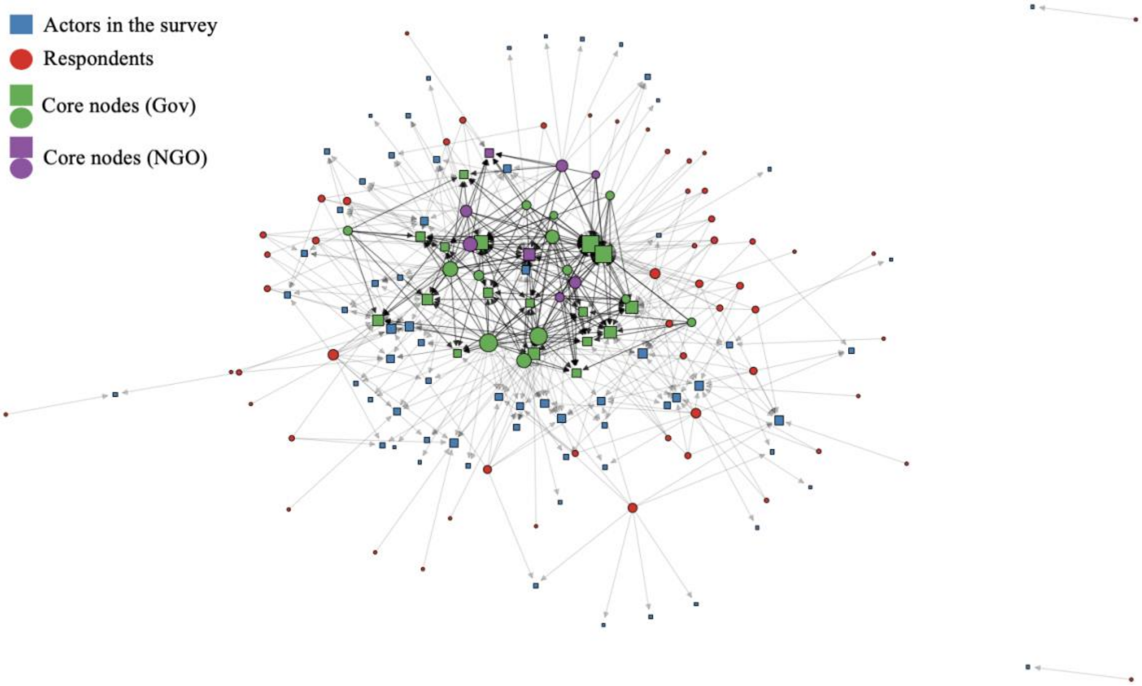


Figure 10 Core and periphery at weekly collaboration; core density: 0.47; darker edges are edges in the core.

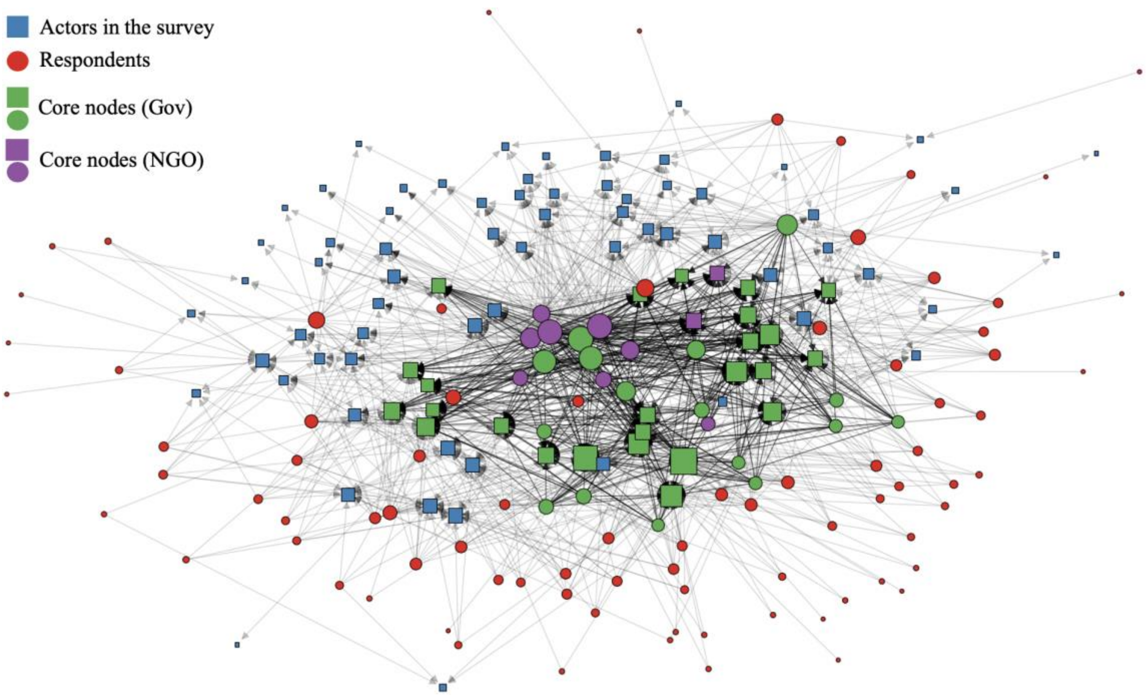


Figure 11 Core and periphery at monthly collaboration; core density: 0.57; darker edges are edges in the core.

Table 2 Number of Governmental and Non-governmental Actors in the Cores.

Governmental & non-governmental actors	**Weekly collaboration level**	**Monthly collaboration level**
Governmental actors	29 (76%)	40 (78%)
Non-governmental actors	9 (24%)	11 (22%)

As illustrated in the Figure 10 and Figure 11, the core nodes at the weekly and monthly collaboration level are densely connected, as the core densities are relatively high: 0.47 and 0.57 respectively. The transportation sector and community development sector make up the largest proportions in the cores, while the transportation sector has the highest proportion in the core of actor network at weekly collaboration, and community development sector has the highest proportion at monthly collaboration. On the other hand, the flood control sector and environmental conservation sector have the lowest two proportion in the cores. Actors of regional governance who could be involved in multiple infrastructure sectors may also play an important role in keeping the cores diverse, as these actors occupy 15.8% and 19.61% respectively in the cores at weekly and monthly collaboration levels. By these actors reasonably distributing their resources to different infrastructure sectors, the procedure would help to keep the core function diverse and improve coordination of hazard mitigation across different sectors.

Furthermore, Table 2 shows that governmental actors comprise 76% and 78% of the core nodes at weekly and monthly collaboration levels respectively. Non-governmental actors have a low proportion in the core, with 24% and 22% at weekly and monthly collaboration respectively. However, Woodruff (2019) finds that non-governmental actors play an important role in the resilience planning process. This means that including more non-governmental actors in the cores would help resilience plans maintain high quality.

The results of core-periphery structure analysis could answer the third and fourth research questions by showing that governmental actors occupy nearly 80% of the cores and most of the non-governmental actors are in the periphery. On one hand, this means that governmental actors have greater influence in the collaboration network in terms of hazard mitigation, as demonstrated by the reactions to Hurricane Harvey. On the other hand, this also means that there are not enough non-governmental actors in the planning process. Including non-governmental actors in the planning process would improve the diversity of the cores and improve communication and coordination among actors from different urban sectors.

Furthermore, the cores of the collaboration network are not essentially diverse. Actors from the transportation and community development sectors comprise more than 50% of the cores, while flood control and environmental conservation sectors comprise less than 8% and 4% respectively. However, because governmental actors occupy a considerable proportion in the cores (15.80% and 19.61% respectively) and are involved in multiple infrastructure sectors, they are important in keeping the cores diverse by distributing their resources reasonably to different infrastructure sectors. This means that governmental actors with multiple departments involved different infrastructure sectors will help information dissemination and improve coordination in hazard mitigation across various infrastructure sectors if they distribute their resources reasonably.

Discussion

The results of SNA highlight that governmental actors had central positions in actor collaboration networks for hazard mitigation in resilience planning. Governmental actors had high degree centrality (both in-degree and out-degree centrality) and high betweenness centrality, and more than 75% actors (76% and 78% for weekly and monthly collaboration respectively) in the cores were governmental actors. The results imply that non-governmental actors were less involved in the resilience planning process. Also, based on results of core composition, we found that the resilience planning process prior to Harvey did not include diverse stakeholders across different urban sectors. The results are consistent with existing works of plan evaluation. Lyles et al. (2014a) found that local planners were less involved in the government-oriented planning process to develop land use approaches, and involving local planner will greatly improve the quality of land use approaches (Burby 2003; Dyckman 2018). Woodruff and Regan (2019) found that non-governmental stakeholders, compared with governmental stakeholders, were less involved in the planning process for climate adaption plan development. They also argued that involving diverse stakeholders will greatly improve the quality of climate adaption plans. Furthermore, Kapucu (2005) and Opdyke et al. (2017) also found governmental actors had central positions in the coordination network of disaster emergency response and disaster recovery, which may cause barrier to effective emergency response and disaster recovery (Gajewski et al. 2011). The SNA of the actor collaboration also facilitated the understanding of the network positions of some important actors involved in hazard mitigation in resilience planning. In the following parts, we will discuss the network position of these actors in the collaboration network for hazard mitigation and we provide some practical recommendations to improve the coordination between governmental and non-governmental actors and actors across diverse urban sectors.

Important Actors and Their Network Positions

The HCFCD, as one of the most important actors of the flood control infrastructure sector, can be identified as occupying an important network location for information dissemination and coordination improvement in hazard mitigation. Results suggest that HCFCD had a relatively high degree centrality (both in-degree and out-degree centrality) and was also identified as the only potential boundary spanner in the flood control infrastructure sector. More importantly, in the cores of the actor networks, HCFCD, as both the actor in the survey and the respondent participated in the survey, contributed the major proportion of flood control sectors at weekly and monthly collaboration levels. This means that HCFCD is in a structurally efficient location to transmit information about hazard mitigation to other actors of different infrastructure sectors in the region. This would improve the coordination of hazard mitigation across diverse sectors in resilience planning. HCFCD has extensive collaboration with other actors (e.g., FEMA, USACE, Harris County Engineering, and City of Houston) regarding hazard mitigation according to its official website. For example, since Hurricane Harvey, HCFCD has completed and is working ongoing flood control programs in collaboration with USACE and FEMA.

The City of Houston has a higher in-degree centrality in the survey; however multiple departments within the City of Houston who responded to the survey have lower out-degree centrality in the stakeholder survey. This can imply that the City of Houston may have many other actors available for hazard mitigation purposes, but the individual city departments may not have essential collaboration with other actors. However, individual departments lacking coordination will still affect hazard mitigation integration in resilience planning and will prove to be a vulnerability to disasters. For example, if the City of Houston Fire Department does not have collaboration with USACE, they cannot get the information regarding how USACE maintains the reservoirs and how they prepare for the disturbances. Lack of this information would make that fire department unprepared for the potential dysfunction of the reservoirs, which would impede the mitigation efforts of their emergency response to the flooding triggered by the release. When federal agencies make hazard mitigation for disasters, the coordination and communication with local actors about their strategies and efforts are extremely important so that the information of hazard mitigation can be disseminated effectively.

USACE had relatively low degree centrality (both in-degree and out-degree centrality), low betweenness centrality and was not in the cores of collaboration networks for hazard mitigation. Based on the results of network properties, USACE had minimal coordination with other actors for hazard mitigation. However, USACE had a large impact on Hurricane Harvey. The release of the Addicks and Barker reservoirs led to flooding in the west Houston, where had never come across flooding in the history and was not flooded before the release. Most of the residents in this area did not purchase insurance for flooding (Shilcutt and Asgarian 2017), which increased their financial loss in the flooding and difficulty in recovery from disruptions. The position of USACE in the actor collaboration network may have increased the likelihood that USACE acted without thorough information of other hazard mitigation efforts going on in the area.

Recommendations

Based on the results of the network property analysis, there are some considerations that might increase the collaboration between actors to improve coordination of hazard mitigation across diverse sectors in resilience planning. First, the actors with multiple departments involved in different infrastructure sectors should take full advantage of their ability to influence the dissemination of information and improve coordination between various sectors. The departments of these actors should actively seek coordination with other actors and the resources between departments should be distributed reasonably to keep the coordination diverse. The actors of flood control sectors, such as the flood plain management departments of each city, should increase their collaboration with other sectors. Federal actors such as USACE should increase their further coordination and engagement with the local actors in hazard mitigation. More non-governmental actors should be involved in the resilience planning process so as to improve the coordination of hazard mitigation and quality of resilience plans. Furthermore, Dong et al. (Dong et al. 2020) proposed that besides the examination of actor coordination networks, the integration of plans and policies that actors involved in, and the congruency of actors' norm could also be examined and improved to improve the institutional connectedness for better resilience planning and management of interdependent infrastructure systems.

Concluding Remarks for Research Study A

The study reported in this paper examined network properties of actor collaboration networks in the Harris County, Texas area. We mapped the actor collaboration networks based on the data collected from a Hurricane Harvey stakeholder survey. Then we examined three network properties in this paper: degree centrality, boundary spanners, and core-periphery structure. Based on the results of examination, we discussed how these network properties affect information dissemination and coordination between actors of different infrastructure sectors, in terms of hazard mitigation across diverse sectors of urban development in resilience planning. The results show that actors, especially governmental actors with multiple departments involved different infrastructure sectors, are strategically located within the network to influence information dissemination and coordination of hazard mitigation. Also found was the fact that the cores of the actor collaboration networks are not sufficiently diverse, which may inhibit broad dissemination of information from a variety of sectors. Maintaining a diverse core would help improve coordination between actors from different infrastructure sectors.

The study provides insights into how the specific types of actors occupied structural locations, which carries important implications for coordination of hazard mitigation in resilience planning. Understanding the structural properties of actor collaboration networks for hazard mitigation and resilience planning may hold the key to understanding and improving the planning and implementation process for disasters such as Hurricane Harvey. Network analysis helps researchers to understand what actors have a potentially significant influence in coordination among network actors. It also highlights which actors play an important role in information dissemination, and how actors in the cores of the networks can improve coordination of hazard mitigation. Based on the results of analyses, recommendations can be made to increase the cohesion of the actor collaboration network, in areas such as Harris County, regarding coordination of hazard mitigation in resilience planning, thus improving the planning process and the quality of resilience plans.

Limitations of Research Study A and Future Directions

This paper has some limitations and evolving future directions can be pursued. For now, there is not a clear threshold for identifying boundary spanners and in this paper, only potential boundary spanners were discussed. Developing a new method to identify boundary spanners could be a potential direction to better understand this network characteristic. Furthermore, only three network properties were discussed in this paper. More network properties could be studied and discussed in the future to better understand different roles of actors in the actor collaboration network. We present these limitations and possibilities for extending this line of research. To understand the structural properties of communication, coordination, and collaboration in hazard mitigation among actors is important so that the urban system would have better chances to improve collaboration and preparation for future disturbances.

CHAPTER III

STUDY B: MODELING OF INTER-ORGANIZATIONAL COORDINATION DYNAMICS IN RESILIENCE PLANNING OF INFRASTRUCTURE SYSTEMS: A MULTILAYER NETWORK SIMULATION FRAMEWORK [‡]

This study proposes and tests a multilayer framework for simulating the network dynamics of inter-organizational coordination among interdependent infrastructure systems (IISs) in resilience planning. Inter-organizational coordination among IISs (such as transportation, flood control, and emergency management) would greatly affect the effectiveness of resilience planning. Hence, it is important to examine and understand the dynamics of coordination in networks of organizations within and across various systems in resilience planning. To capture the dynamic nature of coordination frequency and the heterogeneity of organizations, this paper proposes a multilayer network simulation framework enabling the characterization of inter-organizational coordination dynamics within and across IISs. In the proposed framework, coordination probabilities are utilized to approximate the varying levels of collaboration among organizations. Based on these derived collaborations, the simulation process perturbs intra-layer or inter-layer links and unveils the level of inter-organizational coordination within and across IISs. To test the proposed framework, the study examined a multilayer collaboration network of 35 organizations from five infrastructure systems within Harris

---

[‡] This chapter is submitted and published in the journal of “PLOS One” as an individual paper (Li, Q., Dong, S. and Mostafavi, A., 2019. Modeling of inter-organizational coordination dynamics in resilience planning of infrastructure systems: A multilayer network simulation framework. *PloS one, 14*(11), p.e0224522.8). Reprint is permitted under the Creative Commons Attribution (CC BY) license.

County, Texas, based on the data gathered from a survey in the aftermath of Hurricane Harvey. The results indicate that prior to hurricane Harvey: (1) coordination among organizations across different infrastructure systems is less than the coordination within the individual systems; (2) organizations from the community development system had a low level of coordination for hazard mitigation with organizations in flood control and transportation systems; (3) achieving a greater level of coordination among organizations across infrastructure systems is more difficult and would require a greater frequency of interaction (compared to within-system coordination). The results show the capability of the proposed multilayer network simulation framework to examine inter-organizational coordination dynamics at the system level (e.g., within and across IISs). The assessment of inter-organizational coordination within and across IISs sheds light on important organizational interdependencies in IISs and leads to recommendations for improving the resilience planning process

Introduction

Natural hazards (e.g., hurricanes, sea-level rise, earthquakes, and flooding) pose great threats to infrastructure systems that support the well-being of society. Resilience, the “ability to prepare and plan for, absorb, recover from or more successfully adapt to actual or potential adverse events” is regarded as an important capacity of a city or a community facing stressors (GIAQUINTO and ABELLI 1964; Masterson et al. 2014a). Hence, resilience planning that integrates hazard mitigation across interdependent infrastructure systems (IISs) and proactively deals with urban system hazards is an essential element in successful hazard mitigation implementation (Berke et al. 2015; Malecha et al. 2018).

Resilience planning involves coordination of multi-organizational processes across IISs (Woodruff and Regan 2019). Contradictions and inconsistencies between plans would be expected if the level of coordination among diverse organizations is insufficient (Finn et al. 2007). Organizations of different infrastructure systems usually have different priorities and preferences pertaining to development, hazard mitigation, and resilience improvement (El-Gohary 2010; Taeby and Zhang 2018). For example, in the case of resilience planning for flooding, it is common for organizations from transportation systems to be more concerned about infrastructure development to solve traffic congestion, while organizations of flood control entities and environment conservation groups focus more on hazard mitigation and environment preservation. In addition, the level of coordination across various infrastructure systems may understandably be lower than the level of coordination within the same system. Hence, to get better resilience planning, it is essential to examine and understand coordination dynamics among organizations within and across IISs.

The planning background in Houston also highlights the necessity of examining and understanding inter-organizational coordination dynamics within and across IISs for better resilience planning. Houston is one of the most flood-prone city in the nation. One important reason contributing to flood vulnerability in Houston is the confliction between the rapid urban development and poor urban planning with underinvestment in flood control infrastructure systems. Houston is the only city without zoning policies in

North America and is well known for its modest land use regulations (Qian 2010). Growing urbanism (leading to more dense development patterns) in Houston has made the city vulnerable to natural hazards due to incompatible investment on hazard mitigation infrastructure (Masterson et al. 2014a). Insufficient integration of land use approaches and hazard mitigation strategies with infrastructure plans and projects has increased both social and physical vulnerability (Berke et al. 2015). The insufficient integration among hazard mitigation, land use, and infrastructure plans is, to some extent, due to inadequate coordination for resilience planning of IISs across different infrastructure systems, such as the flood control and transportation system (Berke 2019; Berke et al. 2019; Malecha et al. 2018; Woodruff 2018).

For example, this insufficient integration among plans (due to inadequate coordination among actors) was problematic and led to vulnerability during Hurricane Harvey. In August 2017, Hurricane Harvey hit Houston Texas, and caused an estimated $125 billion in damage (NOAA & NHC 2018). One of the important reasons that Hurricane Harvey inflicted huge losses in the Houston area was the release of two flood control reservoirs (i.e., the Barker and Addicks reservoirs, built in the 1940s). The flood water released to downstream neighborhoods in West Houston caused inundation of more than 9,000 houses for more than two weeks. The West Houston area has never flooded before and did not even flood before the release during Hurricane Harvey. The decision to release flood water was mainly to protect the reservoirs from breaching and preventing even more catastrophic losses. The high-water level in the reservoirs was not only due to the unprecedented rainfall by Hurricane Harvey, but also because of infrastructure development close to the reservoir areas surrounding the newly constructed segment of State Highway 99 (SH-99). While constructing the SH-99 segment intended to improve the roadway network and alleviate the traffic burden in Houston, the inconsistent transportation plans and flood control plans allowed increased development around reservoirs. Such development increased paved area by eliminating the wetlands that could store and absorb the water without increasing the burden of the reservoirs. The example highlights the interdependencies among IISs and negative effects of inadequate cross-system coordination for hazard mitigation in resilience planning.

Interdependencies among IISs is an important aspect of coordination in the resilience planning process. While several studies have examined the interdependencies among IISs, the majority of the existing literature primarily focuses on physical aspects (Dueñas-Osorio et al. 2007; Dunn et al. 2018; Gao et al. 2010), and little is known regarding the dynamics of inter-organizational coordination. Coordination among organizations can be conceptualized graphically as the links between nodes in network theory (Bourbousson et al. 2015; Kapucu 2005). In other words, networks are structures upon which the coordination behavior of IISs involved in resilience planning unfolds. Hence, analyzing the structure and characteristics of inter-organizational networks can provide important insights regarding the dynamics of coordination in resilience planning of IISs. In one stream of research, various studies adopted network analysis in assessing the properties of social networks involved in hazard mitigation, resilience planning, and emergency response. Kapucu (2005) studied the dynamics of inter-organizational networks in response to the terrorist attacks on September 11, 2001. Bodin and Crona (2009) discussed how the characteristics of social networks (e.g., density, centrality, core-periphery, and level of cohesion) affect natural resource governance for the resilience of social-ecological systems. Magsino (2009) concluded the applications of social network analysis (SNA) for building community resilience to disasters. Mills et al. (2014) adopted SNA to understand roles of stakeholders in the systematic planning process, linking regional planning to location actions. Most of the extant works of literature adopted SNA to gather important information regarding the structure and node properties (such as the importance of organizations and their centrality) of inter-organizational networks.

While SNA informs about the structural properties of inter-organizational networks (Fan and Mostafavi 2019; Zhu and Mostafavi 2018), there are multiple factors need to be considered when examining coordination dynamics in resilience planning of IISs using SNA. First, in resilience planning coordination, the link between two organizations represents their communication and interaction, and this can have varying levels of frequency. For example, organizations A and B might collaborate once a year or once a week, and intuitively, a greater frequency of collaboration means more coordination among organizations. Hence, to fully capture the dynamics of coordination, an appropriate network analysis should be able to capture and simulate the varying levels of interaction frequencies among organizations. Second, a proper network analysis needs to consider inter-organizational coordination within and across different infrastructure systems. Therefore, the analysis should enable evaluating interactions among nodes of different types. This aspect is particularly important in examining coordination among organizations within and across IISs, because in resilience planning, the coordination among organizations within the same system (e.g., organizations in transportation systems) might have different frequency compared to coordination among organizations across different systems (e.g., organizations in transportation and flood control systems). Hence, an appropriate methodology should enable representing organizations from different infrastructure systems in a separate layer and facilitate a multi-layer modeling of inter-organizational coordination networks.

Considering these factors, this study proposes a network simulation process to capture the varying levels of interaction frequencies among organizations and employs a multilayer network approach to represent the coordination between organizations of IISs. We convert the collaboration at varying levels of frequency among organizations to the link probability in the network representing the likelihood that collaboration may happen among organizations. Accordingly, perturbations in the links of the network (based on their coordination probabilities) are used to simulate the dynamics of inter-organizational coordination during a time period (e.g., one year). The changes in network-level measures after link perturbation is then used to evaluate coordination performance. The existing literature has specified the common procedure for network characterization based on evaluating network performance: (1) obtaining empirical data to map a network; (2) measuring the investigated network's features; (3) conducting link or node perturbation in the network (Kaluza et al. 2008); (4) assessing the network performance after perturbation (Kaluza et al. 2008; Larocca et al. 2015). For example, Albert et al. randomly removed a small number of the nodes in the network and evaluated the network performance to study the network resilience to failure, finding that a scale-free network has both error tolerance and targeted attack vulnerability properties (Albert et al. 2000). Larocca used node perturbation to simulate random failures in an electric power system caused by operator errors and aging components to evaluate robustness of the electric power system (Larocca 2014). The results indicated the capability of the simulation model to estimate actual performance of the electric power system. Dong et al. studied transportation network resilience by node and link removal approaches to simulate the network disruption effect (Dong et al. 2019c; a; b; Mattsson and Jenelius 2015). The results of the research helped to identify the vulnerability of transportation networks to natural disasters.

The majority of studies regarding infrastructure systems employing network modeling focused primarily on physical interdependencies among IISs. In addition, most of these studies did not fully consider the interactions among organizations managing and operating these systems (e.g., inter-organizational coordination in resilience planning process among IISs) (Dong et al. 2019b; Larocca et al. 2015; Mattsson and Jenelius 2015; Rasoulkhani and Mostafavi 2018a). In this study, we adopt a multi-layer network analysis framework to represent the interactions among organizations of IISs. Multilayer networks enable studying networks with different types of connections, a ubiquitous characteristic in social and engineering systems (Gómez et al. 2018). Figure 12 illustrates a schematic representation of the single-layer network and multi-layer network. Extensive research has been conducted on interdependency analysis within urban systems using multilayer network tools. For example, Cardillo et al. studied the resilience of the air transportation network using a multiplex network formalism (Cardillo et al. 2013); Zhu and Mostafavi investigated critical organizations in the disaster response system by the meta-network representing different types of entities in disaster response systems (e.g., organizations, tasks, information and resources) (Zhu and Mostafavi 2018); Fan and Mostafavi studied disaster management system-of-systems (DM-SoS) by establishing the meta-network framework including stakeholder, information, resource, operation, and policy networks (Fan and Mostafavi 2019); and Solé-Ribalta et al. studied congestion in transportation networks using multiple layers to represent short range transportation and long range transportation (Solé-Ribalta et al. 2016). While multi-layer-network analysis has been utilized in the analysis of interdependencies among systems and processes of IISs, its application is rather limited in examining inter-organizational coordination for resilience planning in IISs. The multilayer network provides a novel approach to studying the inter-organizational coordination within and across IISs. In this approach, organizations are grouped by different infrastructure systems (such as transportation, flood control, and emergency response) to study inter-organizational coordination for hazard mitigation within and across IISs affecting resilience planning (Woodruff and Regan 2019). Hence, the multi-layer network provides insights into the pattern of collective actions at the system/system-of-systems level.

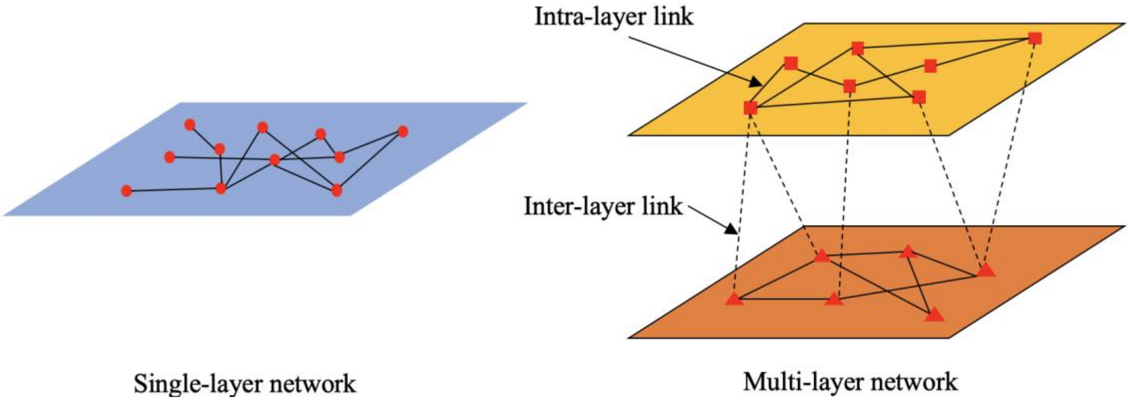


Figure 12 Single-layer network and multi-layer network.

The proposed framework conceptualizes the inter-organizational coordination among IISs embedded in urban systems as a multi-layer network. Each layer represents a specific infrastructure system (e.g., community development, transportation, flood control, emergency response, and environmental conservation) and nodes represent organizations. In terms of hazard mitigation in resilience planning, inter-layer links represent inter-organizational coordination within systems and intra-layer links represent coordination across systems. The simulation process perturbs inter-layer and intra-layer links based on their coordination probabilities (determined based on varying levels of collaboration frequency) within and across IISs. Accordingly, the inter-layer and intra-layer coordination level are determined using two measures related to network global efficiency. The details related to different steps of the proposed framework are discussed in the following section using a case study of Houston area, Texas, prior to Hurricane Harvey.

Data

The city of Houston, Texas, is used as our study site to show application of the proposed framework. We conducted a survey of stakeholders in Harris County, Texas, to collect data regarding collaboration of hazard mitigation in resilience planning among organizations in different infrastructure systems. After Hurricane Harvey in 2017, we identified 95 relevant organizations from five different infrastructure systems: transportation, flood control, emergency response, community development, and environmental conservation. We included these organizations in the survey as a roster of potential organizations with which survey respondents collaborated before Hurricane Harvey. We asked survey respondents about the frequency of hazard mitigation collaboration in resilience planning that occurred prior to Hurricane Harvey. We established the collaborative relationship through following 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 hazard mitigation efforts? If so, how frequently have such collaboration occurred (e.g., yearly, monthly, weekly and daily)?"* The survey was sent to stakeholders in February 2018 and concluded with a total of 198 individual responses representing 160 distinctive organizational departments.

Based on the gathered information regarding collaboration of hazard mitigation in resilience planning between organizations, we mapped two-mode (i.e., bipartite network) collaboration networks at different levels of collaboration frequencies (e.g., yearly, monthly, weekly and daily). Due to the nature of survey questions, relationships between organizations within the original survey roster and among the survey respondent organizations could not be determined. In consideration of this, we selected 35 organizations which were both in the survey roster and among the survey respondents to map the collaboration network. Figure 13 illustrates the process of mapping the collaboration network of these 35 organizations.

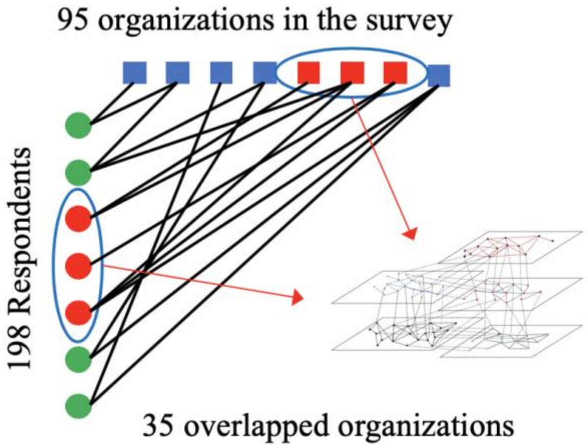


Figure 13 The collaboration network of 35 organizations.

To understand inter-organizational coordination within and across different infrastructure systems, we categorized these 35 organizations into five infrastructure systems: flood control, emergency response, transportation, community development, and environmental conservation. Table 3 shows examples of organizations in each infrastructure system. Each infrastructure system is mapped into one layer of the multi-layer network model; links between organizations indicate coordination in terms of hazard mitigation. We then applied the simulation process to examine inter-organizational coordination among these 35 organizations prior to Hurricane Harvey.

Table 3 Examples of organizations in each infrastructure system.

Infrastructure system	Examples of organizations
Flood control	The Texas Floodplain Management Association, Texas Water Development Board, Harris County Flood Control District, Texas Coastal Watershed Program
Transportation	Metro, Texas Department of Transportation, Houston Transtar, Port of Houston Authority
Emergency response	Harris County Office of Emergency Management, Texas Department of Public Safety, Harris County Office of Emergency Management,
Environmental conservation	Bayou Land Conservancy, Bayou Preservation Association, Houston Wilderness, Urban Land Institute
Community development	Houston Real Estate Council, United Way of Greater Houston, Harris County Community Economic Development Department, West Houston Association

Multi-layer simulation framework

The proposed framework comprises four main steps: (1) conceptualize inter-organizational coordination among IISs as a multilayer network; (2) determine coordination probabilities between organizations based on the reported frequency; (3) perturb links based on assigned coordination probabilities; and (4) evaluate the network performance after link perturbation using measures such as network efficiency and coefficient of variation. These steps are elaborated in the remainder of this section.

Conceptualize Inter-organizational Coordination among IISs as a Multilayer Network

The proposed framework conceptualizes coordination among organizations from different infrastructure systems as a multi-layer network. Each layer in the multi-layer network represents one infrastructure system. Intra-layer and inter-layer links of the multilayer network represent inter-organizational coordination for hazard mitigation in resilience planning within and across IISs. Figure 14 illustrates an example of a multi-layer network of five interdependent infrastructure systems.

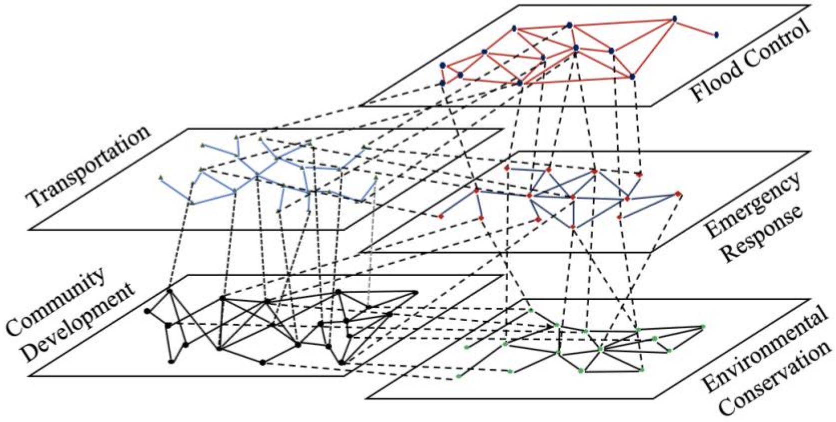


Figure 14 A multilayer network of five interdependent infrastructure systems.

Determine Coordination Probabilities between Organizations

Network simulations requires the probability of node (e.g., organization) or link (e.g., coordination) perturbation as input. But these mathematical probabilities are usually difficult to obtain directly. For example, coordination between organizations is often stated in frequency terms such as daily or weekly. Therefore, we use probability distribution to convert different levels of collaboration frequency (e.g., daily, weekly, monthly, and yearly) to the coordination probability of each link. We are able to obtain these levels of collaboration frequency from survey responses.

In the proposed framework, to determine coordination probabilities, we define daily interaction among organizations as the baseline, in which the probability of coordination between two organizations would be equal to one. We make the following assumptions to determine the daily coordination probability for other levels of collaboration frequency.

(1) We approximate the probability distribution of coordination frequency as a normal distribution.

(2) We define the boundaries for each frequency level (i.e., weekly, monthly, and yearly). The boundary for weekly collaboration is from once a week to seven times a week (e.g., 48–288 days per year) considering seven days one week. The boundary for monthly collaboration is from once a month to four times a month (e.g., 12–47 days per year) considering that one month has 4 weeks. Likewise, considering that one year has 12 months, the boundary for the yearly collaboration is from once a year to 11 times a year (e.g., 1–11 days per year). Finally, we consider daily frequency should have interaction at least once a day (e.g., ≥365 days per year). The boundaries of each collaboration frequency are listed in Table 4.

(3) We treat holidays and weekends with the same weight as other days when determining coordination probabilities as they will not affect the simulation result, but unnecessarily, complicate the process.

Based on these assumptions, the daily coordination probability for organizations which reported a weekly interaction frequency is determined as an average of 96 days per year (i.e., twice a week) with a 95% confidence that the coordination frequency is in the interval of [48, 144] (i.e., once a week to three times a week). Likewise, the monthly coordination frequency is determined as 24 days per year (i.e., twice a month) on average with a 95% confidence to fall in the range of [12, 36] (i.e., once a month to three times a month). The yearly coordination frequency is determined as four days per year on average with a 95% confidence to fall in the range of [2, 6] (e.g., twice a year to six times a year). Table 4 summarizes the calculated daily coordination probabilities at different collaboration frequency levels.

Table 4 Converted daily coordination probabilities between organizations.

Collaboration frequency	Boundary (days per year)	Coordination probability
Daily	≥365	$P = 1$
Weekly	[48, 288]	$P \sim N(\frac{96}{365}, \frac{24}{365})$ [a]
Monthly	[12, 47]	$P \sim N(\frac{24}{365}, \frac{6}{365})$ [a]
Yearly	[1, 11]	$P \sim N(\frac{4}{365}, \frac{1}{365})$ [a]

Accordingly, the daily coordination probabilities are assigned to each link based on Table 4 for the network simulation process. Each normal distribution of weekly, monthly and yearly collaboration generates 100,000 samples during the simulation process. We compare the histograms of iterations for each normal distribution with their theoretical probability density functions. Figure 15 shows the histograms of samples at each collaboration frequency level. The results illustrate that 100,000 samples are large enough for the simulation process because the histograms of samples are very close to the theoretical probability density functions of each proposed normal distribution (indicated by the red curve in Figure 15).

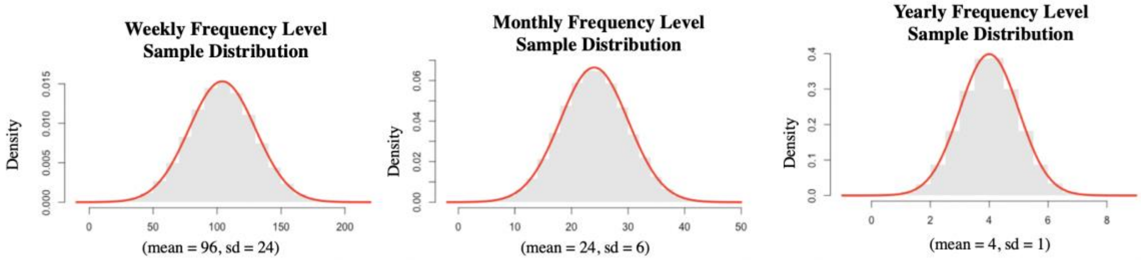


Figure 15 Histograms of generated samples at each frequency level.

Perturb Links Based on Assigned Coordination Probabilities

Each iteration of the simulation process would remove intra-layer and inter-layer links of the multilayer network based on the calculated daily coordination probabilities (i.e., probability of perturbation is equal to 1 - probability of daily coordination) between the organizations. First, we generate a random probability between 0 and 1 (0 and 1 themselves are excluded) in each iteration of the simulation process. Meanwhile, each link will randomly draw a sample among 100,000 generated samples for the assigned distribution. If the selected sample is less than the generated probability, the link is removed in this iteration of the simulation process. This probabilistic perturbation process means that the lower the daily coordination probability of the link is, the higher probability the link will be removed in the simulation process. For example, if the daily coordination probability of a link is 1 (i.e., coordination between organizations with daily frequency), the link would never be removed in the simulation process. We conduct the simulation process with 365 iterations to capture the inter-organization coordination fluctuation in a full year cycle. In the case of investigating the inter-organizational coordination within the specified infrastructure system, we only remove the correspondent intra-layer links. Accordingly, we only remove the inter-layer links when examining the inter-organizational coordination across infrastructure systems. That means, if we want to investigate the inter-organizational coordination within the flood control system, we only remove the links within the flood control system (i.e., intra-layer links); when we want to analyze the inter-organizational coordination across the flood control system and the transportation system, we only remove the links between these two systems (i.e., inter-layer links) in the simulation process. This separate link removal enables examining the level of coordination within and across different systems separately.

Evaluate Network Performance after Link Removal

We adopt two measures for examining the level of coordination within and across IISs: network efficiency and its coefficient of variation after the link perturbation. Network efficiency measures the shortest distances between nodes after the link perturbation. The shortest distances between nodes tend to increase as links are removed, and the increase of distances between nodes can be interpreted as the decrease in the overall level of coordination among various organizations of IISs (Crucitti et al. 2004; Kinney et al. 2005; Rubinov and Sporns 2010). Network efficiency can be calculated using Equation 6 (Latora and Marchiori 2001):

$$E = \frac{1}{N(N-1)} \sum_{i,j} \frac{1}{d_{ij}} \tag{6}$$

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. Network efficiency is very sensitive to the total number of nodes (i.e., network size) in the network (Zanin et al. 2018). As a result, networks with great differences in size should not be compared by network efficiency. The coefficient of the network efficiency variation in multiple iterations can be calculated by Equation 7.

$$CV = \frac{\sigma}{\mu} \tag{7}$$

where σ and μ are the standard deviation and mean of the network efficiency of multiple iterations. This measure implies the stability of coordination during the simulation process.

In order to evaluate the extent to which variation in daily coordination probability between organizations affects overall level of coordination, we examined five scenarios in which we uniformly assigned five different daily coordination probabilities (i.e., 15%, 30%, 45%, 60%, and 75%) to each link in the mapped multi-layer network.

Examine Coordination Increase Strategies

To examine how to increase coordination within and across different systems, we conducted simulation experiments to determine the required coordination probability of links to achieve targeted network efficiency within and across different infrastructure systems. The first step is to uniformly assign each link an initial coordination probability: 1/365. Then the simulation process would be applied within or across different infrastructure systems, and network efficiency is calculated after simulation iterations. If the targeted network efficiency is not met, the coordination probabilities of links are increased by 1/365 increment until the targeted network efficient is met. Figure

16 shows the iterative mechanism to determine the required coordination probability for targeted network efficiency.

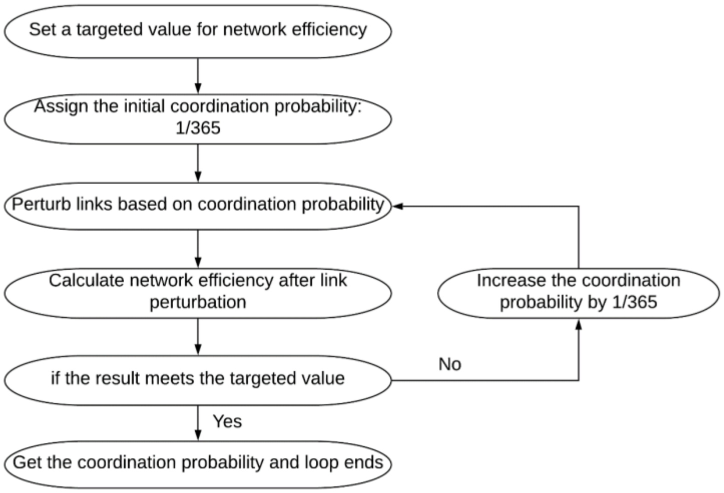


Figure 16 Coordination increase simulation to calculate required coordination probability.

Results

In this section, we show the application of the proposed framework to the data collected from the stakeholder survey in Harris County, Texas. Each infrastructure system is mapped to one layer of the multi-layer network. Figure 17 illustrates the mapped multilayer network structure (generated by the software MuxViz (De Domenico et al. 2015)). The layers of the mapped multilayer network are all of similar size (Table 5) (e.g., the number of nodes in each layer is around 15).

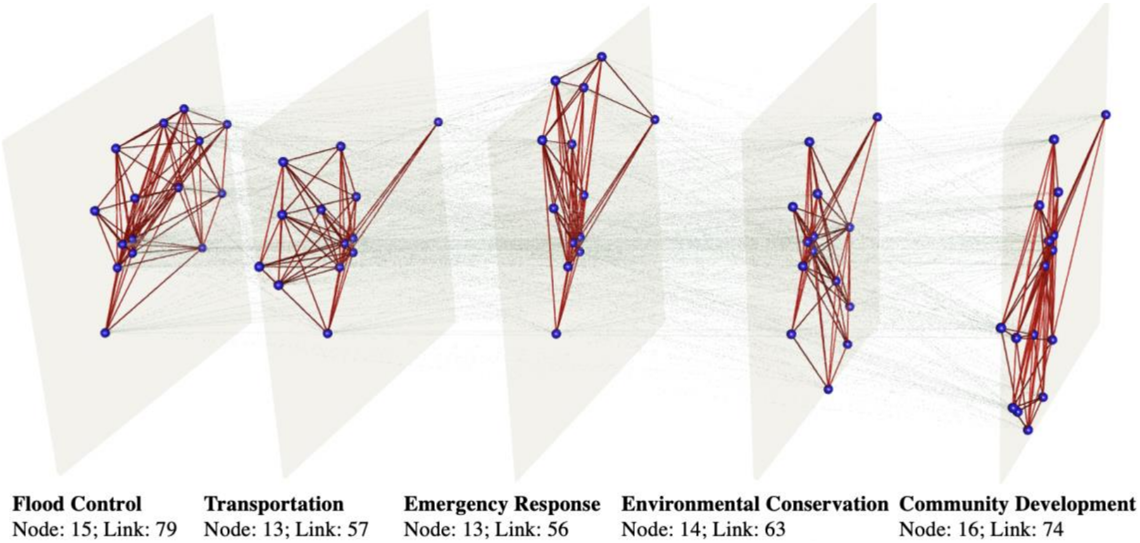


Figure 17 Multilayer collaboration network of 35 organizations.

Table 5 Nodes and links in each layer of the mapped meta-network.

Layer of mapped network	Nodes	Links
Flood control	15	79
Transportation	13	57
Emergency response	13	56
Environmental conservation	14	63
Community development	16	74
Total	71	329

The layer of flood control system has 15 nodes (i.e., organizations) and 79 links representing coordination between organizations in terms of hazard mitigation. The transportation layer comprises 13 nodes and 57 links, while the community development layer has 16 nodes and 74 links. The emergency response layer and environmental conservation layer have 13 nodes with 56 links and 14 nodes with 63 links, respectively. The total number of nodes in the five infrastructure systems is 71, which is more than the total number of organizations, 35. This is because some organizations, such as City of

Houston, American Planning Association, and-Galveston Area Council, have multiple departments involved in different infrastructure systems, and therefore appear in more than one layer.

The simulation results indicate that the lowest daily coordination probability for each link, 15% in this case, leads to the lowest mean of network efficiency (0.355) and the highest coefficient of variance (0.116). The scenario with the highest daily coordination probability for each link, 75%, leads to the highest mean of network efficiency (0.725) and the lowest coefficient of variance (0.009). Figure 18 illustrates that the higher daily coordination probability is (i.e., from 15% to 75%), the higher mean of network efficiency (i.e., from 0.355 to 0.725) and the lower coefficient of variance (i.e., from 0.116 to 0.009) will be after the simulation process.

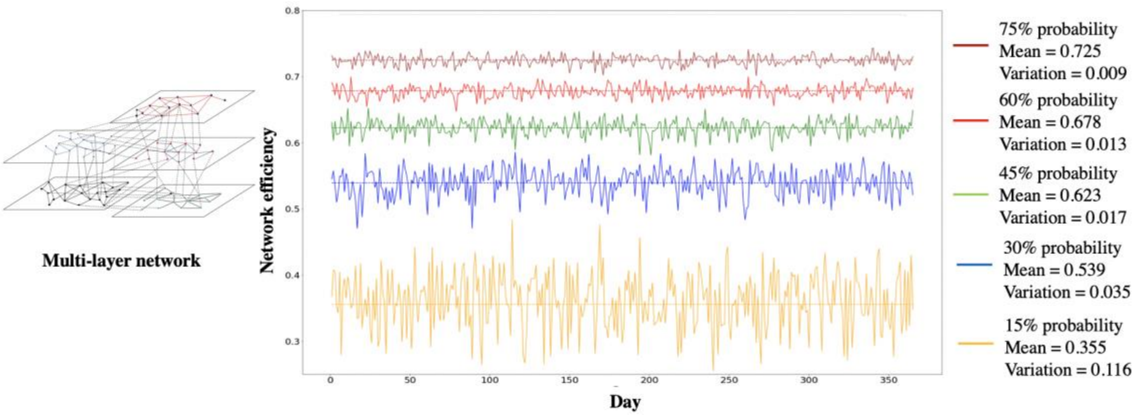


Figure 18 Network efficiency and coefficient of variation with different daily coordination probabilities.

In the next step, we used the daily coordination probability based on the reported collaboration frequency between organizations from the survey. The simulation process perturbs intra-layer and inter-layer links based on the daily coordination probability (from the survey) in each iteration. Mean network efficiency and its coefficient of variation for intra-layer and inter-layer perturbation scenarios is illustrated in Table 6 and 8. To juxtapose the network efficiency using the frequencies obtained in the survey with the maximum network efficiency, Table 7 and 9 list the results of maximum network efficiency within and across different infrastructure systems. Maximum network efficiency is the greatest possible theoretical level of coordination among organizations and is determined when the daily coordination probability for all links in the network equals 1. In other words, maximum network efficiency is determined only by the network structure (e.g., the coordination among organizations of IISs) and will not be affected by the collaboration frequency.

As shown in Table 6, the transportation system has the highest mean value of network efficiency (0.46) and the lowest coefficient of variation (0.13). Community development and environmental conservation systems have the lowest mean of network efficiency (0.25 and 0.26, respectively) and the greatest coefficient of variation (0.23). This result indicates that the coordination within the transportation system is at a high level and consistent. On the other hand, coordination within community development and environmental conservation systems are at lower levels and more unstable.

Table 6 Network efficiency under intra-layer link perturbation.

Infrastructure system	Mean of network efficiency	Coefficient of variation
Flood Control	0.37	0.17
Transportation	0.46	0.13
Emergency Response	0.37	0.18
Community Development	0.25	0.23
Environmental Conservation	0.26	0.23

As illustrated in Table 7, maximum network efficiency within different infrastructure systems is close, ranging from 0.808 (the community development system) to 0.876 (the flood control system). The comparison between the existing (pre-Harvey) network efficiency and the correspondent maximum network efficiency shows that, even for the transportation system (the highest within-system network efficiency), only about 50% of the maximum possible coordination is achieved. For the community development and environmental conservation, this value is approximately 30%.

Table 7 Maximum network efficiency within IISs.

Infrastructure system	Maximum network efficiency
Flood Control	0.876
Transportation	0.865
Emergency Response	0.859
Community Development	0.808
Environmental Conservation	0.846

Table 8 illustrates that, overall, the mean of network efficiency (0.12) across infrastructure systems is much lower and the mean of the coefficient of variation (0.66) is greater than those within infrastructure systems (i.e., 0.34 and 0.19, respectively). This implies a great number of missing and inconsistent cross-system coordination for hazard mitigation in resilience planning. Transportation and emergency response systems have the highest mean of cross-system network efficiency 0.28 and the lowest coefficient of variation 0.2. Transportation and community development systems show the lowest mean of cross-system network efficiency 0.01 and the highest coefficient of variation 1.73. The mean of cross-system network efficiency between flood control and community development systems is also low (0.05) (almost one-third) compared to the value between transportation and flood control systems (0.17). The results indicate that transportation and emergency response systems have a high level of cross-system coordination (i.e., more coordination and consistent). On the other hand, organizations in transportation and community development systems have a low level of cross-system coordination (i.e., less coordination and inconsistent). This is also true for the coordination across flood control and community development systems.

Table 8 Network efficiency under inter-layer link perturbation.

Infrastructure system	Mean of network efficiency	Coefficient of variation
Flood Control and Community Development	0.05	0.36
Transportation and Flood Control	0.17	0.40
Transportation and Community Development	0.01	1.73
Environmental Conservation and Flood Control	0.03	0.93
Emergency Response and Flood Control	0.16	0.33
Emergency Response and Transportation	0.28	0.20

Table 9 indicates that maximum network efficiency across infrastructure systems is lower than the one within the systems, which can be another piece of evidence of missing cross-system coordination. Maximum network efficiency across community development and flood control systems is the lowest: 0.560; emergency response and transportation systems has the highest maximum network efficiency across the systems: 0.762. The comparison between the existing (pre-Harvey) network efficiency and the correspondent maximum network efficiency shows that, even for the highest network efficiency across transportation and emergency systems, only about 37% of the maximum possible coordination is achieved. For the coordination across transportation and community development systems, this value is nearly 1.5%.

Table 9 Maximum network efficiency across IISs.

Infrastructure system	**Maximum network efficiency**
Flood Control and Community Development	0.560
Transportation and Flood Control	0.652
Transportation and Community Development	0.667
Environmental Conservation and Flood Control	0.659
Emergency Response and Flood Control	0.707
Emergency Response and Transportation	0.762

To study how to increase inter-organizational coordination within and across different infrastructure systems, we set the targeted network efficiency as half of the maximum values and applied the coordination increase simulation to calculate the required coordination probability. Table 10 and 11 summarize the required coordination probability of links within and across IISs, respectively. Figure 19 illustrates the required coordination probability and maximal network efficiency.

Table 10 Required coordination probability within infrastructure systems.

Infrastructure system	Required coordination probability	Targeted network efficiency
Flood Control	$P = 62/365$ (weekly)	0.438
Transportation	$P = 64/365$ (weekly)	0.432
Emergency Response	$P = 65/365$ (weekly)	0.430
Community Development	$P = 68/365$ (weekly)	0.404
Environmental Conservation	$P = 65/365$ (weekly)	0.423

Table 11 Required coordination probability across infrastructure systems.

Infrastructure system	Required coordination probability	Targeted network efficiency
Flood Control and Community Development	$P = 114/365$ (weekly)	0.280
Transportation and Flood Control	$P = 92/365$ (weekly)	0.326
Transportation and Community Development	$P = 95/365$ (weekly)	0.334
Environmental Conservation and Flood Control	$P = 90/365$ (weekly)	0.330
Emergency Response and Flood Control	$P = 85/365$ (weekly)	0.354
Emergency Response and Transportation	$P = 77/365$ (weekly)	0.381

Table 10 and 11 indicate that both required coordination probabilities within and across IISs are in the interval of weekly collaboration frequency level (nearly twice and three times a week, respectively). Although the targeted network efficiency within infrastructure systems is greater than those of cross-system values (due to their higher maximum network efficiency), the required coordination probabilities within infrastructure systems (averaging 65/365) are lower than those across systems (averaging 92/365). This implies that achieving a high level of coordination across different systems is more difficult and would require greater frequency of interactions (compared to within system coordination). The flood control system has the highest targeted network efficiency: 0.438 while having the lowest required coordination probability: 62/365. Meanwhile, coordination across flood control and community development systems has the lowest targeted network efficiency: 0.280, while it needs the greatest coordination probability: 114/365. This finding implies that the flood control system can achieve a higher level of coordination more easily compared to other infrastructure systems due to its better collaboration network within the system. However, the interaction between flood control and community development systems is lower, and it would be more difficult to achieve a higher level of cross-system coordination.

Figure 19 illustrates that compared to cross-system coordination, within-system coordination can achieve greater network efficiency with relatively lower frequencies of interactions. Cross-system coordination, however, could achieve a lower maximum network efficiency and requires higher frequencies of interactions among organizations across systems. This would imply that a high level of cross-system coordination is harder to achieve based on the current collaboration network and would require a greater frequency of cross-system interaction and perhaps different mechanisms (e.g., add more links/establish new collaboration) for achieving a high level of cross-system coordination.

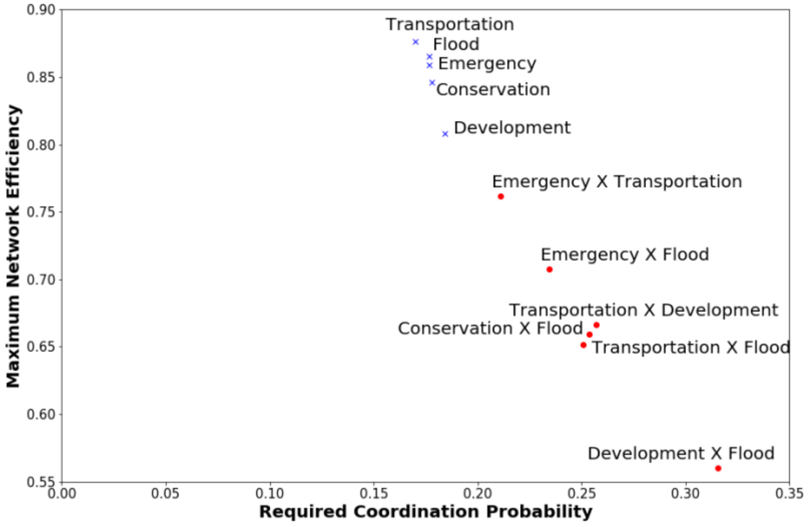


Figure 19 Required coordination probability and maximum network efficiency.

Discussion

The results of the multi-layer network simulation framework examine inter-organizational coordination in IISs for flood hazard mitigation in Harris County. The discussion of the results below focuses on how the level of inter-organizational coordination within and across IISs may affect resilience planning outcomes. We provide anecdotal evidence and link to other studies to reinforce the validity of the findings obtained from the multilayer network simulation framework.

Inter-organizational Coordination within the Infrastructure Systems

As shown by the results, the maximum network efficiency within different infrastructure systems is close (around 0.85), which implies that different infrastructure systems have almost the same potential to reach the same level of within-system coordination. However, the actual coordination for each system varies based on the collaboration frequency obtained from the survey, with the highest level of coordination (transportation: 0.46) being almost twice that of the lowest (community development: 0.25). The transportation system has the highest network efficiency and the lowest coefficient of variance after the intra-link perturbation, implying that prior to Harvey, organizations within the transportation system had more consistent and higher level of coordination with each other compared to organizations in other infrastructure systems.

The flood control and emergency response systems have the second highest network efficiency and the second lowest coefficient of variance for within-system coordination. Also, the flood control system has the highest maximum network efficiency. The flood control and emergency response systems also had relatively consistent and high levels of coordination for hazard mitigation prior to Harvey. The flood control system plays an important role in hazard mitigation and resilience planning. Organizations such as Harris County Flood Control District and Texas Floodplain Management Association within the system are usually responsible for floodplain management and hazard mitigation plan and policy development (e.g., flood control plan and policy of building foundation level lift). Sufficient inter-organizational coordination within the flood control system would be an important foundation for hazard mitigation integration in resilience planning (Woodruff and Regan 2019). Organizations from the emergency response system, such as Harris County Office of Emergency Management and Texas Department of Public Safety, play an important role in response and recovery during and after a disaster (Almquist et al. 2016; Kapucu 2005). Other studies (Aldrich 2012; Campanella 2006; Schweinberger et al. 2014) have also shown that enhanced coordination between organizations within the emergency response system would greatly improve emergency response processes, and thus community resilience.

The network efficiency within the community development system is the least, and it also has the lowest maximum network efficiency. One possible reason is that there is lower level of coordination among organizations within the community development system compared to other infrastructure systems in Harris County. This finding suggests that organizations within the community development system do not fully engage in hazard mitigation processes. Coordination for hazard mitigation among organizations in the community development system is crucial for resilience planning (Berke et al. 2015, 2019). However, as survey data and results show, adequate coordination within the community development system was missing prior to Harvey.

Inter-organizational Coordination across Different Infrastructure Systems

The simulation results show that level of coordination across different infrastructure systems is much lower than coordination level within infrastructure systems. Also, the maximum network efficiency across systems is lower than those within the infrastructure systems. This means that inter-organizational coordination for hazard mitigation across infrastructure systems is harder to achieve a high level compared to within-system coordination. The highest level of coordination within the system (transportation: 0.46) is nearly 1.6 times more than the highest one across systems (transportation and emergency response: 0.28). Organizations in the emergency response system have consistent and high level of coordination for hazard mitigation with organizations in the transportation system indicated by the highest cross-system network efficiency and lowest coefficient of variance. This could be due to the importance of transportation infrastructure (e.g., highways and bridges) in emergency response operations (such as evacuation and relief supply). For example, many roads in Houston were flooded with water more than 25 inches deep during hurricane Harvey, preventing access by fire vehicles. Firefighters had to manage rescues by boat, greatly decreasing rescue efficiency.

The results also show that organizations in the flood control system have less frequent coordination with organizations in the community development system. Also, inter-organizational coordination for hazard mitigation between community development and transportation systems is the lowest despite the high maximum network efficiency. This finding suggests that organizations from the community development system had insufficient coordination for hazard mitigation with organizations in other infrastructure systems prior to Hurricane Harvey.

Coordination Increase Strategies: Establish New Collaboration or Increase Frequency

The results indicate two ways to increase the level of inter-organizational coordination within and across systems: (1) increasing maximum network efficiency, and (2) increasing coordination probabilities. In the context of resilience planning, these two methods essentially suggest establishing new collaborations or increasing coordination frequency among organizations. Maximum network efficiency relates to the number of the shortest paths in networks. Basically, for the same network, a network of greater density implies higher maximum network efficiency (Latora and Marchiori 2001). This implies that adding links in the network, especially links with higher betweenness centrality nodes, will greatly increase the maximum network efficiency (Latora and Marchiori 2001). On the other hand, for the same network, when the maximum network efficiency is relatively high, increasing maximum network efficiency by adding new links would be difficult because it requires large numbers of new links (the density of the network is proportional to n^2, where n is the number of nodes in the network). However, when the maximum network efficiency is low, it requires great coordination frequency to increase the network efficiency.

In summary, to increase the level of inter-organizational coordination within and across IISs, the findings suggest establishing new interactions among organizations when the existing collaboration is small and limited, especially with organizations involved in more than one infrastructure system (such as City of Houston, American Planning Association, and Houston-Galveston Area Council). Forums and workshops in which diverse actors could participate are considered an effective way to establish new interaction regarding resilience planning (Berardo and Lubell 2016). Also, organizations at the higher administration levels (such as City of Houston, and Texas Department of Transportation) could play a boundary-spanning role to help establish coordination among organizations at the lower administration level (such as Houston Transtar and Houston-Galveston Area Council) (Bodin 2017). Furthermore, the combination of establishing new collaboration and increasing interaction frequency would also be a good strategy. Organizations in IISs could establish new collaboration with the aforementioned organizations involved in multiple infrastructure systems or at higher administration levels and increase the interaction frequency with the ones with which they already have established coordination.

Although the planning background in Houston and the example of Hurricane Harvey suggests that more coordination among IISs would have enhanced outcomes in resilience planning, it is important to note that a body of literature highlights that there are often tradeoffs and unintended consequences of higher connectivity and coordination in networks (Chelleri et al. 2015; Chen et al. 2015; Granovetter 1983; Gunderson 2001; Shutters et al. 2015; Ulanowicz et al. 2009). Chelleri et al. studied interactions across scales and systems resulting in resilience trade-offs, and one case study showed that greater community cohesion does not necessarily lead to greater community resilience (Chelleri et al. 2015). Chen et al. found that increased internal interactions in the large-scale infrastructure systems composed of many shared public facilities may lead to greater vulnerability and large-scale failures (Chen et al. 2015). Shutters et al. studied the relationship between system connectedness and resilience. The results showed that in response to a shock, cities with lower social-economic system connectedness have higher resilience (Shutters et al. 2015). Ulanowicz et al. found that tightly constrained ecosystems appear ‘brittle’ to disruptions (Ulanowicz et al. 2009). Panarchy theory pointed out that social-ecological systems with strong interdependencies may have lower resilience as one node failure may lead to cascade failures in the system (Gunderson 2001). While greater connectivity is shown to be correlated with a greater system vulnerability in some physical and ecological systems, some studies showed that this could be generalized to human systems as well. Burt argued that a highly dense network would lead to redundant connection and decrease the efficiency of communications among actors (Burt 2004). In another study, Burt and Granovetter showed that social capital lies in the weak ties between structural holes in human networks (Granovetter 1983; Lazega and Burt 1995a). Based on these findings, it could be the case that increasing coordination among diverse actors may not necessarily lead to better outcomes in resilience planning. Nevertheless, in this paper, we primarily focus on examining inter-organizational coordination and understanding how organizations may increase coordination within and across IISs.

Concluding Remarks of Study B

This study proposes and tests a multilayer framework for simulating the network dynamics of inter-organizational coordination among IISs in resilience planning. The proposed framework and its application in the context of Harris County. Texas, prior to Hurricane Harvey have multiple methodological and theoretical contributions. First, the presented work considers the organizational aspects of interdependencies among IISs, departing from the majority of infrastructure interdependency studies which mainly focus on physical aspects. Second, the proposed framework adopts the simulation process and multilayer network for examining human/organizational networks with heterogenous types of nodes and dynamic links. The proposed framework enables modeling inter-organizational coordination among IISs with heterogenous nodes and capturing the coordination frequency among the nodes. Third, the framework provides new insights into coordination dynamics among organizations within and across different systems. Fourth, from the practical perspective, the framework enables examining the coordination increase strategies and provides recommendations to increase the level of coordination among organizations, which may lead to better resilience planning in IISs.

Limitations of Study B and Future Directions

Some limitations in the proposed framework still exist which can be addressed in future research. This study assumes that coordination frequency is normally distributed. Future studies can further test this assumption by estimating the coordination probability based on the longitudinal data gathering regarding interaction frequencies. Such data collection would require more specific data regarding the dates and mode of coordination interactions among agencies, a task whose implementation would not be straightforward. Also, in the simulation experiments for examining the coordination increase strategies, we increased the same coordination probability for all links in the scenarios (1/365 in each iteration). The future work could examine the increase in coordination probability based on different network reticulation mechanisms, such as preferential attachment. Furthermore, inter-organization networks directly and indirectly influence the networks of plans, as well as infrastructure networks. A low level of coordination in inter-organizational networks may lead to conflicting plans and more vulnerability in physical networks. Hence, understanding the interdependencies among inter-organizational networks, network of plans, and physical networks may hold the key to unlocking a holistic resilience planning process in IISs.

CHAPTER IV

STUDY C: A PLAN EVALUATION FRAMEWORK FOR EXAMINING STAKEHOLDER POLICY PREFERENCES IN RESILIENCE PLANNING AND MANAGEMENT OF URBAN SYSTEMS[§]

The objective of this study was to create and test a methodological framework for examining the extent to which diverse stakeholder policy preferences were captured in various plans related to resilience planning and management of interdependent urban systems. Policy preferences represent what were important and worthy for stakeholders and determine the priorities of stakeholders in resilience planning of urban systems. Stakeholders in different urban sectors (e.g., flood control, transportation, and environmental conservation) may have conflicts of policy preferences in the resilience planning process. A comprehensive understanding of the extent to which plans incorporated and reflected policy preferences of different stakeholders would greatly improve the quality of resilience planning. Hence, we proposed a plan evaluation framework to examine the extent to which various plans captured diverse stakeholder policy preferences in resilience planning of interdependent infrastructure systems. We showed the application of the proposed methodology in evaluation of four plans affecting flood resilience planning in the Houston area. The proposed tool could not only

---

[§] This chapter is published in the journal of "Environmental Science and Policy" as an individual paper (Li, Q., Roy, M. and Mostafavi, A., Berke, P. 2020. A Plan Evaluation Framework for Examining Stakeholder Policy Preferences in Resilience Planning and Management of Urban Systems, Environmental Science & Policy, Elsevier, 124, 125-134). The authors retain the right to include it in a thesis or dissertation.

help identify conflicted stakeholder policy preferences in planning but also enable evaluation of the level of policy consistency in networks of plans.

Introduction

Urban systems currently face great challenges related to the increasing frequency and impacts of natural hazards. Hence, resilience planning of interdependent urban systems (IUSs) is an essential process to enable urban systems to adapt to natural hazards (Berke et al. 2015, 2019; Godschalk 2003). The National Research Council observed that resilience planning is essential to building the capacity of human and physical systems to anticipate, absorb, recover from, or more successfully adapt to actual or potential adverse events (National Research Council 2012). IUSs are complex systems that comprise both physical and human systems; the performance of physical systems being highly dependent on the behavior of human systems (e.g., actions, decisions, plans and policies) (Davis et al. 2018; Li et al. 2020a; Naderpajouh et al. 2018; Srivastava and Mostafavi 2018). Therefore, effective resilience planning of IUSs should take into account interactions between human and physical systems, such as actor coordination networks, network of plans and stakeholder values and norms (Dong et al. 2020).

Resilience planning and management of IUSs involve multiple stakeholders from different urban sectors (e.g., flood control, land use, transportation, environmental conservation) (Berke et al. 2019; Farahmand et al. 2020; Li et al. 2019; Lyles et al. 2014a; Woodruff and Regan 2019).

The involved stakeholders usually have divergent priorities and preferences related to economic/urban development, environmental conservation, flood control and social equity due to their different values (Campbell 1996; Coates and Tapsell 2019). Furthermore, these priorities and preferences in planning are interrelated and cannot be easily steered to one priority (Berke et al. 2015; Campbell 1996). For example, urban development in flood-prone areas would highly affect the need for greater investment in flood-control infrastructure. Natural resources (e.g., wetland, bayou, and prairie) consumed by urban development would adversely affect environmental conservation and ecosystem management (Endter-Wada et al. 2020). Thus, for resilience planning and management of IUSs, evaluating the level of preferences incorporation and consistency across plans based on the understanding of diverse stakeholder preferences in the planning process is an essential step.

To address this need, we proposed a plan evaluation framework to examine how plans reflected and incorporated diverse stakeholder policy preferences in resilience planning of IUSs. We designed and conducted a stakeholder survey to investigate diverse stakeholder policy preferences in flood-resilience planning of IUSs. The stakeholder survey included a list of flood risk reduction policy actions such as land us policies, engineering policies, and monetary policies. Based on the rates of policy actions by participated stakeholders, we developed a preference satisfaction matrix representing stakeholder policy preferences. Then we selected four important plans in Houston area and assessed policies documented in plans using a plan evaluation methodology. The proposed plan evaluation framework enabled answering the following research questions. First, to what extent did different plans incorporate diverse policy preferences of stakeholders? Second, the preferences of what stakeholders from which sectors were more/less captured by plans? Third, what was the level of policy preference consistency across plans? The results, in the context of Houston area, indicated that the hazard mitigation plan incorporated the most overall stakeholder preferences to risk reduction policies among the four examined plans. The regional transportation plan, however, incorporated the fewest overall stakeholder policy preferences. The hazard mitigation plan and the regional conservation plan had the highest level of policy consistency, while the hazard mitigation plan and regional transportation plan have the lowest level of policy consistency.

The following sections of the paper were organized as follows. We first discussed the existing literature regarding stakeholder policy preferences in resilience planning of IUSs, stakeholder engagement in the planning process, organizational behavior, and collaborative environmental management in the literature review part. Second, we provided an overview of the flooding history and planning background in the Houston area. We elaborated five major steps for the proposed plan evaluation framework in the “Methodology and Data” section. Third, the key findings of the application to the four plans in the Houston area and discussion of the insights regarding the resilience planning were presented. Finally, we discussed limitations of the study.

Literature Review

Diverse Stakeholder Policy Preferences in Resilience Planning of IUSs

In the context of resilience planning, policy preferences represent those policies, institutions, and services that diverse stakeholders from IUSs regard as of importance and worth (El-Gohary and Qari 2010; Ros et al. 1999). “Planning is a value-laden activity” (Forester 2013) that caters to diverse needs, capacities and policy preferences (Sandercock 2017). Each stakeholder involved in the planning process may have diverse policy preferences (sometimes even conflicted policy preferences) with different degrees of importance (Bahadorestani et al. 2020; Jahani and El-Gohary 2012; Schwartz 2012). Existing studies showed that stakeholders from IUSs had different priorities and preferences pertaining to urban development, hazard mitigation, social equity and environmental conservation (Campbell 1996; Taeby and Zhang 2019). In the case of flood resilience planning, stakeholders from the transportation sector were more concerned about improving infrastructure systems, while stakeholders in flood control and environment conservation sectors paid more attention to hazard mitigation and environmental preservation (Li et al. 2019, 2020a). Consequently, the validity of plans were influenced by the degree to which they facilitated the dialogue on complex problems (Rittel and Webber 1973) and navigated pluralistic opinions and incorporate them into strategic policy framework (Baer 1997). Substantial planning literature has theorized on different ways to deliberate on value conflicts (Habib 1979) and improve communication gaps (Forester 2013; Healey 1992; Innes and Booher 2004; Sandercock 2017). This segment of the literature was based on the argument that a critical step to managing value conflict that would greatly influence stakeholder policy preferences was communication across differences. A small but impactful body of work focused on the sources of value conflict that would greatly influence stakeholder policy preferences across multiple planning domains (e.g., environmental and economic domains) and finding common benefits to bridge conflicts (Campbell 1996; Godschalk 2004). Along this line of inquiry, a growing number of assessments evaluated the impact of stakeholder policy preference conflicts across multiple plans on vulnerability to hazards (Berke et al. 2015, 2019). Despite these existing studies, there is a lack of methods for quantitative evaluation of stakeholder policy preference conflicts among diverse stakeholders across multiple plans. Quantitative methods could complement existing plan evaluation methods, and are important to develop and implement consistent networks of plans for hazard mitigation and resilience (Berke et al. 2015, 2019).

Importance of Diverse Stakeholder Engagement in Resilience Planning of IUSs

Diverse stakeholder engagement in the planning process is important to improve the quality of resilience plans. Cities are increasingly guided by networks of plans, such as land use, hazard mitigation, parks and recreation, housing, transportation, environmental conservation, and capital improvement plans, developed by diverse stakeholders both within and outside government (Berke et al. 2019). Resilience planning, therefore, requires collective actions (e.g., communication, coordination) by diverse stakeholders across IUSs. Plan contradictions and inconsistencies would arise in the absence of sufficient coordination among diverse stakeholders (Finn et al. 2007; Woodruff and Regan 2019). Existing studies showed that the inclusion of diverse stakeholders enhanced defining core values, increased the collective understanding of complex systems (e.g., ecosystems, infrastructure systems, social systems) and helped address and resolve conflicts in the planning process and environmental governance (Graversgaard et al. 2017; Nutters and Pinto da Silva 2012; Watson et al. 2018; Wiesmeth 2018). Tompkins et al. (2008) highlighted the importance of incorporating diverse stakeholder preferences to ensure the awareness of inherent trade-offs to obtain the long-term stakeholder supports in coastal planning for climate change adaptation. Existing studies also showed that involving local planner who had expertise in land use approaches would greatly improve the quality of hazard mitigation plans and climate change adaptation plans (Burby 2003; Dyckman 2018; Lyles et al. 2014a; Woodruff and Stults 2016). There were multiple studies related to plan evaluation in different domains, such as hazard mitigation (Berke et al. 2015; Lyles et al. 2014b), ecosystem management (Brody 2003) and sustainability planning (Berke and Conroy 2000; Schrock et al. 2015). However, little was known about the extent to which plans in different domains incorporated the policy preferences of stakeholders who were affected by the performance of plans. Also, there are limited theoretical (Hopkins and Knaap 2018) and empirical studies (Berke et al. 2015) to evaluate the level of consistency across plans based on the diverse policies in the planning process. This limitation is in part due to a lack of quantitative methods to evaluate the extent of incorporation and consistency of stakeholder policy preferences in networks of plans.

Existing Work of Examining Stakeholder Policy Preferences

Despite the growing recognition for the importance of congruency among stakeholder policy preferences in resilience planning and management of IUSs, an important dilemma is how to examine and incorporate diverse policy preferences of stakeholders. Stakeholder policy preferences are usually not explicitly expressed and are represented or reflected in diverse forms or concepts, such as goals, standards, needs, and attitudes (Barima 2010). Biesenthal et al. (2018) and Matinheikki et al. (2019) identified preferences of stakeholders (e.g., institutional logics and demands) in infrastructure project based on literature review (mainly from the institutional theory) and stakeholder interviewers. Taeby and Zhang (2018, 2019) conducted a comprehensive literature review to understand different disaster resilience practices. Accordingly, they developed a survey to collect stakeholder preferences towards disaster resilience practices in physical, social, environmental, and economic dimensions. In the context of resilience planning of IUSs, to the best of our knowledge, there is no quantitative measure to examine stakeholder policy preferences across different plans. To address this gap, we proposed a quantitative approach and demonstrate its application in the context of hazard mitigation and flood resilience in Houston area.

Planning Background in Houston Area

Houston is the largest metropolitan without zoning regulations (Fulton 2020; Qian 2010). This lack of zoning was often cited as the cause for repetitive and extensive damage after major flood events (Boburg and Reinhard 2017; Patterson 2017). However, it is not appropriate to posit ‘Houston does not regulate or plan’. Houston supplemented its lack of zoning with a myriad of other regulatory and policy tools. On one hand, there were policies that had managed growth. According to Neuman (2010), Houston plans growth in primarily three ways- first by developing major institutional projects in close collaboration with the development community; second by building expansive infrastructure networks in partnership with state and federal agencies (Binkovitz 2020; Shelton 2017); and third by encouraging neighborhood level planning through Super Neighborhood organizations. Speaking of specific regulatory tools, Fulton (2020) added the use of deed restrictions to regulate land uses on private properties, density bonuses to encourage development in the urban core, a buffering ordinance to impose height restriction outside urban core and lot size restrictions. While these policies supported population growth, a laissez-faire development pattern and affordability (Masterson et al. 2014a; Qian 2010), they also exacerbated vulnerability to flooding (Zhang et al. 2018) and posed environmental justice issues (Neuman and Smith 2010).

In response to multiple major flood events, Houston also planned for flood risk, restricting growth in flood prone areas. Blackburn (2020) discussed the critical role of the Bayou Greenways Initiative, led by Houston Parks board, in protecting and enhancing network of connected open spaces along bayous to increase water carrying capacity of Bayous. Since 2015, U.S. Army Corps of Engineers and the Texas General Land Office explored the efficacy of structural surge infrastructure and coastal ecosystem enhancement (Blackburn 2017) along the Galveston Bay to protect the city from surge and coastal flooding (Bush 2019; Davlasheridze et al. 2019). The Harris County Flood Control District invested in construction and restoration of detention ponds in the city, and supported FEMA home buyouts (Harris County Flood Control District 2017). The City of Houston Office of Emergency Management, through their Hazard Mitigation Plan (2017), focused on retrofitting critical facilities against flood damage, protecting parks and expanding storm sewer systems throughout the city.

Therefore, Houston planned, but planned incrementally and (till 2015) without the broad institutional framework and vision of a comprehensive city plan (Neuman and Smith 2010). Policy responses to flood risk were numerous, varied in scope and involved stakeholders from different planning sectors and geographical scales. Holistic resilience planning would require plans to find synergies between the different planning approaches and incorporate diverse policy preferences of different stakeholders from diverse urban sectors in the Houston area.

Methodology and Data

The proposed plan evaluation framework comprises five major steps to examine how plans reflected and incorporated diverse stakeholder policy preferences in resilience planning and management of IUSs: (1) identify stakeholder policy preferences in flood-resilience planning of IUSs, (2) develop a policy preference satisfaction matrix, (3) assess policis documented in plans using plan evaluation methodology, (4) policy preference aggregation, and (5) evaluate policy consistency across plans. Figure 20 illustrated five steps of the proposed framework, and we explained each step in detail in the rest of this section. In this study, we focused on the flood resilience planning prior to Hurricane Harvey involving diverse urban sectors, including flood control, emergency response, transportation, community development, and environmental conservation.

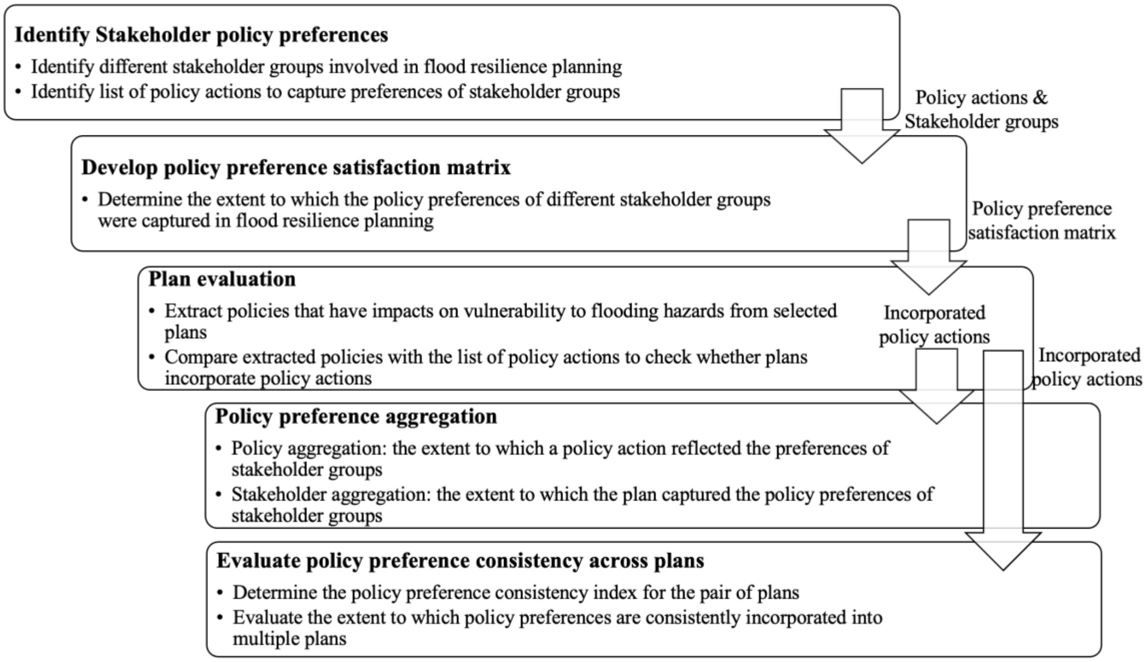


Figure 20 Five steps of the value-based plan evaluation framework.

Identify Stakeholder Policy Preferences

We conducted a stakeholder survey in Harris County, Texas, to understand diverse stakeholder policy preferences in flood resilience planning of IUSs. The survey collected stakeholder preferences with regards to policy actions that could be taken to reduce the risks of future flooding in the Houston area. Table 12 listed the risk reduction policy actions included in the survey. The policy actions were selected based on the discussion of strategies for urban resilience in the literature (Berke and Smith 2009; Brody et al. 2013, 2009; Burby 1998; Burby et al. 1999; Godschalk 2003).

Table 12 Flood Risk Reduction Policy Actions in the Survey.

Policy Description	Policy Description
P1: limit new development in flood-prone areas	P9: protect wetland and open space
P2: elevate buildings	P10: improve stormwater systems
P3: strengthen infrastructure design standards	P11: build additional flood water drainage systems
P4: establish and implement infrastructure resilience program	P12: temporarily prohibit development in the period immediately after a disaster event
P5: minimize additional impervious surfaces, such as parking lots	P13: charge impacts fees for development in flood-prone areas
P6: build additional protective dams	P14: limit the development of public facilities and infrastructure in flood-prone areas
P7: build additional protective levees	P15: limit rebuilding in frequently flooding areas
P8: build more catchment reservoirs and retention ponds	P16: buyout or otherwise acquire damaged property

We classified survey respondents into five urban sector categories based on organizations and departments they represented. These five urban sectors were flood control (FC), emergency response (ER), transportation (TT), community development (CD), and environmental conservation (EC) (Farahmand et al. 2020; Li et al. 2019). We further classified respondents in each urban sector into governmental organizations (Gov) and non-governmental organizations (NGO). Table 13 shows examples of involved organizations and departments in classified urban sectors. Here, we would like to note the intersections of governmental and non-governmental organizations. Some non-governmental organizations, such as the Texas Floodplain Management Association, Bayou Preservation Association, and Houston Wilderness, are professional organizations consisting of related government officials or have long-term collaborations with governmental organizations. Therefore, these professional non-governmental organizations could provide both governmental and non-governmental perspectives toward surveyed policy actions. Also, in this study, we defined stakeholders as "identifiable groups who take an active role in making decisions that affect the planning process (Johnson et al. 2013; Reed 2008)" instead of "those who are affected by or can affect a decision in the planning process (Freeman 2010)." Reed (2008) and Johnson et al. (2013) argued that, although individuals can be stakeholders based on Freeman's definition, studies were suggested to focus on "identifiable groups united by shared interests who hold a stake (whether directly or indirectly) in the scope of their initiative". Thus, following the insights from Reed (2008) and Johnson et al. (2013), we excluded the wider public in survey participants.

Table 13 Examples of Departments and Organizations in Classified Urban Sectors.

Category	Example of involved departments	Example of involved organizations
Flood Control (FC)	Water departments and institutions, drainage and floodplain management	The Texas Floodplain Management Association (NGO), Harris County Flood Control District (Gov), City of Houston Floodplain Management Office (Gov)
Emergency Response (ER)	Disaster management, disaster relief, fire department, police department, resilience offices	Harris County Office of Emergency Management (Gov), Texas Department of Public Safety (Gov), Federal Emergency Management Agency (FEMA) (Gov)
Transportation (TT)	Transportation strategic planning, design, construction, and management departments	METRO (Gov), Houston TranStar (Gov), Port of Houston Authority Texas Department of Transportation (TxDOT) (Gov)
Community Development (CD)	Business and economic services, Academic institutions, public work departments, recreational departments	Houston Real Estate Council (NGO), United Way of Greater Houston (NGO), Harris County Community Economic Development Department (Gov), Bay Area Houston Economic Partnership (Gov)
Environmental Conservation (EC)	Pollution control, waste management	Bayou Land Conservancy (NGO), Bayou Preservation Association (NGO), Houston Wilderness (NGO), Urban Land Institute (NGO), The Nature Conservancy (NGO)

Develop Policy Preference Satisfaction Matrix

To analyze survey responses, we developed a policy preference satisfaction matrix. The matrix was structured to compare support for policies (rows) described by urban sectors represented by respondents (columns) (Please see Table A7 in Appendix A). The goal of this study was to analyze how sector and type of organization influence stakeholder values in resilience planning. For example, did respondents from the emergency response sector on average show more support for engineering solutions such as P6: build protective dams, compared to land use solutions such as P9: protect wetlands and open space? Furthermore, is there a preference consensus for certain policies by all respondents, regardless of sector and type of organization? To this end, we averaged the level of policy support (Table 13) of respondents in each sector and type of organization. Then we conducted a linear transformation to map the level of policy support to the 0–10 scale (Equation A1 in the Appendix A). Also, to capture the extent of congruency that respondents valued the listed policy actions, we calculated the variances in the level of policy support of respondents in categories.

Each cell in the policy preference satisfaction matrix, therefore, represented transformed average level of policy support of respondents in categories (e.g., FC/GO, ER/NGO, TT/NGO, CD/GO, EC/NGO). We also developed a second matrix for variances in the level of support by urban sectors and types of organizations. The transformed average level of policy support can represent a measure of opposition or support toward this policy action, reflecting the policy prefereces of stakeholders in this category. Variances in the level of policy support of respondents could indicate the level of congruency for this policy action among stakeholders in the category. A high variance in the level of policy support indicated that stakeholders in this category had divergent preferences towards this policy action, while a low variance of policy support indicates that stakeholders in the category tended to have a shared preference towards this policy action.

Plan Evaluation

We selected four plans that reflect diverse policy preferences of different stakeholders in resilience planning and management of IUSs. The selected plans included the 2016–2020 Capital Improvement Plan (CIP), the 2017 Gulf-Houston Regional Conservation Plan (RCP), the 2040 Regional Transportation Plan (RTP), and the 2017 Hazard Mitigation Plan (HMP).

We focused on flood resilience planning involving diverse urban sectors in Houston area. Among the selected plans, the CIP, RCP, and RTP were developed before Hurricane Harvey, while the 2017 HMP were updated immediately after Hurricane Harvey. The CIP outlines strategies to improve the infrastructure system of the City of Houston. The CIP aims to address current and expected infrastructure needs to improve the physical facilities and well-being of Houstonians. The RCP is a compilation of regional environmental and conservation projects in the eight-county Houston-Galveston region. The RCP identifies conservation needs, collaborative opportunities and initiatives for improving the environmental systems in an eight-county area. The 2040 RTP provides a guide for the maintenance and development of the transportation system. The RTP identifies transportation investment priorities, and aims to improve safety, manage and mitigate transportation congestion. The RTP not only determines the development of transportation infrastructure systems, but also affects urban development triggered by the development of transportation infrastructure. The HMP includes mitigation goals and strategies for potential natural hazards in the City of Houston, such as thunderstorm wind, lightning, tornados, and hurricane/tropical storms. The HMP aims to eliminate or reduce the risks to people and properties from future hazards and their effects. The selected plans represent three main areas affecting flood resilience planning (e.g., infrastructure development, hazard mitigation, and environmental conservation).

These four plans can serve as a comprehensive information source to examine divergent stakeholder values in resilience planning and management of IUSs.

Using the Plan Integration for Resilience Scorecard Methodology (Berke et al. 2015, 2019; Malecha et al. 2018), two coders independently conducted plan content analysis to extract policies and evaluate the values supported by the policies. First, we extracted policies from selected plans that meet three criteria: one, the policy has a clearly defined policy tool; second, the policy tool has substantial impact on vulnerability to flooding hazards; and third the policy language is spatially specific. Consider the policy in Table 3 "*Protect acreage along riparian corridors in a holistic approach for each of the four Galveston bay sub-watersheds*" (RCP, p3). The policy tool "protect acreages" spatially applies to Galveston Bay riparian corridors and has the potential to reduce vulnerability to flooding in Houston by both absorbing impact of hazards and avoiding development in sensitive areas. Next, both coders scored each selected policy +1 if the policy reduced vulnerability, -1 if the policy increased vulnerability, or 0 if effect on vulnerability was neutral. Initial inter-coder percentage agreement on policy selection ranged from 75% to 82% (CIP, 81%; RCP, 82.3%, HM, 76.9%; and RTP, 75%). Using established content analysis procedures (Stevens et al. 2014), coders discussed and reconciled differences in policy selection and scoring. Based on discussions, we finalized a reliable list of policies that could potentially affect vulnerability to flooding in Houston.

Next, we compared this policy list from the plan analysis with the 16 flood risk reduction policy actions in the survey (Table 12) and identified content overlaps across lists. We interpreted overlaps between policy tools in plans and stakeholder surveys as a policy in a plan successfully capturing the value of stakeholders. We then assigned to that policy numerical values in the policy preference satisfaction matrix—average level of support of stakeholders from all the categories. If a policy from a plan did overlap with survey policies, that policy got a zero. Table 14 showed examples of extracted policies from selected plans and obtained scores for the policies.

Table 14 Examples of Extracted Policies and Scores for the Policies.

Plan	Extracted Policy	Included survey policy action	Score
CIP	Buffalo Bayou Detention Basin: street & traffic control & storm drain dedicated drainage and street renewal fund; Project addresses watershed storm water quantity and quality requirements. It includes design and construction of a detention basin	P10: improve stormwater systems, P11: improve drainage systems	Level of support for P10 and P 11
RCP	Protect acreage along riparian corridors in a holistic approach for each of the four Galveston bay sub-watersheds and develop habitats to develop plans to improve habitat for birds, preserving and protecting the ecological value of land/water ecosystems and habitats	P9: protect wetland and open space	Level of support for P9
RTP	Enhance State of Good Repair Adequate maintenance (includes bridges, roadways, transit facilities, port facilities, railroads) will extend the life and ensures safety of current facilities at a fraction of the cost of constructing new ones. Improve existing infrastructure which makes it safer and more resilient.	P4: establish infrastructure resilience program	Level of support for P4
HMP	Acquisition or mitigation reconstruction of repetitive loss properties: Acquisition or mitigation reconstruction	P16: buyout or acquire property	Level of support for P16

Policy Preference Aggregation

The fourth step was to compare the policy tool in plans with stakeholder support for that policy from surveys. After we extracted the policies from plans and obtained the average level of support scores for the extracted policies, we aggregated the scores by policy action tools (rows in the value satisfaction matrix) and by stakeholder categories (columns in the value satisfaction matrix). Therefore, there are two types of policy preference aggregation—policy aggregation and stakeholder aggregation. The policy aggregation can indicate the extent to which a policy action reflected the preferences of all the stakeholders involved in flood resilience planning, and the stakeholder aggregation can indicate the extent to which the evaluated plan captured the policy preferences of stakeholders from one urban sector within or outside government. Table A8 in Appendix A showed the calculation of two aggregations based on the obtained scores by the evaluation of each plan.

Evaluate Policy Consistency across Plans

We also wanted to evaluate if certain policies are consistently incorporated into multiple plans. Therefore, we proposed a policy consistency index: D_{AB} that would indicate the level of policy consistency in two plans (Please refer to Equation A2 in Appendix A). The policy consistency index D_{AB} is not only influenced by the number of same policy actions incorporated in plans A and B, but also affected by the number of incorporated policy actions in the evaluated plans. Therefore, a high D_{AB} would imply that a large proportion of polices in both plan A and plan B reflected the same policy preference. Conversely, a low D_{AB} indicates inconsistent policy integration across the pair of plans.

Results

Policy Preference Satisfaction Matrix and Results of Policy Preference Aggregation

Table 15 showed the policy preference satisfaction matrix of transformed average level of policy support and the results of policy preference aggregation. We can observe from Table 15 that 16 flood risk reduction policy actions included in the survey satisfied the fewest policy preferences for stakeholders from the transportation sector, with 68.6% and 65.1% for stakeholders from government and non-government organizations (NGOs), respectively. The 16 policy actions satisfied the highest policy preference for stakeholders from government organizations in the environmental conservation sector (81.2%), while stakeholders from NGOs in the flood control sector showed the second highest level of support towards the policy actions (76.8%).

The results of policy aggregation also showed that P15 (limit rebuilding in high-frequency flood areas) gained the highest overall level of support by stakeholders from different categories (81.2%), while P3 (strengthen infrastructure design standards), P1 (limit new development in flood-prone areas), and P10 (protective wetland and open space) gained relatively high level of support as well, with ratings of 79.4%, 79.4%, and 79.0%, respectively. This result indicated that P15, P3, P1, and P10 could reflect collective and shared stakeholder policy preferences. P12 (temporarily prohibit development in the period immediately after a disaster event) gained the least overall support from the stakeholders from different categories (54.2%), while P6 (build additional protective dams) gained the second least support from the stakeholders. In other words, these two policy actions, P12 and P6, reflected few policy preferences of stakeholders from different sectors.

Table 15 Policy Preference Satisfaction Matrix and Results of Policy Preference Aggregation.

Policy	FC /Gov	FC /NGO	ER /Gov	ER /NGO	TT /Gov	TT /NGO	CD /Gov	CD /NGO	EC /Gov	EC /NGO	Sum	Percent
P1. Limit new development (Land use policy)	7.50	8.33	7.61	8.08	8.44	5.83	8.22	7.92	9.50	8.00	79.43	79.4%
P2. Elevate buildings (Engineering policy)	8.33	8.75	6.68	6.15	5.36	5.00	7.84	6.42	7.50	6.75	68.78	68.8%
P3. Strengthen infrastructure (Engineering policy)	7.33	8.75	7.61	7.50	7.19	8.33	7.96	7.50	9.00	8.25	79.42	79.4%
P4. Establish infrastructure resilience program (Engineering policy)	7.14	8.75	7.34	7.50	7.50	6.67	7.96	7.58	8.50	9.00	77.94	77.9%
P5. Minimize impervious surfaces (Land use policy)	5.54	6.67	5.71	5.96	6.43	6.67	6.35	6.75	8.50	6.50	65.07	65.1%
P6. Building dams (Engineering policy)	5.63	5.00	6.39	6.73	6.07	5.83	6.21	6.77	6.50	5.25	60.39	60.4%
P7. Building levees (Engineering policy)	5.42	7.50	6.19	7.50	5.71	7.50	5.96	7.12	6.00	7.25	66.15	66.2%
P8. Building reservoirs/retention ponds (Engineering policy)	6.73	10.00	7.45	8.08	7.14	6.67	7.43	7.65	7.50	7.25	75.90	75.9%
P9. Protect wetlands/open space (Land use policy)	7.14	8.33	7.61	7.31	7.14	5.83	7.24	7.34	9.00	8.50	75.45	75.4%
P10. Improve stormwater (Engineering policy)	7.83	8.33	8.24	8.08	7.81	7.50	8.09	7.95	8.13	7.00	78.97	79.0%
P11. Improve drainage systems (Engineering policy)	7.32	10.00	7.93	8.08	7.14	7.50	7.83	8.18	7.50	7.00	78.48	78.5%
P12. Temporarily prohibit development after disasters (Land use policy)	5.71	3.33	5.34	5.96	5.63	5.00	6.09	6.25	5.63	5.28	54.22	54.2%
P13. Charge impact fees (Monetary policy)	6.25	5.83	6.59	6.92	6.43	6.67	6.62	6.41	8.13	6.39	66.23	66.2%
P14. Limit development of public facilities (Land use policy)	7.86	6.67	7.34	7.29	7.81	5.83	7.57	6.81	10.00	7.25	74.43	74.4%
P15. Limit rebuilding in frequent flooding areas (Land use policy)	9.11	8.33	7.99	7.31	7.19	7.50	8.29	7.26	10.00	8.25	81.22	81.2%
P16. Buyout or acquire property (Monetary policy)	8.00	8.33	7.22	6.35	6.79	5.83	7.70	6.67	8.50	7.50	79.43	79.4%
Sum	112.8	122.9	113.2	114.8	109.8	104.2	117.4	114.6	129.9	115.4		
Percent	70.5%	76.8%	70.8%	71.7%	68.6%	65.1%	73.4%	71.6%	81.2%	72.1%		

Notes: Gov denotes governmental organizations; NGO denotes non-governmental organizations. Green marks show the highest rates and red marks show the lowest rates among urban sectors.

Furthermore, we can observe that NGO stakeholders in the flood control sector indicated the lowest level of support (score 3.33) towards P12 while they showed the highest level of support (full score 10) towards P8 (build more catchment reservoirs and retention ponds) and P10 (improve storm water systems). NGO stakeholders in the environmental conservation sector showed the highest level of support towards P4 (establish and implement infrastructure resilience program), while they showed the lowest level of support towards P6. This result indicates that P4, P8, and P10 could highly reflect the shared policy preferences of stakeholders in the environmental conservation and flood control sector, especially for the NGOs involved in those sectors.

Figure 21 illustrated the results of variances in levels of policy support. For more detailed information regarding the calculated variances in level of policy support of stakeholders in each category, refer to Table A9 in the Appendix A.

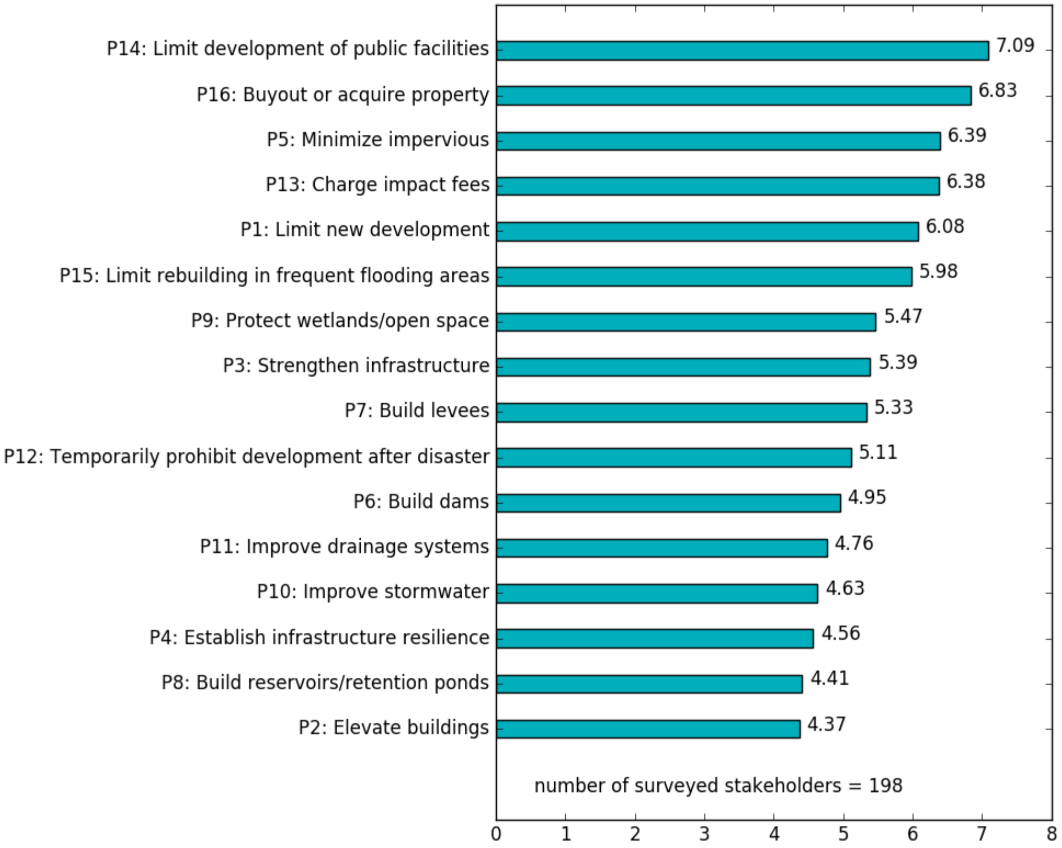


Figure 21 Results of variances in level of policy support.

We can observe from Figure 21 that stakeholders from different sectors indicated an overall high level of congruency towards P2 (elevate buildings) because the overall variance of P2 is the lowest. Because the average rating for P2 was relatively low (68.8%, Table 15), the high level of congruency here indicated that most stakeholders showed a low level of support towards P2. On the other hand, P14 (limit the development of public facilities and infrastructure in flood-prone areas) had the lowest level of congruency because the variance of value satisfaction rating is the highest. Stakeholders from different urban sectors had highly divergent preference towards P14.

Stakeholders from NGOs in the flood control and community development sectors showed the lowest two congruencies towards P14 (with variances 1.56 and 1.17, respectively), while stakeholders from government organizations in the environmental conservation sector showed the highest congruency (with zero variance). These examples showed how the variance in the policy preference ratings could be used to evaluate value congruence among stakeholders within each urban sector.

Based on the results in Table 15 and Figure 22, we can conclude that engineering policy actions (P2, P3, P4, P6, P7, P8, P10, P11) have the highest average supports by all the urban sectors, while monetary policy actions (P13, P16) have the lowest average supports by all the urban sectors. Furthermore, engineering policy actions have the highest support by the non-governmental organizations in the flood control sector and have the lowest supports by governmental organizations in the transportation sector. Land use policy actions and monetary policy actions gain the highest supports by governmental organizations in the environmental conservation sector and gain the lowest supports by non-governmental organizations in the transportation sector. Also, engineering policy actions have the lowest overall variance of rates and monetary policy actions have the highest overall variance of rates. This means that monetary policy supports are polarized while actors from different urban sectors have more consistent attitudes towards engineering policy actions.

Results of Plan Evaluation

Figures 22 illustrated the results of plan evaluation and policy preference aggregation for selected plans. Detailed results of plan evaluation and value aggregation calculation for each plan were shown in Tables A10–A13 in Appendix A.

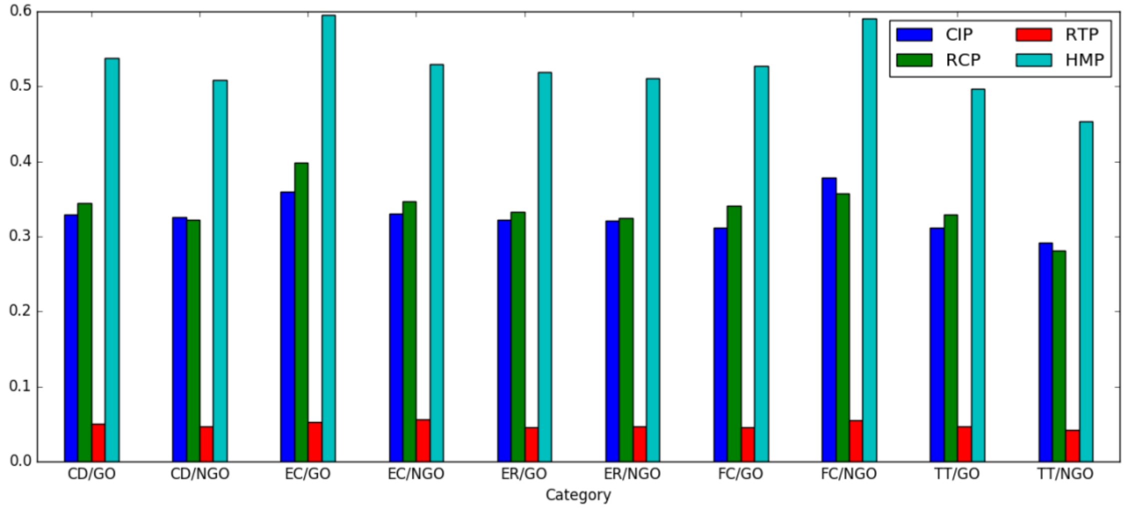


Figure 22 Stakeholder aggregation for four examined plans.

In the CIP, the preferences of stakeholders from NGOs in the flood control sector were captured the most (37.8%), while the stakeholder policy preferences of NGOs in the transportation sector were captured the least (29.3%). We would like to note that most NGOs participated in the stakeholder survey were professional organizations that included related governmental officials or have long-term collaboration with governmental organizations. This could be the reason why preferences of stakeholders from NGOs in the flood control sector were captured the most in the CIP. We would like to also note that different types of NGO stakeholders may have distinctive policy preferences in the planning process. To illustrate, professional NGO such as the Texas Floodplain Management Association and West Street Recovery may have different values in the resilience planning, although they both worked on flood resilience in Houston. The CIP focuses on improving the infrastructure system in the City of Houston. We found that this plan favors preferences of stakeholders in the flood control and environmental conservation sectors, because the CIP included many projects, such as drainage system improvement and ecosystem enhancement, enhancing flood risk reduction and resilience in the region.

Figure 22 illustrated that the RCP was most effective in capturing the preferences of stakeholders from government organizations in the environmental conservation sectors. In contrast, the RCP was least effective in capturing the preferences of stakeholders in NGOs in the transportation sector. We can find that the RCP reflected more preferences of stakeholders in the environmental conservation and flood control sectors. This was because the policies in the RCP focused on the ecosystem enhancement, open space requirements, and land acquisition, and these policies also indicated high preferences of stakeholders in the flood control sector.

The RTP addressed only one policy action (P4: establish and implement infrastructure resilience program). Therefore, the RTP captured the fewest overall stakeholder preferences among the four examined plans. The RTP focuses mainly on the maintenance and improvement of the transportation system. Most policies in the RTP relate to transportation infrastructure development (e.g., expand the roadway system), and cannot capture diverse stakeholder policy preferences related to flood risk reduction and resilience.

Figure 22 illustrated that the HMP captured the most overall stakeholder policy preferences among the four examined plans. The preferences of stakeholders from government organizations in the environmental conservation and stakeholders from NGOs in the flood control sector were captured the most (nearly 59%), while the stakeholder preferences of NGOs in the transportation sector were captured the least (45.3%) in the HMP. The goal of HMP was to develop mitigation strategies for multiple potential natural hazards in the City of Houston, and thus included mitigation policies such as land requisition, construction guidelines and requirements, infrastructure enhancement or weatherproofing, drainage improvement, and flood control.

Policy Consistency across Plans

We also examined the level of policy consistency across four plans in terms of the extent to which they captured diverse stakeholder values. Figure 23(a) illustrated the 16 policy actions in the survey included in the four plans examined in this study. Circles represented four plans, and sizes of circles were proportional to the number of incorporated flood risk reduction policy actions. Policy actions in the overlaps of circles indicated that they were incorporated in multiple plans. Figure 23(b) illustrated the results of policy consistency index among evaluated plans. Detailed calculation of the index was shown in Table A14 in Appendix A.

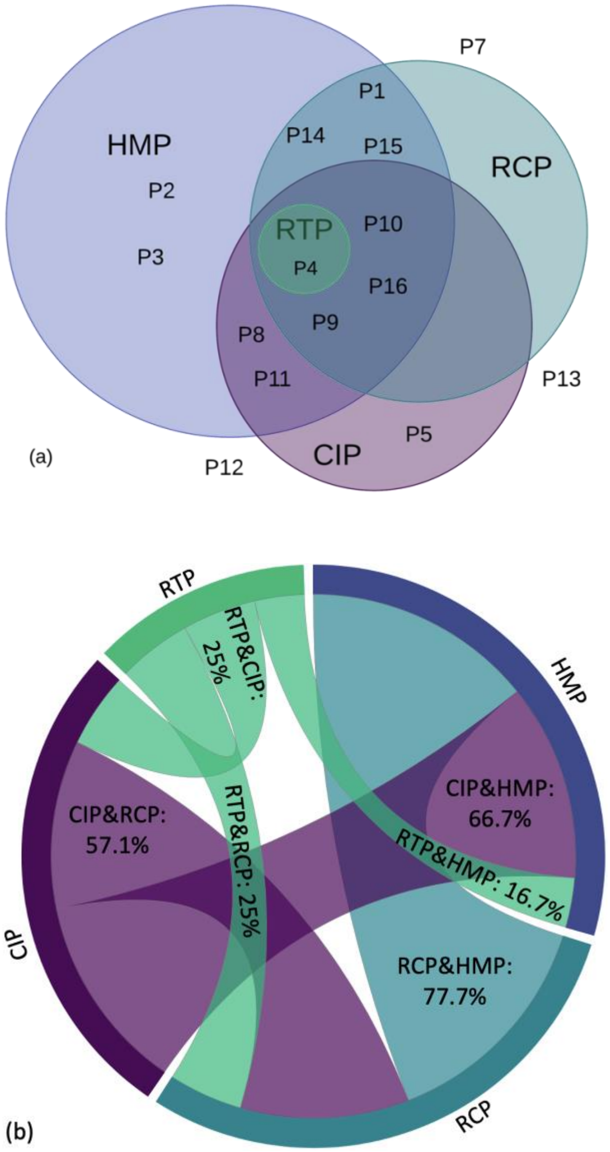


Figure 23 Policy consistency across plans: (a) policy actions incorporated in four plans (b) policy consistency index.

We can observe from Figure 23(a) that only P4 (Establish infrastructure resilience) was addressed in all four plans. This implies that these four plans all paid much attention to policies related to improving infrastructure resilience. P9 (protect wetlands/open space), P10 (improve stormwater system) and P16 (buyout or acquire property) were addressed in three plans, but not the RTP. These three plans included diverse types of policies: P9 is the land use policy, P10 is the infrastructure policy, and P16 is the monetary policy. The HMP includes all the policy actions that the RCP and CIP incorporated except for P5 in the CIP. P6 (build dams), P7 (build levees), P12 (temporarily prohibit development after disaster), and P13 (charge impact fees) were not included in any examined plans. Although P6 and P7 as typical structural resistance policies were widely used before (Beatley 2012; Godschalk 2003) and gained overall support (60.39% and 66.15%, respectively) by the surveyed stakeholders, the plan examination results indicated that P6 and P7 are not addressed in the planning for hazard mitigation in the region. On the other hand, we found that P12 and P13 were not clearly addressed in the examined plans, and we decided not to include them in the plan examination results. As illustrated in Figure 23(b), the HMP and RCP had the highest level of polic consistency (77.7%), while the HMP and RTP had the lowest level of policy consistency (16.7%) in terms of incorporating the policy preferences of diverse stakeholders.

Discussion

Based on the above results, we can answer the three research questions. To what extent did different plans incorporate diverse policy preferences of stakeholders? The preferences of what stakeholders from which sectors are more/less captured by plans? What was the level of policy consistency across plans in terms of incorporating policy preferences of diverse stakeholders? For the first research question, among the four examined plans, the HMP incorporated the policy preferences of stakeholders from different categories the to the greatest degree (52.7%), while the RTP captured the stakeholder policy preferences the least degree (4.9%) in policy actions for flood risk reduction and resilience. HMP incorporated 11 out of the 16 policies that stakeholders supported—with the most support (81.2%) shown for P15: “limit rebuilding in frequently flooding areas.” HMP did not, however, include policies to reduce impervious cover (P5), engineering policies to build new structural protection, such as dams (P6) and levees (P7), and financial tools (P13) to discourage development. This suggested that stakeholders and HMP consistently preferred to avoiding floods over resisting through infrastructure. In fact, a few engineering policies (P6, P7) and finance tools (P13) were excluded from all four plans. Among these “charge impact fees for development in flood-prone areas” was consistently less preferred (66% support) by stakeholders compared to land-use policies (73% mean support). This potentially undermined the effectiveness of other highly preferred policies, such as enforcing development restrictions (81.2% support) or encouraging resilience through green infrastructure (79% support) in Houston.

The RTP, on the other hand, contained only one policy, “establish and implement infrastructure resilience.” Thus, while failed to capture diverse policy preferences, the one policy reflected the preference held by 79% of stakeholders. Given that RTP played a pivotal role in infrastructure growth and by extension urbanization and runoff in Houston, however, it is concerning that the plan did not incorporate policies to address impervious cover or to improve stormwater systems.

Second, we asked if plans captured more/less preferences of certain urban sectors and types of organizations? Policy preferences of stakeholders from both government organizations and NGOs in the environmental conservation sector were captured the most in the examined plans, while preferences of stakeholders from NGOs in the transportation sector were captured least effectively. Furthermore, the plans also captured the preferences of stakeholders from NGOs in the flood control sector the second most effectively. The HMP did the best job of addressing both governmental and NGO policy preferences.

Finally, we asked what is the level of policy consistency among plans? The transportation plan and the hazard mitigation plan had the lowest level of policy consistency, while the hazard mitigation plan and the environmental conservation plan have the highest level of policy consistency in terms of incorporating diverse stakeholder values. This siloed approach to resilience was consistent with past assessments of plans in cities across the United States. For instance, Berke et al. (2019) evaluated policies from six flood-prone cities in United States and recommend that comprehensive plans further integrate land use based–hazard mitigation. Woodruff and Regan (2019) found that involving diverse stakeholders from different urban sectors both within and outside government would greatly improve the quality of resilience plans. These findings reiterated the need for more collaboration across plans (Godschalk 2003; Godschalk et al. 1999), and further argued in favor of incorporating diverse policy preferences that were shared by a large number of stakeholders. The capital improvement plan and the hazard mitigation both had relatively high levels of policy consistency. This finding is encouraging as the capital improvement plan could function as a medium for implementing policies in hazard mitigation plans.

The results could provide a complementary perspective of networks of plan analysis. Cities are increasingly guided by multiple plans. However, if diverse stakeholders involved in the planning process act only in pursuit their own interests and values that influence their policy preferences, the networks of plans would be less integrated and inclusive (Finn et al. 2007). Berke et al. (2015) developed a resilience scorecard that could evaluate the extent of plan integration. They found that local plans were not well integrated (e.g., land use and hazard mitigation), and some local plans surprisingly increased the physical and social vulnerability in the target areas. The proposed plan evaluate framework can complement existing approaches to better examine networks of plans related to environmental hazards and urban resilience in a perspective of stakeholder policy preference incorporation. Based on the results above, we found that the transportation plan captured the diverse stakeholder policy preferences least effectively and had the lowest level of policy consistency with the hazard mitigation plan. If transportation plans and transportation planners are not aligned with other plans and planners in either values or policies, we may end up perpetuating a transportation system that exacerbates rather than mitigates climate change-related flooding. One good example is the increase in flood risk due to the development in the upstream of Addicks and Barkers reservoirs. The development caused the loss of green land, and subsequently contributed to water release from the reservoirs in Hurricane Harvey. The release of water led to the unprecedented flooding in the west Houston area.

The release of water from the reservoirs was to protect the reservoirs from breaching that may lead to catastrophic losses. However, the high water level in the reservoirs was not only due to the rainfall by Hurricane Harvey, but also due to the triggered urban growth and development because of the newly constructed segment of State Highway 99 (SH-99) (Li et al. 2019). The inconsistent transportation plans and flood control plans led to increased development and urban sprawl near the segment of SH-99 and around reservoirs. Such development led to more paved areas and eliminated the wetlands that could store and absorb the water without increasing the burden of the reservoirs.

The results also highlighted the divergent policy preferences of diverse stakeholders in the resilience planning process. The environmental conservation plan and the hazard mitigation plan captured the preferences of stakeholders in the transportation sector the least. The transportation plan also did not incorporate the preferences of stakeholders from other sectors. Resilience planning, however, requires collective actions (e.g., communication, coordination) among diverse stakeholders across IUSs. Plan contradictions and inconsistencies would arise due to insufficient coordination among diverse stakeholders. Evaluation of diverse stakeholder policy preferences in networks of plans would effectively facilitate stakeholder preference incorporation across plans and improve the level of collective actions among stakeholders across IUSs in the resilience planning process.

Concluding Remarks of Research Study C

This study proposed and tested a plan evaluation framework. The proposed value-based plan evaluation framework and its application to four selected plans in the context of Houston, Texas, have multiple methodological and theoretical contributions. First, the presented framework enables the quantitative evaluation of the extent to which plans incorporate diverse stakeholder policy preferences in resilience planning of IUSs. The framework enables better incorporation of stakeholder policy preferences in various plans, which in turn would lead to better implementation of policies across networks of plans. Second, the proposed policy consistency index enables comparison between the level of policy consistency across plans in terms of diverse stakeholder policy preference incorporation. The evaluation of stakeholder policy consistency across networks of plans is essential in collective action problems, such as flood risk reduction and urban resilience. Third, the proposed framework could help identify conflicts of stakeholder preferences in the planning process and facilitate the development of strategies to reconcile the conflicts and achieve shared preferences among diverse stakeholders.

Limitations of Research Study C and Future Directions

We would like to note some limitations in this study. First, we did not consider citizen participation in the planning process. Existing studies showed that citizen participation has been playing an increasingly important role in community development, policy analysis, and public management (Mannarini and Talò 2013). Future research could account for citizen participation in the planning process due to various policy preferences based on the examination of developed indicators of citizen participation (Morrissey 2000). While we did not consider citizens’ policy preferences in this study, the proposed methodology could be used in future studies to examine the extent to which citizens’ policy preferences were incorporated across various plans and to what extent their policy preferences differed from other stakeholder groups. Second, stakeholder policy preferences are not static but evolve over time (Iii et al. 2011; Johnson et al. 2013; Willigers et al. 2009). This study, however, did not consider the evolutions of stakeholder policy preferences based on the survey results. Future research could conduct a longitudinal study to account for the evolutions of stakeholder policy preferences.

CHAPTER V

STUDY D: A META-NETWORK FRAMEWORK FOR ANALYSIS OF ACTOR-PLAN-TASK-INFRASTRUCTURE NETWORKS IN RESILIENCE PLANNING AND MANAGEMENT [**]

This study proposes a meta-network framework for modeling dependent Actor-Plan-Task-Infrastructure networks. The proposed framework is able to quantitatively evaluate the extent to which coordination among actors and integration among plans reflect infrastructure dependencies in resilience planning. Since resilience planning involves multiple actors and various plans, it is critical that actor coordination and plan integration are consistent with infrastructure dependencies. The absence of objective evaluation of infrastructure dependencies during the resilience planning process inhibits the formation of integrated plans that reduce the vulnerability to hazards. The proposed meta-network framework provides quantitative measures to identify missing links in actor coordination and plan integration. The application of the proposed framework is indicated using a case study of Houston in the context of flood resilience planning. Three different regional plans representing infrastructure development, flood control and environmental conservation are examined to map the Actor-Plan-Task-Infrastructure networks. The results of the analysis reveal that: (1) dependencies between flood control and transportation infrastructure systems are not fully considered in the studied plans,

---

[**] This chapter is submitted and published in the journal of "Natural Hazards Review" as an individual paper (Li, Q., Dong, S. and Mostafavi, A., 2020. Meta-network Framework for Analysis of Actor-Plan-Task-Infrastructure Networks in Resilience Planning and Management. Natural Hazards Review, 21(2), p.04020016.). Reprint with permission from ASCE.

which leads to inconsistent plans, policies and tasks; (2) the plans do not highlight the required level of coordination among actors to implement the plans based on the consideration of infrastructure dependencies. The application shows the capabilities of the proposed framework for modeling Actor-Plan-Task-Infrastructure dependencies and evaluating the gaps in actor coordination and plan integration related to resilience planning of dependent infrastructure. The proposed framework not only contributes to the dependency modeling among actor, plan, task, and infrastructure networks, but also provides a new means to help stakeholders improve their coordination, as well as plan integration by taking infrastructure dependencies into account in resilience planning.

Introduction

Urban systems currently face increasing challenges of disturbance and uncertainty caused by nature, technology, and human dynamics (Norris et al. 2008; Taylor et al. 2015). Natural hazards, in particular, have posed a great threat to the well-being of our society (Palmisano et al. 2018; Shen et al. 2018). With increasing frequency over the past decade, extreme forces of nature such as hurricanes, sea-level rise, earthquakes, and flood events have occurred. For example, Texas was hit by Hurricane Harvey in 2017; California and Mexico City have endured earthquakes and wildfires (Murnane 2006; Siegel 2000); South Florida and 52 United States counties along the northern Gulf of Mexico faced the challenge of rising sea-levels (N. Lam et al. 2016; Sallenger et al. 2012). The increasing frequency of natural hazards requires integrated resilience plans based on the understanding of complex dependencies among urban systems (Godschalk 2003; Sutley et al. 2017).

Resilience planning in dependent infrastructure systems involves multiple actors and various plans and requires essential coordination among actors (e.g., organizations, agencies or stakeholders) and integration of their plans across different sectors (e.g., flood control, transportation, environmental conservation) (Berke et al. 2015; Malecha et al. 2018; Rasoulkhani and Mostafavi 2018b; Woodruff and Regan 2019). Woodruff and Regan (2019) found that coordination among a wide range of actors in the resilience planning process would highly improve the quality of resilience plans. Contradictions and inconsistencies between various plans, on the other hand, would be expected in the absence of essential coordination among actors (Finn et al. 2007). Actors from different urban sectors usually have different focuses in infrastructure development, hazard mitigation, and environment conservation (Hughes et al. 2003). For example, it is common for transportation sectors to be more concerned about infrastructure development to solve traffic congestion, while flood control entities and environment conservation groups focus more on hazard mitigation and environment preservation. The problem arises when each infrastructure system is managed and operated based on plans and policies that developed by uncoordinated actors who has limited comprehension of infrastructure dependencies (Bodin 2017). Consequently, plans (e.g., land use, transportation, flood control, and environmental conservation) are not fully integrated and do not take into consideration the underlying infrastructure dependencies. Land use approaches would be weakly integrated in flood control plans, leading to infrastructure development in hazard prone areas (Berke et al. 2015). Conflicting plans and policies will severely affect the effectiveness of infrastructure resilience planning, design, and operation process (Malecha et al. 2018). Constructing a new highway segment such as Texas State Highway 99 (SH 99) can encourage infrastructure development when it is located in previously undeveloped hazard areas (Berke et al. 2015). The lack of integration among various plans (e.g., flood control and transportation plans) would lead to negative cascading effects and unintended consequences that make the whole urban system more vulnerable to hazards (Malecha et al. 2018).

Hence, to improve actor coordination and plan integration in resilience planning of dependent infrastructure, it is essential to model and analyze Actor-Plan-Task-Infrastructure networks. The actor network represents coordination between local and regional actors in infrastructure systems where actors are organizations, agencies or stakeholders from different urban sectors (e.g., flood control, transportation, and environmental conservation). The plan network represents relationships between local and regional plans and policies, while the task network captures dependent tasks and projects included in various plans and policies. The infrastructure network represents dependencies among infrastructure assets. Actor, plan, task, and infrastructure networks are dependent and influence each other. For example, actor networks develop and implement plans and policies. Plans and policies includes tasks and projects that would influence infrastructure development and their dependencies. Therefore, modeling and analyzing dependencies among actors, plans, tasks and infrastructure is important for evaluating the extent of actor coordination, plan integration and task consistency in resilience planning of infrastructure systems (Rasoulkhani et al. 2017; Rasoulkhani and Mostafavi 2018a). However, a methodology for modeling and evaluating dependencies among Actor-Plan-Task-Infrastructure networks is still missing. In the existing literature, these networks are often studied in isolation. Social science studies dependencies among actors using actor networks vis-`a-vis planning and governance (Dempwolf and Lyles 2010; Heaney and McClurg 2009; Ward and Pede 2015), urban planning studies plan dependencies by networks of plans (Berke et al. 2015; Krippendorff 2011; Lyles and Stevens 2014), and engineering studies infrastructure dependencies by modeling infrastructure networks (Dueñas-Osorio et al. 2007; Dunn et al. 2018; Gao et al. 2010). Studies related to infrastructure dependencies do not account for actor and plan networks that would drive infrastructure dependencies (Ip and Wang 2011; Koetse and Rietveld 2009; Nowell et al. 2015; Van Vliet et al. 2012). Despite existing efforts to study dependencies between actors and plans in resilience planning, the extant methodologies do not offer an objective approach to examining how infrastructure dependencies are considered in terms of actor coordination and plan integration. For example, in the plan resilience scorecard, plans and policies are evaluated for their effects on social and physical vulnerability in targeted areas, yet infrastructure dependencies are not considered in those areas (Berke et al. 2015, 2019; Malecha et al. 2018).

To bridge this methodological gap, this paper proposes a meta-network framework for modeling dependencies among actor, plan, task and infrastructure networks. The proposed framework determines potential Actor-Plan-Task-Infrastructure networks based on the ideal situation in which actor coordination and plan integration are consistent with infrastructure dependencies. The potential networks are then compared with the actual networks that reflect existing Actor-Plan-Task-Infrastructure networks. Accordingly, missing links between actors, plans and tasks can be identified. Based on the identified missing links, quantitative measures are introduced to assess the extent of actor coordination, plan integration and task consistency in terms of infrastructure dependencies. The application of the proposed framework is then demonstrated in a case study of Houston.

Meta-network Framework

The proposed meta-network framework is built by three activities: (1) conceptualize urban systems as a meta-network, (2) determine the potential meta-network, and (3) evaluate actor coordination and plan integration (illustrated in Figure 24) Each component is described in the following sections.

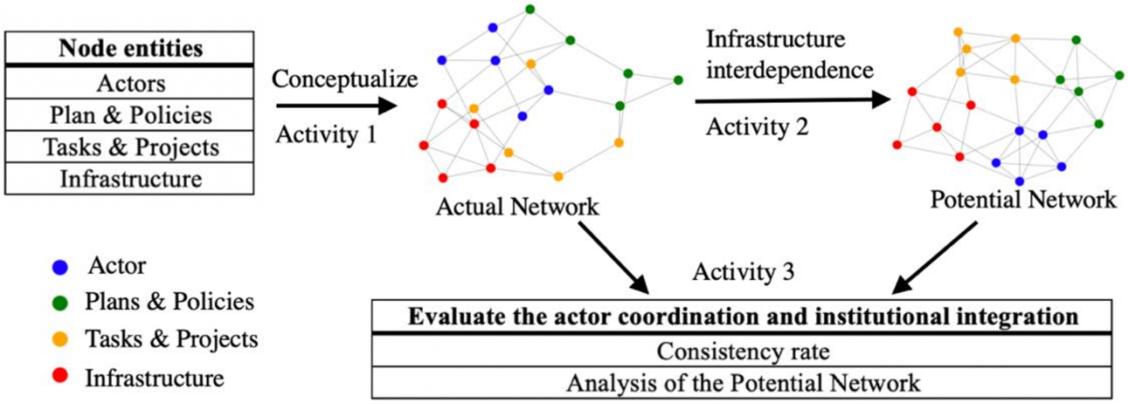


Figure 24 Activities for the meta-network framework.

Conceptualize Urban Systems as a Meta-network

Meta-network analysis is an effective approach to studying dependencies among systems with heterogeneous nodes and links. Different from traditional social network analysis (SNA) that focuses on homogeneous networks, meta-network analysis enables building complex networks with multi-types of nodes and links. Krackhardt and Carley (1998) developed a meta-network analysis framework to capture the structure of an organization with a set of nodes (e.g., people, resources, and tasks) and links among them. Schreiber and Carley (2005) mapped the meta-network of NASA with the nodes of people, technology, knowledge and tasks to study the organizational risks (e.g., ineffective leadership and communication barriers) in NASA. Recently, meta-network analysis was used to map coupled human-physical network to study disaster management for urban resilience (Fan and Mostafavi 2019; Zhu and Mostafavi 2018). Zhu and Mostafavi (2018) constructed the disaster response meta-network composed of organization, information, resource, and task networks to understand the complex process involving various interconnected organizations, information, resources, and tasks. Through identifying the critical nodes in the conceptualized meta-network, effective planning strategies in disaster response planning could be developed. Fan and Mostafavi (2019) studied disaster management system-of-systems (DM-SoS) by establishing the meta-network framework including stakeholder, information, resource, operation, and policy networks. The proposed framework introduced quantitative indicators (e.g., information accessibility, the capacity of self-organization, and effectiveness) to assess the performance of DM-SoS. In this paper, we propose a meta-network framework with four types of node entities and eight kinds of links to model the dependencies among networks of actors, plans, tasks and infrastructure. The proposed framework studies the required level of actor coordination and plan integration accounting for infrastructure dependencies in resilience planning. Figure 25 illustrates the elements of proposed meta-network.

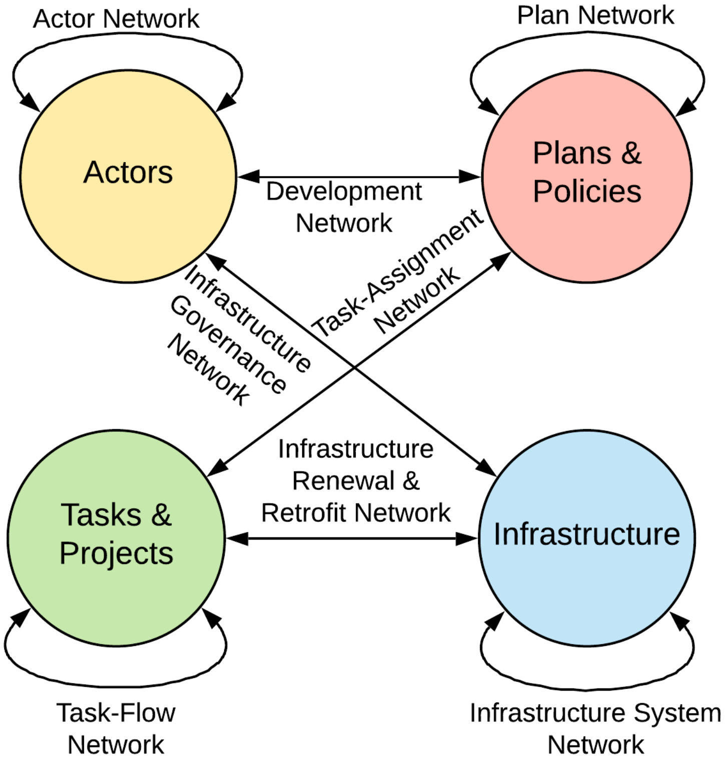


Figure 25 Proposed the meta-network embedded in urban systems.

The four types of node entities in the proposed framework are Actors, Plans & Policies, Tasks & Projects and Infrastructure. Actors represent organizations, agencies or social groups from different urban functions such as transportation, flood control, planning associations and environment conservation groups. In the context of resilience planning, some actors develop plans, and some actors govern the infrastructure based on the plans. Plans & Policies are the institutions developed and used by different Actors. Examples of plans include flood control plans, transportation plans, and environmental conservation plans. For example, transportation agencies would develop plans to improve transportation systems, and flood control agencies would develop flood control plans to reduce flood risks. Tasks & Projects are components of Plans & Policies. Examples of tasks and projects include road extension and retention basin construction, which would affect the status and dependencies of Infrastructure. In the meta-network framework, the Infrastructure entity represents not only physical infrastructure, such as pump station, reservoirs, and roads, but also green infrastructure, including bayous, prairies and creeks. Abstraction and analysis of node entities should be implemented at a specific level (e.g., regional level or local level) when conceptualizing urban systems as a meta-network (Janssen et al. 2006).

Table 16 Types of Links between the Actors of Meta-Network.

Links	Interdependencies represented by the links
A – A	Which Actors have coordination with one another
A – I	Which Actors govern/are responsible for which Infrastructure
A – P & P	Which Actors enact which Plans & Policies
P & P – P & P	Which Plans & Policies are related to one another
P & P – T & P	Which Plans & Policies develop which Tasks & Projects
T & P – T & P	Which Tasks & Projects are relatd to one another
T & P – I	Which Infrastructure is affected by which Tasks & Projects
I – I	Which Infrastructure depends on/affects one another

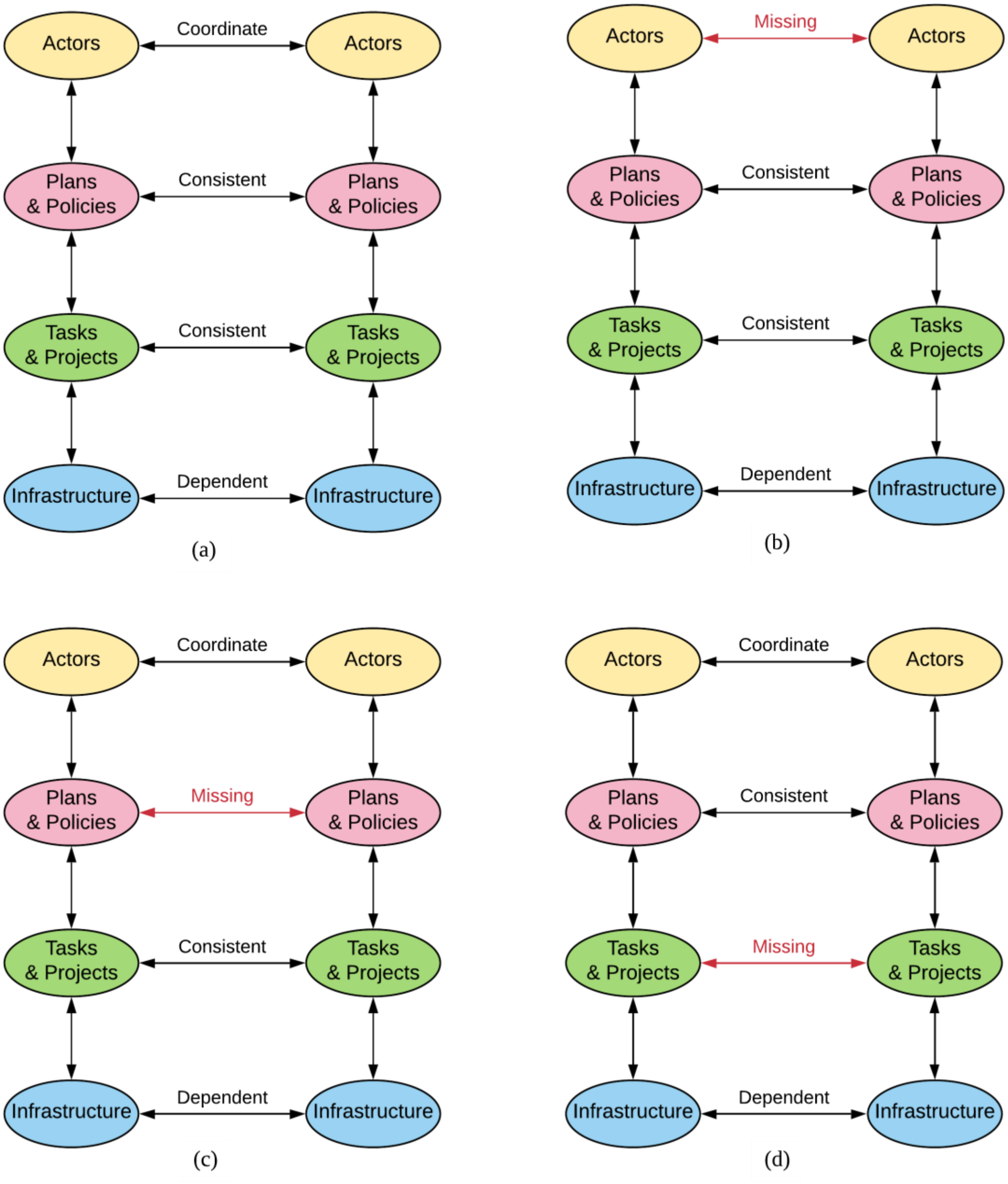
Table 16 shows eight types of links between four types of node entities. Links between Actors represent coordination between two actors when they develop or implement plans and policies. Links between Actors and Infrastructure represent which

Actors are responsible for managing and governing a specific Infrastructure. For example, a transportation actor governs a particular highway, and these two nodes are connected via a link. Links between Actors and Plans & Policies represent what Actors develop or utilize a specific Plans & Policies. Links between Plan & Policies mean that one plan relates to another plan or policy. For example, the transportation plan may relate to the Clean Water Actor because when a project in a transportation plan would affect the natural environment, the project would need permits required by the Clean Water Act. Another example of dependency between Plans & Policies is that when developing a regional transportation plan, the plan incorporates policies from another plan (e.g., local transportation plans or flood plans). Links between Plan & Policies and Tasks & Projects represent that Tasks & Projects are included in Plan & Policies. Links between Tasks & Projects indicate that these Tasks & Projects would influence each other. For example, one task is the prerequisite of another. Links between Tasks & Projects and Infrastructure represent tasks and projects influencing infrastructure. For example, a project for widening a particular flood control channel is represented by a link between the project and the channel node entities. Finally, links between Infrastructure represent various infrastructure dependencies such as functional dependencies (e.g., the electricity system and pump stations) or co-location, which means two components are close enough to affect each other. For example, when a bayou is near a road, the flood water overflows from the bayou could affect the road.

Sources of information can be used to abstract node entities and map the links between them. For example, actors, plans, tasks and projects can be abstracted from the review and analysis of various plans including hazard mitigation, resilience, and infrastructure development plans. Dependencies among infrastructures (e.g., co-location) can be abstracted from spatial maps. The outcome of conceptualizing and mapping of node entities and links enables constructing the actual meta-network for a specific region. In the proposed framework, the conceptualized meta-network includes four types of node entities and eight kinds of relationships embedded in urban systems. The meta-network represents the interaction that actor networks develop and implement plans and policies. Plans and policies include tasks and projects that influence infrastructure development and dependencies. Insufficient coordination among actors and limited consideration of infrastructure dependencies, on the other hand, would lead to inconsistent plans and tasks that lower the effectiveness of resilience planning. To study the required level of coordination among actors as well as consistency among plans and tasks accounting for infrastructure dependencies in resilience planning, we determine the potential network based on infrastructure dependencies to compare with the actual network.

Determine the Potential Meta-network

The meta-network can exist in two basic forms: the potential network and the actual network (Carley 2001). The actual meta-network is obtained from abstraction of the existing node entities and links. The potential meta-network represents the ideal structure that links between various node entities are consistent with infrastructure dependencies. Through comparing the missing links between the potential network and the actual network, the extent to which actor coordination and plan integration reflect infrastructure dependencies could be assessed. Also, how actors should coordinate with each other, how plans should be integrated and how tasks should be implemented to take infrastructure dependencies into better account can be identified through analyzing the potential network. Figure 26(a) illustrates ideal links between nodes of the potential meta-network of urban systems. The process for determining the potential meta-network is based on the infrastructure dependencies identified in the actual infrastructure network. Tasks & Projects relates to the dependent infrastructure and should be consistent with each other; therefore, links between these Tasks & Projects should exist in the potential meta-network. For example, if the bayou and the road are co-located, the tasks implemented on them, such as bayou flood risk mitigation project and expand/widen the road, should be consistent and account for the infrastructure dependency. The related plans, such as hazard mitigation plan and transportation development plan, should be integrated with each other. Moreover, if the Plans & Policies require integration, actors should have essential coordination when developing these plans and policies. For instance, a transportation agency should have essential coordination with flood control department to ensure the plans (e.g., flood control plan and transportation development) are integrated. In the potential meta-network, the links between the actors represent this coordination.



(a) (b)

(c) (d)

Figure 26 The potential network and the actual network; (a) The potential meta-network; (b) Communication absence: missing coordination between actors; (c) Plan inconsistency: plans are inconsistent for tasks acting on dependent infrastructure; (d) Task inconsistency: tasks are inconsistent for dependent infrastructure.

Evaluate Actor Coordination and Plan Integration

Based on the actual network and the determined potential meta-network, the missing links (Figures 26(b), 26(c), 26(d)) in the potential network can be determined to evaluate the extent to which plans, policies and tasks are consistent, and actors are coordinated, accounting for infrastructure dependencies. Furthermore, based on the analysis of the potential networks, the plans needing greater integration, the actors requiring better coordination, and the tasks needing more consistency to take infrastructure dependencies into better account could be identified. Two measures to evaluate actor coordination and plan integration will be introduced below.

<u>Consistency rate</u>: Mapping urban systems as a meta-network enables a large body of network measures, such as density, node centrality (Jackson 2010), clustering (Watts and Strogatz 1998), and community detection (Everitt 2018; Newman 2003b). Carley (2001; 2013) developed some measures for characterizing organizational architectures at the meta-network level, such as resource allocation, access redundancy, and overall task completion; however, still lacking are measures that can assess actor coordination and plan integration in light of infrastructure dependencies. In this paper, three measures are proposed to quantify the extent to which networks of actors, plans and tasks are consistent with infrastructure dependencies. Through comparing the missing links between the actual network and potential network, the consistency rate C reflects the extent of consistency between Plans & Policies (Figure 26(c)), Tasks & Projects (Figure 26(d)), and the coordination between Actors (Figure 26(b)) that accounts for infrastructure dependencies. Consistency rate C is calculated by Equation 8

where L_a denotes the number of links between Actors, Tasks & Projects, and Plans & Policies in the actual network, and L_p represents the number of correspondent links in the potential network.

$$C = \frac{L_a}{L_p} \tag{8}$$

The consistency rate can extend to two other measures. The rate of tasks that do not reflect infrastructure dependencies could be speculated from the consistency rate of tasks (Equation 9). If Tasks acting on the dependent infrastructure inconsistently, will have a negative effect on infrastructure (Figure 26(d)); the measure, affected infrastructure rate, is calculated by Equation 10. In Equation 9, T_u denotes the number of tasks that did not consider infrastructure dependencies, and T_{all} represents the total number of the tasks. In Equation 10, I_a denotes the number of affected infrastructures. It is determined based on the number of infrastructures related to inconsistent tasks. I_{all} is the total number of infrastructures in the meta-network.

$$T = \frac{T_u}{T_{all}} \tag{9}$$

$$I = \frac{I_a}{I_{all}} \tag{10}$$

<u>Analysis of the potential network</u>: The potential meta-network represents the ideal structure that links between node entities are consistent with infrastructure dependencies. Determining the potential network can identify not only the missing links in Actor-Plan-Task-Infrastructure networks, but also critical nodes in the potential network. we employ the measure, node betweenness centrality, in the analysis of the

potential networks, because nodes with higher betweenness centrality are in the important positions to spread the information and maintain coordination (Jackson 2010). Through the analysis of the potential network, actors with higher node betweenness centrality, meaning they require better coordination considering the plan consistency, can be identified. Also, plans and policies with higher betweenness centrality need greater integration accounting for infrastructure dependencies. Tasks and projects with higher betweenness centrality imply that the implementation of these projects would involve more dependent infrastructure. The analysis of each potential network (such as the potential actor network) using node betweenness centrality would help identify critical nodes in the potential networks. These nodes play important roles to improve actor coordination, plan integration, and task consistency in resilience planning based on infrastructure dependencies.

Meta-network Modeling of Urban Systems in Houston Area

To demonstrate the application of the proposed meta-network framework, the research team reviewed transportation, hazard mitigation, and environmental conservation plans in Houston area; the corresponding meta-network was constructed as a case study. In the case study, the meta-network framework was used to examine the network relationships affecting resilience planning in Houston area prior to Hurricane Harvey. We forensically examined different network dependencies resulting in severe physical vulnerabilities during Harvey. In particular, the case study focused on two primary infrastructure systems influencing urban systems to flooding: transportation and flood control infrastructure.

Plan Selection

Three regional plans related to transportation and flood control infrastructure were selected and reviewed to map node entities and their links to build a meta-network model of Houston's resilience planning prior to Harvey. The three regional plans are the 2040 Regional Transportation Plan (RTP), the Gulf-Houston Regional Conservation Plan (RCP), and the Capital Improvement Program (CIP). We selected these plans based on the focus of the case study on transportation and flood control infrastructure.

The latest RTP developed by Houston-Galveston Area Council (H-GAC) provides a guide for maintaining and improving the current transportation system. The RTP also identifies transportation investment priorities. The primary goals of this plan are to improve safety, manage and mitigate transportation congestion.

The Gulf-Houston RCP is developed by environmental, business and governmental entities within the eight-county Houston-Galveston region. The Gulf-Houston RCP is a compilation of regional environmental and conservation projects. The Gulf-Houston RCP identifies conservation needs, collaborative projects and initiatives for improvement of the environmental and economic health of eight-county area.

The CIP developed by Harris County Flood Control District (HCFCD) “provides flood damage reduction projects that work, with appropriate regards for community and natural values”. The goal of the CIP is to create a framework to plan, acquire, design, and construct flood control infrastructure annually. We considered projects before 2018 in this case study.

These three plans can serve as a comprehensive information source to map the elements of the meta-network model. The selected plans represent three main areas affecting resilience planning (e.g., infrastructure development, flood control and environmental conservation). The RTP focuses on infrastructure development to improve transportation systems. The CIP focuses on hazard mitigation and flood control. The Gulf-Houston RCP relates to environmental conservation. The resilience planning requires the integration of infrastructure development, flood control and environmental conservation. To this end, selecting these tree plans would help us evaluate the resilience planning for Houston area. We conduct analysis on the level of actor coordination, plan integration and task consistency in the selected plans and discuss what would be the impacts on infrastructure systems.

Map the Actual Meta-network

The plans were reviewed to manually abstract relevant node entities (e.g., actors, plans, tasks and infrastructure) and their dependencies to map the meta-network model. Nodes in the meta-network were abstracted based on plan statements. For example, a task to expand roadway network—the extension of IH-10W was identified in RTP. Then the node IH-10W was abstracted as infrastructure, and node Expand roadway network was abstracted as a task. In another example, CIP reported a project to excavate the Inwood stormwater basin to reduce flood risks along White Oak Bayou, and the project belongs to the policy Main channel flood damage reduction for the White Oak Bayou. Based on this, we can abstract the infrastructure nodes Inwood stormwater detention basin and White Oak Bayou; task node Excavation of Inwood stormwater detention basin; and policy node Main channel Flood Damage Reduction. Tables A15 to A17 show the extracted nodes from the three plans. (Please refer to Appendix A for abstracted node entity details.)

The links between infrastructure were identified based on their co-location using spatial maps. For example, the Addicks and Barker reservoirs are close to the Interstate 10 (I-10) segment between State Highway 99 and Beltway 8. As the release of water from the reservoirs will affect this segment of I-10, it is represented as a link between the reservoirs and the I-10 segment. In addition, RTP mentions that if the task Expand roadway network directly impacts the protected natural environment, the task Wetland mitigation process must be completed prior to the building of the roadway, in accordance with the Clean Water Act. Therefore, the tasks Expand roadway network and Wetland mitigation process were linked. In another example, CIP stated that the task Little Cypress Creek sub-regional frontier program management relies on the task Cypress Creek overflow management study, and the link between them was established based on this statement. Links between Plans & Policies were identified based on the statement that one plan includes the policy in another plan. For example, RTP incorporated the policies from the state plan—Transportation Improvement Plan. Based on this, the link between RTP and Transportation Improvement Plan was established. The links between Actors were mapped based on the cooperation specified in the plans. For instance, CIP mentioned that HCFCD cooperated with U.S. Army Corps of Engineers (USACE), and the Federal Emergency Management Agency (FEMA). RTP mentioned that H-GAC cooperated with Texas Department of Transportation. RCP mentioned cooperation between conservation groups such as The Nature Conservancy, Houston Audubon, Trust for Public Land, and Galveston Bay Foundation. Table 17 provides more examples of node and link abstraction in selected Plans.

Table 17 Examples of Node and Link Abstraction from Selected Plans.

Statements in the plan	Node abstraction	Link abstraction
Expand roadway system includes the extension of IH-10W and SH 249 (RTP)	I: IH – 10W and SH-249 T & P: Expand roadway system	T – I: Expand roadway system – IH-10W Expand roadway system – SH 249
Main channel flood damage reduction includes a project to excavate the Inwood stormwater basin to help reduce flood risks along White Oak Bayou. (CIP)	P & P: Main channel flood damage reduction T & P: excavate the Inwood stormwater basin I: Inwood stormwater basin, White Oak Bayou.	P & P – T & P: Main channel flood damage reduction - excavate the Inwood stormwater basin T & P – I: excavate the Inwood stormwater basin - Inwood stormwater basin
If expanding roadway system directly impacts the protected natural environment, the wetland mitigation process must be completed prior to the building of the roadway, in accordance with the Clean Water Act. (RTP)	P & P: Clean Water Act T & P: Expand roadway system, Wetland mitigation process	P & P - P & P: RTP – Clean Water Act P & P - T & P: Clean Water Act - Wetland mitigation process T & P - T & P: Expand roadway system - Wetland mitigation process
The four 2040 RTP strategies link the performance measures to both the long-range vision and project selection in the Transportation Improvement Program (TIP).	P & P: Transportation Improvement Program	P & P - P & P: RTP - TIP
Previously completed components of regional and federal projects on White Oak Bayou (in partnership with the U.S. Army Corps of Engineers) prevented damages to about 1,800 homes and businesses that otherwise would have flooded. (RIP)	A: USACE I: White Oak Bayou	A – A: HCFCD – USACE A – I: HCFCD – White Oak Bayou USACE – White Oak Bayou

After abstracting all the node entities and links, we created the actual meta-network model of the study region. Figure 27 shows the mapped actual meta-network model abstracted from three regional plans. The actual meta-network comprises 174 nodes and 559 links in total. Different colors in the meta-network represent actors, plans, tasks and infrastructure. To keep the figure concise, we use number IDs to denote the nodes. The correspondent relationships between the nodes and number IDs are presented in Tables A18 to A22 in Appendix A. The actual meta-network model was then used for evaluating different network relationships and detecting missing links that would negatively affect resilience planning.

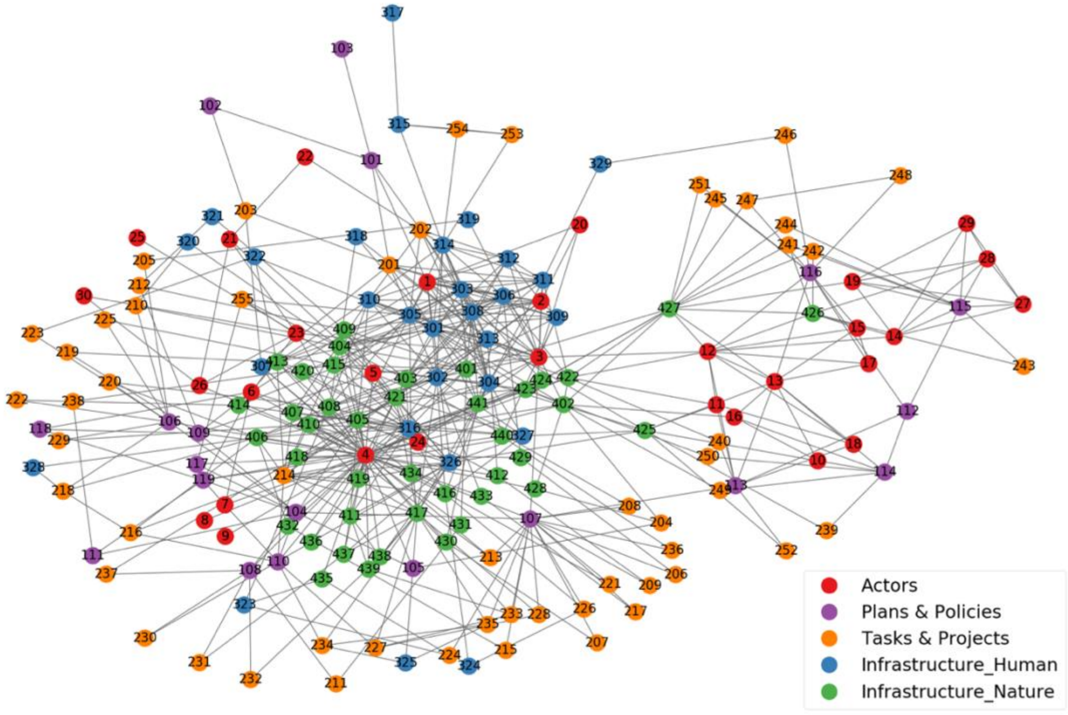


Figure 27 Actual meta-network of the study region: 174 nodes and 559 edges.

Determine the Potential Meta-network

The potential meta-network related to the Houston area was determined based on the approach introduced in Figure 26. First, links identified between infrastructure in the actual network (e.g., infrastructure dependencies) could determine the missing links between tasks, and the potential task network was mapped (Figure 26(d)). For example, task Expand roadway network and task Smith Road channel diversion should link to each other because they will act on dependent infrastructures Beltway 8 and Smith Road channel. Second, potential links between plans and policies were determined based on the dependent tasks in the potential task network (Figure 26(c)). Since tasks Expand roadway network and Smith Road channel diversion are dependent, the related plans and policies, i.e., 2040 RTP and Main channel flood damage reduction, should also be consistent. Finally, the potential actor network was determined by considering the links between plans and policies identified in the potential plan network (Figure 26(b)). For example, as there is a link between the plan and policy, 2040 RTP and Main channel flood damage reduction, actors H-GAC and HCFCD, who developed the referenced plan and policy, should also connect with each other in the potential actor network. Figure 28 shows the determined potential meta-network with 174 nodes and 887 links. A total of 328 more links between actors, plans and tasks were determined in the potential network. Figures 29 to 31 illustrate the actual and potential sub-networks of actors, plans and tasks. The potential network not only enables computing the quantitative measures introduced in the framework, but also enables identifying the important nodes in the potential network through the network analysis. This would inform us which actors play an important role and require greater coordination, which plans need better integration, and which tasks will involve more dependent infrastructure and affect other tasks when implementation.

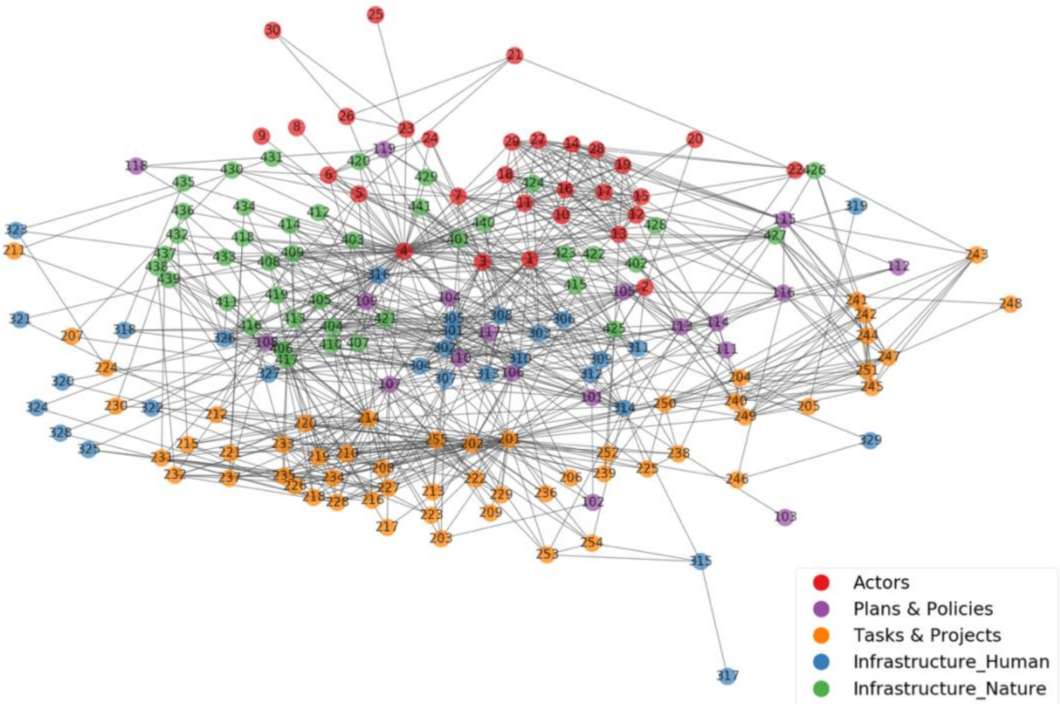


Figure 28 Potential meta-network of the study region: 174 nodes and 887 edges.

Evaluate Actor Coordination, Plan Integration and Task Consistency

After mapping the actual and potential meta-networks, actor coordination, plan integration and task consistency can be evaluated through introduced quantitative measures and potential network analysis. The results of analyses are described below.

Consistency Rate

According to Equation 8, the rates of consistency *C* are calculated and presented in Table 18. Also, based on Equation 9 and 10, the rate of tasks that do not consider infrastructure dependencies *T*, and the affected infrastructure rate *I* were calculated as listed in Table 19.

Table 18 Consistency Rates of Actors, Plans and Tasks.

Network	Number of Links between Actors	Number of Links between Plans	Number of Links between Tasks	Total
Potential Meta-network	147	62	200	409
Actual Meta-network	54	19	8	81
Consistency rate: C	0.367	0.306	0.04	0.198

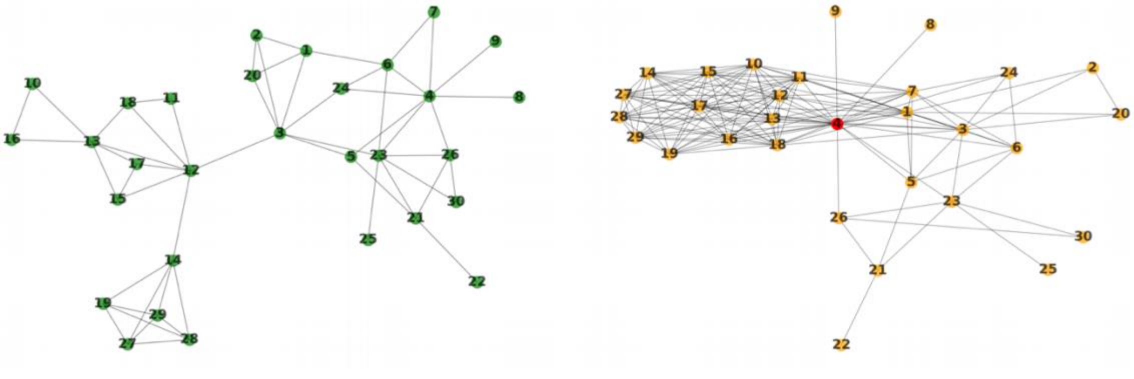
Table 19 Rates of Tasks do not Consider Infrastructure Dependencies and Affected Infrastructure.

Indicators	Values
Total task: T_{all}	55
Number of tasks that did not consider infrastructure dependencies: T_u	52
Rate of tasks do not account for infrastructure dependencies: T	95%
Total infrastructure: I_{all}	70
Number of affected infrastructures: I_a	61
Affected infrastructure rate: I	87%

As illustrated by Table 18 and 19, the consistency rate *C* of Tasks & Projects is 4% and the consistency rates of Plans & Policies and Actors are 30.6% and 36.7%, considering infrastructure dependencies. The consistency rate of Tasks & Projects is less than 5%, and the consistency rates of Plans & Policies and Actors are less than 40%. This means that most of the tasks and almost two-thirds of the plans and policies are not consistent. More than half of the actors have insufficient coordination due to limited consideration of infrastructure dependencies. Table 19 shows that the rate of tasks does not consider infrastructure dependencies is 95% and affected infrastructure rates *I* is 87%. This means that more than two-thirds of the infrastructures would be affected by inconsistent tasks.

Potential Actor Network Analysis

As indicated in Figure 29, the potential actor network has 93 more links than the actual actor network, considering infrastructure dependencies. Links between HCFCD and TxDOT (nodes 4 and 3), HCFCD and H-GAC (nodes 4 and 1), and Katy Prairie Conservancy and Houston Audubon (nodes 17 and 10), were successfully identified in the potential network. This implies that current plans do not specify the required cooperation among actors to be consistent with the infrastructure dependencies. Figure 30(b) illustrates that node 4, HCFCD (the red node) has the highest betweenness centrality in the potential actor network. This means that HCFCD has the most important role in the potential actor network to spread information and perform coordination across different actors. Also, this implies that HCFCD requires more coordination with other actors to take infrastructure dependencies into better account in different plans.

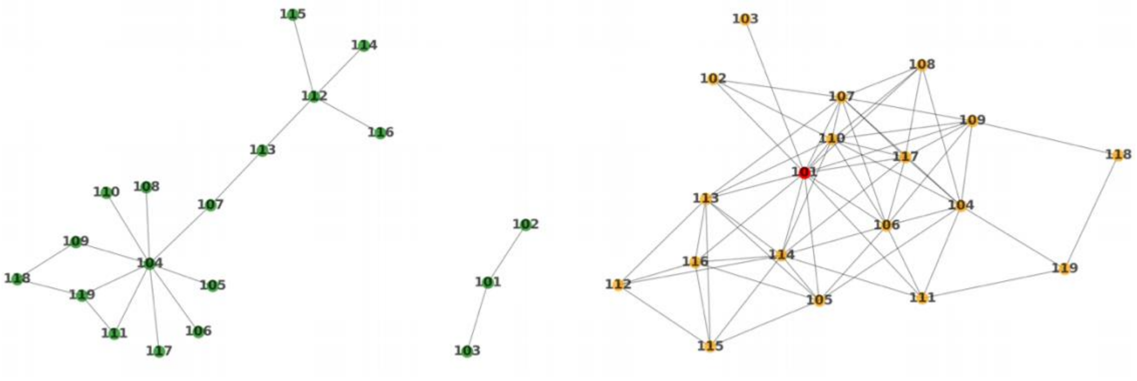


(a) Actual actor network (b) Potential actor network

Figure 29 The actual and potential actor networks; (a) Actual actor network; (b) Potential actor network.

Potential Plan Network Analysis

Figure 30 presents the actual plan network and the potential plan network. A total of 43 more links were identified in the potential plan network. The results show that the flood control plan has no link with the transportation plan in the actual plan network. The links between the flood control plan and the conservation plan are rather limited. The potential plan network shows the requirements for consistent plans accounting for infrastructure dependencies. Links between 2040 RTP and North Canal Bypass Plan (nodes 101 and 117), 2040 RTP and Bayou Greenways Initiative (nodes 101 and 113), and Tributary flood damage reduction and Clean Water Act (nodes 107 and 102) were identified in the potential plan network. The red node (the 2040 RTP) has the highest betweenness centrality in the potential network. This indicates that the transportation plan would greatly affect plan integration and should be more integrated with the flood control and conservation plans.

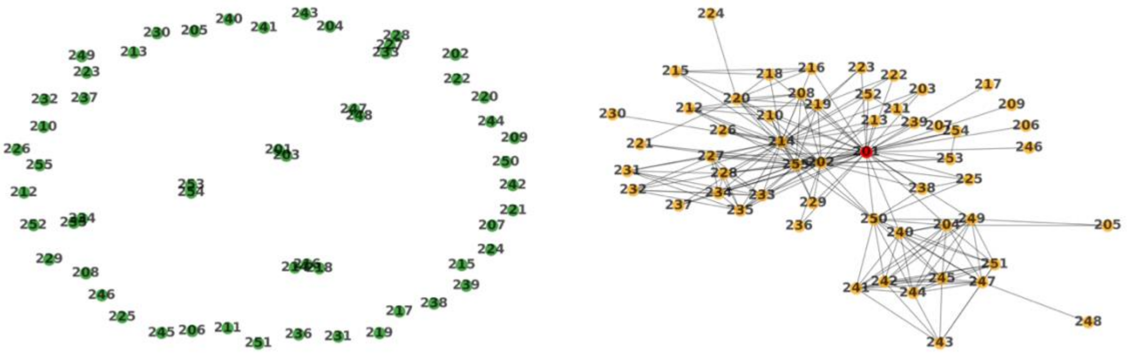


(a) Actual plan network (b) Potential plan network

Figure 30 The actual and potential plan networks; (a) Actual plan network; (b) Potential plan network.

Potential Task Network Analysis

Figure 31 illustrates the actual task network and potential task network. Figure 31(a) indicates that only eight links between Tasks & Projects were identified in the actual meta-network based on plan statements. Although currently there is very limited information in plans and policies regarding dependencies among tasks, the proposed methodology still can identify the potential links between tasks based on the identified infrastructure dependencies. Furthermore, network analysis of the potential task network can identify critical task nodes which involve more dependent infrastructure and tasks need to be more consistent with other ones. Figure 31(b) illustrates that 200 more links in potential networks were identified based on infrastructure dependencies. Links between tasks Expand the roadway network and Greens Bayou federal flood risk management project (nodes 201 and 219), Flood-way right-of-way acquisition on Armand Bayou and San Bernard Woods preserve (nodes 204 and 250), and Bender environmental mitigation bank site permitting, and Construction high flow diversion channel (nodes 213 and 255) were successfully identified. The red node (node 201) that represents the task of Expand the roadway network in RTP has the highest betweenness centrality in the potential task network. This implies that the task Expand the roadway network involves the most dependent infrastructures and is required to be highly consistent with the other tasks.



(a) Actual task network

(b) Potential task network

Figure 31 The actual and potential task networks; (a) Actual task network; (b) Potential task network.

Discussion

The application of the proposed meta-network to three selected plans shows that the consistency rates of Actors, Plans & Policies, Tasks & Projects are 36.7%, 30.6% and 4% respectively. The rates of tasks do not account for infrastructure dependencies and affected infrastructure are 95% and 87% respectively. Based on the potential network analysis, HCFCD was identified that it needs more coordination with other actors to take infrastructure dependencies into better account in different plans. The RTP has the highest betweenness centrality in the potential plan network, indicating that the transportation plan would highly affect plan consistency and should be well integrated with flood control and conservation plans. The task, Expand the roadway network in RTP, involves the most dependent infrastructure and should be well consistent with other tasks.

The results of the quantitative analysis (e.g., consistency rate) and qualitative analysis (e.g., network topology measures of potential networks) imply that dependencies between infrastructures are not fully considered when actors develop plans and tasks. Actors need more cooperation and plans and tasks should take infrastructure dependencies into better account to improve resilience planning and management. The inconsistent plans and tasks will have negative impacts on infrastructure when facing uncertainties such as natural hazards.

In 2017, Hurricane Harvey hit Houston, causing at least $125 billion in damage, largely due to the flooding in the downtown Houston area caused by unprecedented rainfall (NOAA & NHC 2018). Hurricane Harvey exposed previously undiscovered and multi-faceted problems related to the resilience planning of dependent infrastructure systems in the face of ever-growing urban flooding. Disaster-related events occurred during Harvey uncovered the importance of the understudied dependencies among flood control, transportation, and emergency response infrastructure systems. Also, the policy, planning, and resource allocation decision systems that underlie public infrastructure assets were found having limited consideration of infrastructure dependencies. For example, aging flood control reservoirs (i.e., Barkers and Addicks built in 1940s) in West Houston led the operator to release flood water to downstream neighborhoods, causing inundation of more than 9,000 houses (almost all of which did not have flood insurance) for more than two weeks. The decision to release flood water was mainly to protect the reservoirs from breaching (and preventing even more catastrophic losses) as both reservoirs had been identified as “high risk” and the water levels had reached the maximum level. In addition to the unprecedented rainfall, the increased water level in the reservoirs was in part due to the urban development in the reservoir areas surrounding the newly constructed State Highway 99 (SH-99). While the SH-99 project was planned to improve the traffic and mobility in Houston, the lack of integration between transportation plans with flood control and hazard mitigation plans (in the absence of land-use planning in the city) allowed increased development surrounding flood control reservoirs. The increased development led to more pavements and elimination of green land that could reduce the water levels in the reservoirs’ watershed. The water release from the reservoirs also caused prolonged flooding of major roads (e.g., I-10 and Eldridge Parkway) and road closures that reduced the access of emergency responses to certain neighborhoods. There lacks knowledge regarding the infrastructure network characteristics, dependencies between flood control, transportation infrastructure and development patterns in floodplains, and a firmly integrated resilience planning coordinating infrastructure systems. All of these made it difficult to proactively identify and respond to affected neighborhoods.

From this example, it can be seen that the long-term limited comprehension of dependencies among actor, plan, task, and infrastructure networks led to inconsistent plans in Houston. The transportation plan is not integrated with the flood control plan due to insufficient coordination between actors of different urban sectors. The inconsistent plans have caused highly risky infrastructure development in hazard prone areas. Tasks such as constructing SH-99 (included in Expand roadway network) and flood mitigation in the Barker and Addicks area (included in Cypress Creek overflow management study) were implemented without consideration of the infrastructure dependency (such as SH-99 and the Addicks and Barker reservoirs). Because the Addicks and Barker reservoirs are close to the SH-99 segment and flooding from the reservoirs would affect the SH-99 segment, taking this infrastructure dependency into consideration would have avoided infrastructure development near the reservoirs and made the SH-99 segment far away from the reservoirs during the resilience planning process. The proposed methodology identified the missing links between actors, plans, and tasks, juxtaposed against the impacts of Hurricane Harvey in Houston and demonstrated the consequences of not considering infrastructure dependencies in resilience planning.

Concluding Remarks of Research Study D

The research reported in this paper proposed and tested a meta-network framework for modeling dependent Actor-Plan-Task-Infrastructure networks embedded in urban systems. The proposed framework captured dependencies between four node entities is that Actors responsible for Infrastructure develop Plans & Policies which include Tasks & Projects acting on Infrastructure. The captured dependencies aim to study the required level of coordination between actors as well as consistency between plans and tasks to improve resilience planning. The proposed methodological framework can facilitate conceptualization of the potential network and identify missing links between actors, plans and tasks based on infrastructure dependencies. The missing links represent insufficient coordination between actors and inconsistency between plans and tasks that do not reflect infrastructure dependencies in resilience planning. Missing links could lead to contradictions and inconsistencies between plans and may cause more vulnerability to infrastructure (e.g., infrastructure development in hazard prone area). Quantitative measures such as the consistency rate were then calculated to assess the extent of actor coordination, plan integration and task consistency in the actual networks.

To test the proposed meta-network framework, a case study of Houston area was conducted, and four selected plans were reviewed. The actual meta-network of urban systems in the Houston area is mapped by three different regional plans (i.e., the transportation plan, the flood mitigation plan, and the environment conservation plan) and the potential network was determined based on the infrastructure dependencies. The results of the quantitative analysis showed that there is insufficient coordination among actors when developing plans. Plans and tasks are inconsistent and do not fully take infrastructure dependencies into account. Inconsistent tasks and plans would severely affect infrastructure systems. These findings are juxtaposed against the impacts of Hurricane Harvey in Houston to demonstrate the catastrophes when dependencies among infrastructure in resilience planning are missing.

The case study showed the capabilities of the proposed framework in modeling dependent Actor-Plan-Task-Infrastructure networks for evaluating the extent to which actors are coordinated, plans and tasks are consistent in resilience planning of dependent infrastructure. Modeling dependencies among actor, plan, task, and infrastructure networks not only contributes to extant studies of dependency modeling, but also well informs how limited comprehension of infrastructure dependencies would affect actor coordination, plan integrity and task consistency in resilience planning. In addition to the quantitative measures introduced in the proposed meta-network, the qualitative analysis of potential networks could help stakeholders involved in resilience planning identify which actors require additional coordination, which plans need greater integration, and which tasks need more consistency to take infrastructure dependencies into better account. The proposed framework can be adopted to evaluate Actor-Plan-Task-Infrastructure networks in resilience planning in other regions (not limited in Houston area). The results could evaluate the current plan and policy consistency in terms of infrastructure dependencies in the region, and help stakeholders to improve their coordination, as well as plan integration by taking infrastructure dependencies into better account.

Limitations of Research Study D and Future Directions

As an exploratory study, there exits some limitations in the research, and several future directions can be pursued. The proposed framework examines the coordination among actors as specified in the plans. As plans change, actors and coordination among them could evolve as well. Future studies could extend the meta-network framework to consider the extent to which changes in actors and interactions among them would influence the resilience planning process. The proposed meta-network did not consider all the aspects would impact underlying integration of projects, plans and policies (such as economic aspects), which could be promising directions for future research. Also, there should be indirect relationship between Actors and Tasks \& Projects, and Plans \& Policies and Infrastructures. To simplify the model, we just focused on the direct relationships. The indirect links between node entities could be considered in expanding the current framework in the future. For now, plans cannot reflect all the links between node entities, especially in cases of very limited information regarding task flow in plans. Interviews and surveys could supplement the network mapping to fill gaps in data. Also, the proposed framework cannot identify the potential links across the three networks. This would be helpful to uncover the ideal relationships across various node entities. Furthermore, the proposed study only mapped the meta-network based on the plans before Hurricane Harvey. It would be a promising research topic to map and compare the meta-network based on revised plans after Hurricane Harvey. Finally, the network analysis approach proposed in the framework is one of the many ways to study the dependencies among Actor-Plan-Tasks-Infrastructure networks. The development of new methods for the meta-network study can be pursued in future research.

CHAPTER VI

STUDY E: LOCAL INTERACTIONS AND HOMOPHILY EFFECTS IN ACTOR COLLABORATION NETWORKS FOR URBAN RESILIENCE GOVERNANCE

Understanding actor collaboration networks and their evolution is essential to promoting collective action in resilience planning and management of interdependent infrastructure systems. Local interactions and choice homophily are two important network evolution mechanisms. Network motifs encode the information of network formation, configuration, and the local structure. Homophily effects, on the other hand, capture whether the network configurations have significant correlations with node properties. The objective of this paper is to explore the extent to which local interactions and homophily effects influence actor collaboration in resilience planning and management of interdependent infrastructure systems. We mapped bipartite actor collaboration network based on a post-Hurricane Harvey stakeholder survey that revealed actor collaborations for hazard mitigation. We examined seven bipartite network motifs for the mapped collaboration network and compared the mapped network to simulated random models with same degree distributions. Then we examined whether the network configurations had significant statistics for node properties using exponential random graph models. The results provide insights about the two mechanisms—local interactions and homophily effect—influencing the formation of actors' collaboration in resilience planning and management of interdependent urban systems. The findings have implications for improving network cohesion and actor collaborations from diverse urban sectors.

Introduction

Collaboration among diverse actors is critical for effective resilience planning and management of interdependent infrastructure systems (IISs) (Li et al. 2019, 2020a; c). In the context of this study, resilience is defined as “the capacity of human and infrastructure systems to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events (National Research Council 2012).” This definition highlights the importance of human systems affecting urban resilience that involve actors from diverse urban sectors (e.g., transportation, emergency response, environmental conservation, and flood control) with diverse priorities, resources, and responsibilities. For example, actors from transportation sectors would focus on the improvement of roadway networks, while actors from flood control and environmental conservation may focus on flood mitigation and natural resource preservation. Urban resilience improvement is a collective action problem, and therefore needs to account for complex interactions and collaboration among diverse actors (Norris et al. 2008). Existing studies highlight the importance of actor collaboration for planning (Godschalk 2003; Woodruff 2018), emergency response (Comfort 2005; Eisenberg et al. 2020; Kapucu 2005; Kapucu and Van Wart 2006), and recovery (Aldrich 2011; Berke et al. 1993; Gajewski et al. 2011; Rajput et al. 2020) before, during and after urban disruptions. In the context of resilience planning and management of IISs, inadequate collaboration and coordination among diverse actors in the planning process exacerbates a lack of institutional connectedness (Dong et al. 2020) and would lead to contradictions and inconsistencies among networks of plans (e.g., land use, hazard mitigation, and environmental conservation) and increase social and physical vulnerabilities to urban disruptions (Berke et al. 2015, 2019; Malecha et al. 2018). For example, inconsistencies among land use approaches and hazard mitigation plans would allow urban growth in hazard-prone areas (Godschalk 2003).

Existing studies related to disaster management and environmental governance have explored factors that form the collaboration and social ties among diverse actors (Kapucu 2005; Kapucu and Van Wart 2006; Nohrstedt and Bodin 2019). There is empirical evidence that actors with cognitive, organizational, and geographical proximity tend to form collaborations and social ties in inter-organizational networks (Balland 2012; Broekel and Hartog 2013). Matinheikki et al. (2016, 2017) found that actors with shared values tend to establish collaborations in a construction project. Hamilton et al. (2018) found that actors tend to engage in within-level (e.g., regional, local, and state) linkages in environmental governance compared with cross-level linkages. Studies regarding social network analysis demonstrated homophily phenomenon that implies actors with similar attributes tend to establish ties with each other (Gerber et al. 2013; Kossinets and Watts 2009; Shalizi and Thomas 2011). On the other hand, the heterophily phenomenon also exists; studies have shown that actors with dissimilar attributes tend to form social ties (Barranco et al. 2019; Kimura and Hayakawa 2008; Lozares et al. 2014; Rivera et al. 2010). The theory of structural holes in social networks suggests that actors seeking to advance their positions and to broaden their influence tend to form ties with those with different resources and skills (Burt 2004; Lazega and Burt 1995b). McAllister et al. (2015) also argued that the links in networks related to urban governance were shaped based on the choices that actors make either to increase bonding capital, to reinforce shared norms and trusts, or to increase bridging capitals, linking with exotic resources. Asikainen et al. (2020) found that triadic closure (i.e., a structural property representing ties among three actors) and choice homophily are two important mechanisms for the evolution of social networks (e.g., communication networks), and that these two mechanisms are dependent upon each other. Although multiple existing studies explored the mechanisms that form the collaboration and social ties in different fields, such as organizational teams, very few studies investigated the drivers for collaboration in actor collaboration networks for resilience planning and management of IISs. Also, the majority of collective action studies in the context of disaster management and environmental governance focus primarily on the structural properties of actors' social networks and have paid limited attention to local interactions (based on examining motifs as topological signatures) and homophily effect (based on assessment of actor node attributes). The examination of these two mechanisms is essential for understanding and improving essential coordination in actors' networks for resilience planning and management of IISs.

In this study, therefore, our goal is to examine two important mechanisms for actor collaborations: local interactions and homophily effects in resilience planning and management of IISs. We mapped actor collaboration networks for hazard mitigation before Hurricane Harvey based on a stakeholder survey administered in Harris County, Texas. The stakeholder survey captured collaboration among actors in various urban sectors (e.g., transportation, emergency response, flood control, environmental conservation, and community development) involved in hazard mitigation efforts. Also, the survey examined preferences of actors towards different types of flood risk reduction policies (e.g., land use approach, monetary policy, and engineering policies). Based on the mapped collaboration networks, we adopted network motif analysis and exponential random graph models (ERGMs) to examine the drivers for actor collaboration formation. We elaborate on the network motif analysis and ERGMs in the following sections.

Study Context and Data Collection

During Hurricane Harvey, a Category 4 hurricane that made landfall on the Texas Gulf Coast in 2017, flooding due to release of water from Addicks and Barker reservoirs inflicted property and infrastructure damage in Harris County totaling 125 billion, particular in the Houston area. The release of water was necessitated to avoid even more severe damage if the impounded water would have breached the dams (NOAA & NHC 2018). Houston is a flood-prone city: Hurricane Harvey is only one in the long history of hurricane events in the Houston area. From 1935 to 2017, ten major flooding events occurred in the Houston area. Just before Hurricane Harvey, flooding caused by the Memorial Day and Tax Day storms hit Houston in 2015 and 2016, and caused 16 casualties and more than $1 billion in losses (Berke 2019).

After Hurricane Harvey, we administered a stakeholder survey that focused on the Harris County area in Texas. The intent of the survey was to collect, among other things, essential data regarding actor collaboration for hazard mitigation and resilience planning of IISs, as well as actor preferences to different flood risk reduction policies.

To map the actor collaboration network, we identified 95 influential actors involved in resilience planning from different urban sectors, including community development (CD), flood control (FC), transportation (TT), environmental conservation (EC), and emergency response (ER). These actors were listed in the survey roster as the actors that the survey respondents may have collaborated with. We asked the survey respondents the following question to collect the collaboration data: *This question focuses on understanding the collaborations and relationships among key organizations and how they work together in dealing with catastrophic events such as Hurricane Harvey. 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? Note: You may leave a row blank if you have not had any interaction with an organization*. The survey respondents could select one of following options: *1 Daily, 2 Weekly, 3 Monthly, 4 Several times per year, and 5 Not at all.*

Furthermore, we developed flood risk reduction policy actions to investigate preferences of actors from different urban sectors. The developed risk reduction policy actions included land use policies, engineering policies, and monetary policies. We identified these policies based on the strategies for urban flood resilience improvement discussed in existing literature (Berke and Smith 2009; Brody et al. 2013, 2009; Burby 1998; Burby et al. 1999; Godschalk 2003). Table 20 lists the policy actions in the survey. We asked the survey respondents the following question to identify their preferences to the developed policy actions: *Here are some policy actions that could be* *taken to reduce the dangers of future flooding in the Houston area. To the best of your knowledge, please indicate your organization's level of opposition or support for each of the following policy options*. The survey respondents need to select one of following options: *1 Strongly oppose, 2 Oppose, 3 Neutral, 4 Support, and 5 Strongly support.*

Table 20 Flood Risk Reduction Policy Actions in the Survey.

Policy Description	Policy Description
P1: limit new development in flood-prone areas	P9: protect wetland and open space
P2: elevate buildings	P10: improve stormwater systems
P3: strengthen infrastructure design standards	P11: build additional flood water drainage systems
P4: establish and implement infrastructure resilience program	P12: temporarily prohibit development in the period immediately after a disaster event
P5: minimize additional impervious surfaces, such as parking lots	P13: charge impacts fees for development in flood-prone areas
P6: build additional protective dams	P14: limit the development of public facilities and infrastructure in flood-prone areas
P7: build additional protective levees	P15: limit rebuilding in frequently flooding areas
P8: build more catchment reservoirs and retention ponds	P16: buyout or otherwise acquire damaged property

Network Models

We mapped the collaboration among diverse actors involved in hazard mitigation and resilience planning of IISs based on the survey results. We also mapped actor collaboration networks at different collaboration frequency levels, such as daily and weekly collaboration networks. The mapped networks are bipartite networks with two node sets: one comprises actors in the survey roster; the other, survey respondents. The edges in the mapped network represent collaborations among the actors for hazard mitigation and resilience planning of IISs. Figure 32 illustrates the way to map the actor collaboration network. Considering that monthly collaboration was the most representative answer, our analysis focused on the monthly collaboration network.

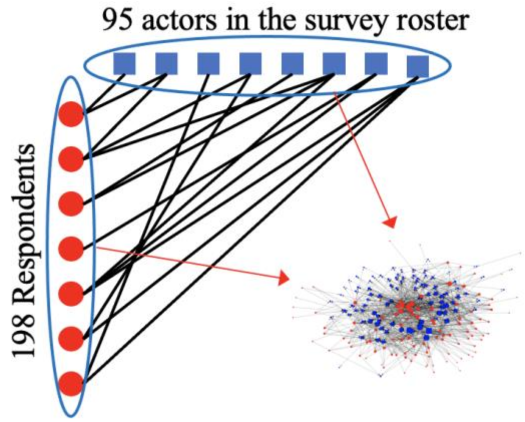


Figure 32 Map actor collaboration network based on survey results.

We assigned the actor preferences to flood risk reduction policy actions as attributes to the nodes of the mapped actor collaboration network. Each node could have one of three preferences states for each policy action: Oppose, Neutral and Support. In the data processing process, we grouped the survey results of “Strongly oppose” and “Oppose” and “Strongly support” and “Support.” Furthermore, we divided survey respondents into five urban sectors based on the organizations and departments they represented: community development (CD), flood control (FC), transportation (TT), environmental conservation (EC) and emergency response (ER) (Dong et al. 2020; Farahmand et al. 2020; Li et al. 2019, 2020c). The urban sectors of actors were also assigned to each node as one of the node attributes in the mapped collaboration network to examine the homophily effect.

Methodology

The examination of the local interactions and homophily effects that form the social ties and contribute to the evolution of social networks are usually regarded as a bottom-up process (Boyd and Jonas 2001). As such, network motif analysis and ERGMs are suitable approaches for revealing the network configurations that encode the importation information related to tie and collaboration formation. Hence, we adopted network motif analysis for the examination of local interactions and ERGMs for the assessment of homophily effects in the actor network in the context of resilience planning and management of IISs in Harris County.

Network Motif Analysis

Network motifs are defined as the network structural elements in complex networks that have significantly larger counts compared with the random networks (Milo et al. 2002). Compared with the global network measures, network motifs reveal the patterns of local interactions, thus playing an important role in understanding the hidden mechanisms behind complex networks. Network motifs have been widely studied in social, neurobiology, biochemistry, financial, and engineering networks. To name a few studies, Dey et al. (2019b) showed that distributions of network motifs (i.e., the patterns of local interactions) are strongly connected with the robustness of systems (e.g., power-grid networks, transportation networks). Saracco et al. (2016) detected the early-warning signs of the financial crisis through analyzing the motifs of the bipartite world trade networks. Schneider et al. (2013) studied the motifs of human mobility network and unraveled the mobility patterns. Gorochowski et al. (2018) studied organizations of 12 basic motif clusters in natural and engineered networks. The results showed that the organizations of motif clusters were different between networks of various domains. Robins and Alexander (2004) examined seven bipartite network configurations to study the small-world effects and distance in corporate interlocking networks. These examples highlight the growing use and capability of network motif analysis to study local interactions and hidden mechanisms that contribute to the robustness, organization, and functionality of complex networks.

In this study, we focused seven basic network configurations of bipartite networks without network projections, because studies showed that network projections may lose important information of bipartite networks (Robins and Alexander 2004; Zhou et al. 2007). Figure 33 illustrates seven network configurations of bipartite networks in which the blue square and the red circle represent two-node sets. Table 21 shows the relative statistics and interpretations of the network configurations.

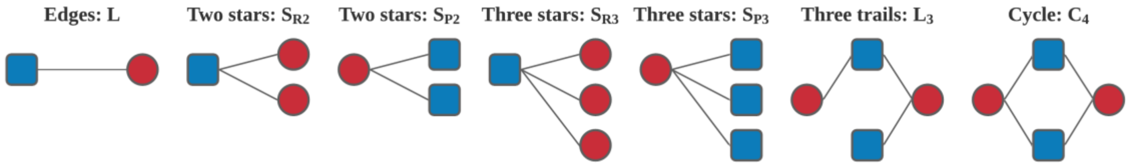


Figure 33 Seven network configurations of bipartite networks: R and P represent two node sets of bipartite networks (Roster actors and Participants respectively in this study); blue squares represent node set R; red circles represent node set P.

Table 21 Statistics of Network Configurations of Bipartite Networks.

Network Configurations	Network Statistics	Interpretation
Edges: L	$\sum_{R=1}^{R}\sum_{P=1}^{P} M_{RP}$	Number of edges in the bipartite network
Two stars: S_{R2}	$\sum_{R=1}^{R}\sum_{P'>P}^{P} M_{RP}M_{RP'}$	Correspondent to an edge between node set P in the 1-mode network
Two stars: S_{P2}	$\sum_{P=1}^{P}\sum_{R'>R}^{R} M_{PR}M_{PR'}$	Correspondent to an edge between node set R in the 1-mode network
Three stars: S_{R3}	$\sum_{R=1}^{R}\sum_{P''>P'>P}^{P} M_{RP}M_{RP'}M_{RP''}$	Correspondent to a triangle between node set P in the 1-mode network
Three stars: S_{P3}	$\sum_{P=1}^{P}\sum_{R''>R'>R}^{R} M_{PR}M_{PR'}M_{PR''}$	Correspondent to a triangle between node set R in the 1-mode network
Three paths: L_3	$\sum_{P'>P}^{P}\sum_{R'>R}^{R} M_{PR}M_{PR'}M_{P'R}(1 - M_{P'R'})$	Reflect global connectivity in bipartite networks
Circle: C_4	$\sum_{P'>P}^{P}\sum_{R'>R}^{R} M_{PR}M_{PR'}M_{P'R}M_{P'R'}$	Local closures in bipartite networks

Notes: M_{RP} represents the value of the elements in the bi-adjacent matrix of the bipartite network. If node R and P are linked, $M_{RP} = 1$. Otherwise $M_{RP} = 0$.

As illustrated in Table 21, Robins and Alexander (2004) introduced two new configurations, three paths and circle, to study the local structures of bipartite networks. It is worth noting that these two configurations would lose the information of local interactions if we conducted network projections. Therefore, it is essential to include these two network configurations for bipartite networks. Robins and Alexander argued that three paths could reflect the global connectivity of the bipartite network and circles represent local closures in the bipartite network. For the bipartite networks with similar sizes and densities, more three paths and fewer circles will increase the levels of connectivity and shorten the average path of the network, while more circles and fewer three paths indicate stronger localized closeness. The bipartite clustering coefficient,

$4 \times C_4/L_3$, could quantify the length of the average path and the strength of local closeness in the bipartite network.

Network motif analysis also involves comparing the numbers of network configurations in the examined network with those in random networks. In this research, we generated random bipartite networks with the same degree distributions and compared them with the examined network (Saracco et al. 2015). The configuration model that generated random graphs had fixed node degree distribution was regarded as one of the most insightful null models in monopartite networks (Chung and Lu 2002). We extended the configuration model to bipartite networks (Saracco et al. 2015). In this analysis, we used sequential importance sampling to simulate bipartite networks with fixed degree distributions (Admiraal and Handcock 2008; Blitzstein and Diaconis 2011).

Although network motif analysis is a powerful method to investigate local interactions and reveal hidden mechanism behind complex networks for collaboration, it does not fully account for node attributes. Therefore, we adopted ERGMs to investigate the extent to which the node attributes affect the ties in the actor collaboration network.

Exponential Random Graph Models (ERGMs)

ERGMs are a family of statistical models that could fit the local structures or network configurations to model the network formations using maximum likelihood estimations (Wang et al. 2009). In a defined network space $\mathcal{Y}$ that includes all possible networks with *n* nodes, a random network $Y \in \mathcal{Y}$, where $Y_{ij} = 0$ or 1 depending on whether the pair of nodes (i, j) are connected or not, then the probability of Y could be determined based on the counts of a set of network configurations. The general form of ERGMs could be written as follows:

$$P(Y=y)=\frac{1}{k(\theta)}\exp\left\{\sum\nolimits_{i=1}^{p}\theta_i S_i(y)\right\}, y\in\mathcal{Y} \tag{11}$$

where $S_i(y)$ represents any user-defined network statistics measured on the network Y, and θ_i are associated parameters to be estimated. $k(\theta)$ is the normalizing constant to ensure the legitimate of the defined probability distribution. Here, we provide a illustrative model inspired by Bomiriha (2014) for the general readers. For an undirected friendship network in which edges represent mutual friendships and has probability p_1 between students live in the same dormitory and probability p_2 between students live in different dormitories. Then the ERGM model for investigating $p_1$and p_2 could be written as follows:

$$P(Y=y)\propto\exp\left\{\theta_1\sum_{i<j}y_{ij}+\theta_2\sum_{i<j}y_{ij}I\{i\ and\ j\ lives\ in\ the\ same\ dormitory\right\} \tag{12}$$

The first set of statistics in Equation 12 represent the number of edges and the second set of statistics is the number of edges connecting nodes living in the same dormitory. Based on this model, we can easily get that p_1 equals to $e^{\theta_1+\theta_2}/(1+e^{\theta_1+\theta_2})$ and p_2 equals to $e^{\theta_1}/(1+e^{\theta_1})$. Furthermore, the coefficient θ_2 could show the homophily (with $\theta_2>0$) or heterophily (with $\theta_2<0$) effect in the studied friendship network. More in-depth discussion regarding the theory of ERGMs could be found in Robins et al. (1999, 2007) and Wang et al.'s works specifically for bipartite networks (2009)

ERGMs provide a powerful tool for generating quantitative evidence for the tie formation process related to network configurations and node attributes. The existing literature has adopted ERGMs to study the dynamics and mechanisms of social tie formations behind different kinds of networks, such as collaborative networks (Nohrstedt and Bodin 2019), partnership networks for urban development (McAllister et al. 2015), inter-organizational knowledge sharing networks (Broekel and Hartog 2013), Facebook friendship networks (Traud et al. 2011, 2012; Wimmer and Lewis 2010), and hospital networks of patient transfers (Lomi and Pallotti 2012). In this paper, we focus on the examination of the homophily effect in the actor collaboration network in resilience planning and management of interdependent infrastructure systems. Homophily in the bipartite networks is represented by two neighbors with the same attributes connected to the same node (illustrated in Figure 34) because they cannot directly connect with each other (Bomiriha 2014). We adopted network statistics developed by Bomiriha (2014) to model homophily for bipartite networks. The adopted network statistics (i.e., b1nodematch and b2nodematch) are included in the R package: *ergm* (Hunter et al. 2008).

Figure 34 Homophily and heterophily effect in bipartite networks. Squares represent the node set of actors in survey rosters; circles represent the node set of survey participants; node colors represent different node attributes.

Results

The network motif analysis shows that the actor collaboration network has strong local interactions. Figure 35 illustrates the network configurations in the observed network and those in the simulated 1000 random models. Table 22 shows the detailed statistics of network configurations in the observed network as well as mean values and standard deviations in the random models.

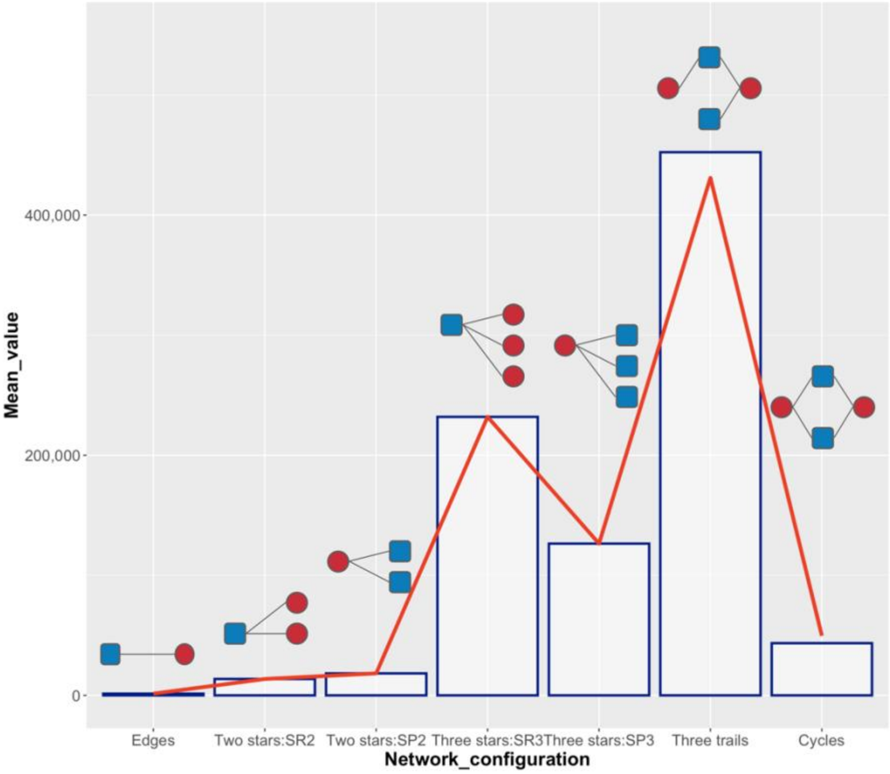


Figure 35 Network configurations in the observed network and null models: bars show the mean value of configurations in generated null models, and line chart shows the counts of configurations in the observed network.

Table 22 Statistics of network configurations in the observed network and null models.

Statistics	Observed Network	Simulated Models	Z-score
Edges: L	1414	1414 (0)	0
Two stars: S_{R2}	13635	13635 (0)	0
Two stars: S_{P2}	18302	18302 (0)	0
Three stars: S_{R3}	231964	231964 (0)	0
Three stars: S_{P3}	126400	126400 (0)	0
Three trails	430999	452387 (1393)	-15.4
Cycle	49626	43464 (946)	+6.51
Clustering Coefficient: $4 \times C_4/L_3$	0.46	0.384 (0.001)	+76

Notes: for the simulation models, numbers in the parentheses are standard deviations and number outside the parentheses are mean values

We can find from Figure 35 and Table 22 that the observed actor collaboration network has significantly fewer three trails (Z-score: -15.4) and more cycles (Z-score: +6.51) compared with the simulated random models. Also, the local clustering coefficient of the observed actor collaboration network is significantly higher (Z-score: +76) than the simulated random models. Apparently, the algorithm that we applied, *Networksis* package in R, fixed the number of edges, two stars, and three stars to generate the random models with same degree distributions (Admiraal and Handcock 2008). The results of the motif analysis indicate that: (1) there are hidden mechanisms and additional social processes to form the collaborations among actors due to significantly different counts of three trails and cycles compared with the random models; and (2) the observed actor collaboration network has a long average path length and strong local closeness due to its fewer three trails, more cycles, and higher clustering coefficient compared with the random models. The results imply that the formations of the actor collaborations are due to strong local interactions, such as collaborations in the same urban sectors or collaborations among actors with same policy preferences. Also, collaborations outside the local clusters are limited due to their long average network path length. The ERGMs could help in further investigations of the factors affecting the actor collaboration.

The ERGMs demonstrate both significant homophily effects and heterophily effects for actor collaboration in resilience planning and management of IISs. The results show the significant homophily effects within the transportation sector, significant heterophily effects within the emergency response sector, and varied homophily and heterophily effects due to different flood risk reduction policy actions. This finding implies that: (1) the actors in the transportation sector are less likely to build collaboration ties with actors from other urban sectors; and (2) emergency response actors are likely to form collaboration ties with actors of other sectors. Table 5 shows the estimated coefficients of variables in ERGMs. We include the Markov Chain Monte Carlo (MCMC) diagnostic plots in the Appendix B. The plots were obtained from randomly generated networks from the fitted models. The MCMC diagnostic plots showed evidence of random variation and approximately normal-shaped distributions centered at zero, which are consistent with good performance in model fitting (Bomiriha 2014).

Table 23 Estimated Coefficients of Variables in ERGMs.

Variables	Estimate	SD	*p*-value
Edges	-2.8619	0.1598	<0.0001***
Urban Sector: CD	0.145608	0.3075	0.6358
Urban Sector: EC	-0.0738	0.2755	0.7887
Urban Sector: ER	-0.9879	0.2830	0.00048***
Urban Sector: FC	0.0064	0.2801	0.9818
Urban Sector: TT	1.2971	0.2948	<0.0001***
P1: support	-1.5173	0.2124	<0.0001***
P2: support	0.5311	0.1527	0.0005***
P3: support	-0.3806	0.2123	0.0730*
P4: support	-0.0070	0.2126	0.9739
P5: support	0.1821	0.1493	0.2225
P6: support	-0.1374	0.1585	0.3859
P7: support	-0.8195	0.1578	<0.0001***
P8: support	1.1925	0.1971	<0.0001***
P9: support	0.6813	0.1533	<0.0001***
P10: support	-0.4283	0.2378	0.0717*
P11: support	0.8013	0.2522	0.00015**
P12: support	-0.6022	0.1451	<0.0001***
P13: support	0.1483	0.1353	0.2729
P14: support	-0.7729	0.1651	<0.0001***
P15: support	0.4627	0.2130	0.0298**
P16: support	1.4522	0.1755	<0.0001***

Note: ***significant at 99%, **significant at 95%, *significant at 90%; here support combines survey response strongly support and support.

We can observe from Table 23 that the probability of edges is $e^{-2.8619} = 0.057$, excluding all the homophily effects in the table, which is lower than the density of the observated network: 0.0756. This result implies that the structure of the observed network is shaped by homophily effect, which is consistent with the results of network motif analysis that the network showed a strong local closeness effect (actors of the same sector are more likely to collaborate with each other). Also, we found that actors from the emergency response sector (ER) showed significant heterophily effects. When an actor from ER collaborates with an actor in the survey roster, another actor from the emergency response sector would have reduced probability ($e^{-2.8619-0.9879}$ = 0.021) to collaborate with the same actor in the survey roster. This result is consistent with the real situation that actors from the emergency response sector usually collaborate with actors from other sectors (e.g., flood control and transportation sectors) for hazard mitigation during disasters. Furthermore, the actors from the transportation sector (TT) showed significant homophily effect. When an actor from the transportation sector collaborates with the actor in the survey roster, another actor from the transportation sector would have increased probability ($e^{-2.8619+1.2971} = 0.209$) to connect with the same actor in the survey roster. This result shows strong local interactions in the transportation sector. The results are also consistent with our former studies regarding actor collaboration within and across different urban sectors for hazard mitigation and resilience planning of IISs (Li et al. 2019). Actors from the transportation sector showed the highest within-sector collaboration, while actors from the emergency response had highest across-sector collaborations. However, we cannot see significant homophily effects in other urban sectors, such as the community development (CD), environmental conservation (EC) and flood control (FC) sectors. This result may imply that the formation of collaboration is not purely due to the organizational proximity.

We also found significant heterophily effects in some flood risk reduction policy actions including P1 (Limit new development), P3 (Strengthen infrastructure), P7 (Build levees), P10 (Improve stormwater system), P12 (Temporarily prohibit development after disasters), and P14 (Limit development of public facilities). The actors have preferences to these policy actions had significantly reduced probability to collaborate with the same actors in the survey roster. Based on the structural hole theory, this heterophily effect may suggest collaboration among these actors was sought to increase bridging capitals, to seek exotic resources and skills to advance their positions, and to broaden the influence in the network (Burt 2004; Lazega and Burt 1995b; McAllister et al. 2015). We also found significant homophily effects in some flood risk reduction policy actions, including P2 (Elevate buildings), P8 (Build reservoirs/retention ponds), P9 (Protect wetlands/open space), P15 (Limit rebuilding in frequent flooding areas), and P16 (Buy out or acquire property). The actors indicating preferences to these policy actions had a significantly increased probability to collaborate with the same actors in the survey roster. The intent of collaboration among these actors was to increase the bonding capital and to reinforce shared norms and trusts (McAllister et al. 2015).

Discussion

The results did not indicate that the urban sectors of actors were a pure driver to form the collaborations among actors. Actors from the flood control, environmental conservation, and community development sectors did not show significant homophily effects in formation of ties. The results indicated that actors from emergency response sectors had significant collaboration with actors from other urban sectors. Previous studies showed that emergency response actors, such as Houston Fire Department, Harris County Office of Emergency Management, and Texas Department of Public Safety, collaborated with actors from other sectors, including environmental conservation, community development, and transportation sectors, for first response and recovery during and after disasters (Li et al. 2019). Existing studies also highlighted the importance of collaboration among actors from diverse sectors for effective emergency response and disaster recovery (Aldrich 2012; Campanella 2006; Gajewski et al. 2011). The results also showed strong within-sector collaborations for actors from the transportation sector. The transportation sector in Texas has great and wide-ranging authority and is a leading voice in infrastructure development driven by real estate development. Transportation planning in Texas, however, lacks resilience metrics for the long run. Furthermore, the transportation sector has its own planning and environmental affair divisions, which may contribute to its limited collaboration with other urban sectors. The results of network motif analysis showed that the collaboration network has a long average path length and strong local closeness, which also implied that actors from the transportation sector have strong local interactions but limited collaboration with actors from other sectors. A lack of collaboration with actors from the flood control sector, however, may lead to urban growth without compatible investments on flood control infrastructures. Also, insufficient collaboration between flood control and transportation sectors may lead to infrastructure development in hazard-prone areas.

The results of network motif analysis and homophily effects of actors from urban sectors in ERGMs are consistent with the planning background in the Houston area. Houston repeatedly suffers from extensive damage due to major flood events (Boburg and Reinhard 2017; Patterson 2017). One major reason is rapid urban growth without holistic planning for flood risks. On one hand, Houston plans growth primarily by developing major institutional projects, building expansive infrastructure networks, and encouraging neighborhood-level planning through super neighborhood organizations (Neuman and Smith 2010). Also, Houston adds density bonuses to encourage development in the urban core (Fulton 2020). Although these policies support population growth (Masterson et al. 2014b; Qian 2010), they also exacerbate flooding vulnerability (Zhang et al. 2018). On the other hand, Houston mitigates flood risk with projects such as the Bayou Greenways Initiative to protect and enhance the network of connected open spaces along bayous (Blackburn 2020), development of structural surge infrastructure, and coastal ecosystem enhancement along Galveston Bay (Blackburn 2017), construction and restoration of detention ponds, supporting home buyouts (Harris County Flood Control District 2017), and retrofitting critical flood control infrastructures through the Hazard Mitigation Plan (Harris County Flood Control District 2017). Planning in Houston, however, is driven largely by the real estate development serving the desire for economic growth. Houston lacks a compatible planning crosswalk between urban growth and the investment on flood control infrastructure, which requires the involvement and collaboration of diverse stakeholders from urban sectors and scales. The findings of this study showed the need for a greater cross-sector collaboration to expand local interactions, as well as the important roles certain actors could play to span boundaries and bridge ties among actors of various sectors with similar and dissimilar preferences to flood risk reduction policy actions.

Furthermore, we found both significant homophily and heterophily effects in actor preferences to flood risk reduction policy actions in ERGMs. The results indicated mixed mechanisms for collaboration among actors. The heterophily effect indicates that a part of actor collaboration was to increase the bridging capitals, to seek exotic resources and skills to advance the positions, and to broaden the influence in the network. The involved actors usually play a brokage role in the collaboration network, helping connect different actors from diverse urban sectors. Based on network measures, such as betweenness centrality, we can identify these actors in the collaboration network (Li et al. 2020c). The homophily effect indicates that a part of collaboration was to increase bonding capitals, reinforcing shared norms and trusts. The involved actors usually are in the core of networks or local clusters. We can identify these actors in the collaboration network through core-periphery analysis and community detection (Li et al. 2020c; b). The ERGMs provide insights into the mechanisms for collaboration among diverse actors, helping to develop strategies to increase network cohesion and to improve collaboration among actors from diverse urban sectors.

The results of the study highlight some resilience characteristics embedded in human systems for urban resilience governance. The first is multi-scale governance (Paterson et al. 2017; Wagenaar and Wilkinson 2015). Urban resilience requires multi-level collaborations across complex boundaries at social, physical, and ecological dimensions (Boyd and Juhola 2015; Li et al. 2020a). Also, resilience planning is the outcome of interdependent plans at different scales (e.g., city, regional, state, and federal). In a study of resilience practitioners in 20 cities, Fastiggi et al. (2021) pointed out that external collaborations, such as multi-disciplinary consultants, advisory committees, resilience consortiums, and peer networks, would be of great help in improving multi-governance for urban resilience governance. Another resilience characteristic is the knowledge co-production and trust (van der Jagt et al. 2017). Existing literature stressed the importance of diverse stakeholder engagement to improve knowledge co-product and trust in urban resilience governance (Graversgaard et al. 2017; Nutters and Pinto da Silva 2012; Watson et al. 2018; Wiesmeth 2018). The inclusion of diverse stakeholders across various urban sectors would improve the collective understanding of complex systems, solve conflicts, and enhance shared values.

Furthermore, given that existing studies usually examined these resilience characteristics separately, Dong et al. (2020) proposed the institutional connectedness for effective urban resilience governance, accounting for three synergistic areas embedded in human systems: the actor collaboration of actor networks, the plan integration of networks of plans, and the shared norm and values. Our study provides a new way to examine the actors' network and their attributes simultaneously. The level of local interactions could shed lights on the need for external collaborations, and ERGMs provides insights into policies and norms for actor collaborations. Furthermore, institutional connectedness stresses shared norms among actors to increase network cohesion and actor collaborations for resilience governance. In our study, we found that the heterophily effect is also an important factor for tie formation in actor collaboration networks. The result is consistent with those from existing studies that highlighted the heterophily effect for the tie formation in different types of social networks (Barranco et al. 2019; Kimura and Hayakawa 2008; Lozares et al. 2014).

Concluding Remarks of Research Study E

In this paper, we examined two important mechanisms, local interactions and homophily effects for actor collaboration in resilience planning and management of IISs. We conducted a stakeholder survey to collect data regarding actor collaboration for resilience planning of IISs and actor preferences to a list of flood risk reduction policy actions. We mapped the bipartite network and adopted network motif analysis and ERGMs to investigate network configurations and related node attributes, which encode important information of collaboration among actors. The paper has both theoretical and practical contributions: (1) we combined network motif analysis and ERGMs models which both focus on the network configurations and a bottom-up process in the formation of social networks. The results of network motif analysis and ERGMs have different focuses and could be complementary to each other. (2) the study could provide empirical evidence regarding drivers of collaboration among diverse actors in resilience planning and management of IISs. These results could help develop strategies to foster collaboration among actors from diverse urban sectors involved in the process of resilience planning and management of IISs.

This study and its findings complement the existing literature related to actor collaborative network analysis in collective action problems related to disaster management and environmental governance by the examination of two mechanisms contributing to network formation and evolution: local interactions and the homophily effect. Many of the existing studies primarily focused on topological properties of actor networks but did not fully account for actor node attributes. The combined analysis of network structure and node attributes (i.e., sectors and policy preferences of actors) and findings provide deeper insights into the institutional connectedness of human systems that influence urban resilience. In addition, this study contributes to the field of urban resilience planning and management of IISs by advancing the empirical understanding of actors’ network properties and the underlying mechanisms that govern the creation of ties/links in actor collaboration networks.

Limitations of Research Study E and Future Directions

The study has some limitations. We found significant homophily and heterophily effects for preferences to different risk reduction policy actions; however, we did not explore whether the policy actions led to the homophily or heterophily effects. Future studies could explore the reason based on the essential knowledge of public policies. Second, we applied an algorithm to generate random networks with fixed degree distributions. The algorithm fixed the counts of edges, two stars, and three stars, which lost some information of the network motif analysis. Although Saracco et al. (2015) noted that higher-order network motifs (e.g., three trails and cycles) encode much more network information compared with the lower-order network motifs, future studies could test and apply different algorithms to examine the significance of network motifs.

CHAPTER VII

CONCLUSIONS

In this study, we investigated the dynamics of coupled human-infrastructure networks for urban resilience. We proposed an institutional connectedness framework as a property of human systems affecting infrastructure systems for urban resilience. We focused on three synergistic areas embedded in human systems: actor networks, networks of plans, and values, norms and cognition to account for the interdependencies among human systems and infrastructure systems for urban resilience. We administered a stakeholder survey in Harris County, Texas, to collect the data of actor collaborations for resilience planning before Hurricane Harvey, and actor preferences to flood risk reduction policy actions. We selected four plans, the 2016-2020 Capital Improvement Plan, the 2017 Gulf-Houston Regional Conservation Plan, the 2040 Regional Transportation Plan, and the 2017 Hazard Mitigation Plan, which target in Harris County area, Texas to examine the plan consistency in terms of infrastructure interdependencies and the extent of incorporating and reflecting diverse stakeholder values in resilience planning and management of interdependent infrastructure systems. Based on the collected data, we mapped actor collaboration network for resilience planning and conducted network analysis to investigate the network positions of actors, within-sector and across sector collaborations, and local interactions and homophily effects in resilience planning and management of interdependent infrastructure systems.

The results of actor network positions highlight that governmental actors had high degree centrality, high betweenness centrality and most actors in the core were governmental actors (76% and 78% for weekly and monthly collaboration network respectively). Non-governmental actors, on the other hand, were most in the periphery of the collaboration network of resilience planning. The results of network simulations demonstrate that within-sector coordination was much more than across-sector coordination. The transportation sector had the highest level of within-sector coordination, while the community development sector had the lowest level of within-sector coordination. The transportation sector and the emergency response sector had the highest level of cross-sector coordination, and the community development sector had very low level of cross-sector coordination with the transportation and flood control sectors. The examination of diverse stakeholder values in selected plans show that the Hazard Mitigation Plan incorporated the greatest degree of diverse stakeholder values, while the Regional Transportation Plan incorporated the least degree. The transportation plan and the hazard mitigation plan had the lowest level of value consistency, while the hazard mitigation plan and the environmental conservation plan had the highest level of consistency in terms of incorporating diverse stakeholder values. The results of modeling infrastructure-actor-plan-task meta-network in selected plans highlight that consistency rates of actors, plans and tasks were low in terms of accounting for infrastructure dependencies. Harris County Flood Control District was identified that needed more coordination with other actors to better account of infrastructure dependencies in different plans. The transportation plan had the highest betweenness centrality in the potential plan network, indicating that the transportation plan would highly affect consistency of networks of plans and should be well integrated with other plans. The task, Expand the roadway network in Regional Transportation Plan, involves the most dependent infrastructure and should be well consistent with other tasks. Finally, the examination of local interaction and homophily effects for collective action in resilience planning reveal that there were strong local interactions, especially in the transportation sector. The strong local interactions and fewer three paths in the actor collaboration network indicate a lack of cross-sector coordination. Also, both homophily and anti-homophily effects were identified and suggested different mechanism to form collective action in resilience planning of interdependent infrastructure systems. The results of analyses highlight the following conclusions.

The Lack of Diverse Stakeholder Involvement in Resilience Planning

We found that governmental actors had greater influence in the collaboration network for resilience planning, while there were not enough non-governmental actors in the planning process. Existing studies, however, showed that involving diverse stakeholders will greatly improve the quality of plans. For example, Lyles et al. (2014a) evaluated the land use approaches and found that involving local planner in the government-oriented planning process will greatly improve the quality of land use approaches. Woodruff and Regan (2019) found that involving diverse stakeholders will greatly improve the quality of climate adaption plans. Resilience planning, in particular, is the process requiring diverse stakeholder involvement across multiple urban sectors and scales (e.g., local, county, regional and state). Gajewski et al. (2011) pointed out that non-governmental actors had their own strength and resources, which could not only be a good supplement to government resources, but also could be potential boundary spanners to help disseminate information, bridge the gaps between communities and governmental actors, and educate and promote the cohesion within communities. Existing studies also highlighted the importance role of non-governmental actors in disaster response and recovery. Non-governmental actors usually are closer and more familiar with communities compared with governmental actors. Therefore, non-governmental actors could effectively help communities respond to disruptions and assist the recovery process (Kapucu 2005). Furthermore, Palttala et al. (2012) pointed out the communication gaps between governmental and non-governmental actors in disasters, which could lead to inefficient decision making and ineffective emergency response. Comfort (2005) suggested that to improve the communication and collaboration between governmental and non-governmental actors, networks of actors should be more flat and flexible instead of being hierarchical. The analysis and network properties, such as network positions and structures, could provide insights into the development of strategies to improve network cohesion.

The Lack of Cross-sector Coordination

We found that within-sector coordination was much more than cross-sector coordination in resilience planning and management of interdependent infrastructure systems. Local interactions were identified as a significant mechanism for collective action in resilience planning, while overall long average path of the collaboration implied less cross-sector coordination. Especially, multiple results demonstrate that the transportation sector had the strongest within-sector coordination among five studied urban sectors. The results imply that the urban sectors worked siloed in resilience planning, which may lead to inconsistent plans due to diverse stakeholder values such as traffic congestion improvement, natural resource preservation, and hazard mitigation, in the resilience planning process. Existing studies highlighted the leading position of actor network in the planning process (Godschalk 2003), and the importance of actor collaboration for the planning (Finn et al. 2007) and governance of infrastructure systems (Bodin 2017). Sufficient coordination among diverse actors is essential for better accounting for interdependent infrastructures and is essential for better plan integration.

The results also suggest that the transportation sector in Texas has high authority, many resources and a leading voice in resilience planning and management of infrastructures. Actually, the transportation sector in Texas has its own planning and environmental affair divisions, which may contribute to its limited coordination with other urban sectors except for the emergency response sector. The results show that there were relatively high level of coordination between the emergency response sector and the transportation sector, suggesting that emergency response operation highly depend on transportation infrastructures. For instance, roads were reported inundated during Harvey which prevent the access by fire vehicles. Firefighters had to manage rescues by boat or helicopter, which greatly decreasing the rescue efficiency while increasing the extra costs.

The Inconsistencies among Networks of Plans

The study demonstrates that the networks of plans including the transportation plan, the capital improvement plan, the hazard mitigation plan, and the environmental consistent plan lacked consistencies in terms of accounting for infrastructure dependencies and incorporating diverse stakeholder values in resilience planning and management of interdependent infrastructures. The transportation plan incorporated and reflected the least diverse stakeholder values compared with other plans. However, the transportation plan had the highest betweenness centrality in the potential plan network that fully account for infrastructure dependencies. This suggests that the transportation plan is in a strategic position in networks of plans that could greatly affect the plan consistency of networks of plans in terms of infrastructure dependencies. Improving the consistencies between the transportation plan and other plans will greatly improve the plan consistency of networks of plans.

The study highlight that the flood risk in the Houston area is partly due to inconsistencies among networks of plans: the rapid urban growth with incompatible land use regulations and limited infrastructure investment on hazard mitigation (Berke 2019). Existing studies showed that inconsistencies plans will increase the social and physical vulnerabilities in the target area (Berke et al. 2019; Malecha et al. 2018). Berke et al (2015) developed a resilience scorecard to evaluate plan consistency based on the social and physical vulnerabilities. In our study, we evaluated the plan consistency based on the stakeholder value incorporation and infrastructure dependencies, which could be a good complement for evaluating consistency of networks of plans.

Planning in Texas and Houston Area

The conclusions suggest the uniqueness of planning in Texas. Texas is famous for its laissez-faire development and vulnerability to natural hazards. Flooding and hurricanes have inflicted huge losses in Texas. Nearly 6 percent area of Texas is vulnerable to flooding, while a third of population and economic activities in Texas are located in the flood prone areas. Meanwhile, Texas puts minimal state intervention in planning and is greatly in favor of the free market, private property rights and the power of local governments. Therefore, planning in Texas often yields to economic development behind rapid population growth and the autonomy of local governments. Planning in Texas is regarded extremely challenging as it “goes against Texans’ highly individualistic and entrepreneurial cultural values, which are too focused on maximum exploitation of the environment to effectively husband natural resources” (Burby et al. 1998).

Furthermore, Houston is well-known for its non-zoning policies. However, as we stated in Study C, Houston has its own plans and policies to regulate the land use, manage the urban growth and plan for flood risks. For example, Houston is famous for its numerous deed restrictions of master-planned communities for land use regulations. Still, planning in Houston is largely driven by real estate development and lacks a broad institutional framework and a vision of comprehensive city plan. Houston also needs policy actions to reduce negative consequences of economic activities mainly due to the real estate development. Existing studies discussed different strategies to increase the effectiveness of planning in Houston, such as improving public engagement in planning process, improving plan qualities and implementation, and paying attention to the symbolic meaning of the policies (Buitelaar 2009; Burby et al. 1998; Welborn et al.

1997). In this study, I will make more recommendations based on the results of actor collaboration network analysis.

Recommendations

Based on the results of actors' network positions, non-government actors need to improve the coordination efficiency with other non-government actors in the planning process. According to the coordination strategy analysis, if the non-government actor does not have many existing collaborations with other non-government ones, establishing new collaborations will be more effective to improve coordination efficiency. On the other hand, if the non-government actor does have existing collaborations with other non-government actors, increasing the collaboration frequencies will be more effective to improve coordination efficiency. Considering these guidelines, building up planning forums and encouraging diverse actors to participate in would be a good strategy to improve the overall level of coordination among actors in the planning process. Government actors have shown their high degree centrality, betweenness centrality and core position in the actor collaboration network. Therefore, they could play an intermediate role to help connect more non-government actors to increase network cohesion in the planning process.

Also, potentially network analysis helps us identify strategic actors, plans and tasks to efficiently improve the actor coordination, plan integration and task consistency. The potentially network analysis identifies actors, plans and tasks with the highest betweenness centrality that reflects the extent to which the node lies in the shortest path between any pairs of nodes in the observed network. Therefore, establishing the coordination with the identified actor, improving the integration with the identified plan, and improving the consistency with the identified task will efficiently improve the level of actor coordination, plan integration and task consistency.

Furthermore, the results of network analysis suggest that the transportation sector has high resources, strong within-sector coordination and limited cross-sector coordination. This could be partly due to the uniqueness of planning in Texas and Houston area we discussed before, an example of negative externalities due to planning driven by the real estate development. Based on this observation, relevant policies could be developed. However, in this dissertation, we will not discussion about the policy itself and the results could be a good reference for planners.

Contributions

The study has multiple theoretical, methodological and practical contributions. First, we proposed an institutional connectedness framework as an emerging property of human systems affecting infrastructure systems for urban resilience, focusing on three synergistic areas: actor networks, networks of plans and actor values, norms and cognition. Second, we proposed a multi-layer network simulation framework for examining actor networks with heterogeneous types of nodes and dynamic links. The multi-layer network simulation framework provides a networks-of-networks perspective on inter-organizational coordination dynamics within and across urban sectors. Third, we proposed a value-based plan evaluation framework to quantitively examine the incorporation of diverse stakeholder values in plans. The framework enables quantitively evaluation of the extent to which diverse stakeholder values are incorporated in plans.

Fourth, we proposed a meta-network framework to model interdependent actor-plan-task-infrastructure network and developed quantitively measures to access actor coordination, and plan and task consistency in terms of infrastructure dependencies. Modeling interdependencies among actor, plan, task and infrastructure network contributes to extant studies of interdependencies modeling as well as improves comprehension of infrastructure interdependencies affected by actor coordination, plan integrity and task consistency in resilience planning. Finally, we combined the network motif analysis and ERGMs models which both focus on network configurations and provide a bottom-up perspective to form collective action in resilience planning. Practically, the proposed framework could be used in the context of other regions (not only limited in the Houston area). The results could inform the decision makers of the extent of actor coordination, plan integrity and task consistency in resilience planning and help make strategies to improve the actor coordination, plan integrity and task consistency.

REFERENCES

Abbasi, A. (2014). “Link formation pattern during emergency response network dynamics.” *Natural Hazards*, 71(3), 1957–1969.

Admiraal, R., and Handcock, M. S. (2008). “networksis: A package to simulate bipartite graphs with fixed marginals through sequential importance sampling.” *Journal of Statistical Software*, 24(8).

Aerts, J. C. J. H., Botzen, W. J., Clarke, K. C., Cutter, S. L., Hall, J. W., Merz, B., Michel-Kerjan, E., Mysiak, J., Surminski, S., and Kunreuther, H. (2018). “Integrating human behaviour dynamics into flood disaster risk assessment /704/242 /706/689/2788 /706/2805 perspective.” *Nature Climate Change*, 8(3), 193–199.

Afroz, S., Cramb, R., and Grunbuhel, C. (2016). “Collective management of water resources in Coastal Bangladesh: Formal and substantive approaches.” *Human Ecology*, 44(1), 17–31.

Albert, R., Jeong, H., and Barabási, A.-L. (2000). “Error and attack tolerance of complex networks.” *Nature*, 406(6794), 378–382.

Aldrich, D. P. (2011). “Ties that Bond, Ties that Build: Social Capital and Governments in Post Disaster Recovery.” *Studies in Emergent Order*, 4, 58–68.

Aldrich, D. P. (2012). *Building resilience: Social capital in post-disaster recovery*. University of Chicago Press.

Aldrich, D. P., and Meyer, M. A. (2015). “Social Capital and Community Resilience.”

American Behavioral Scientist, 59(2), 254–269.

Allenby, B., and Fink, J. (2005). “Toward inherently secure and resilient societies.” *Science*, 309(5737), 1034–1036.

Almquist, Z. W., Spiro, E. S., and Butts, C. T. (2016). “Shifting Attention: Modeling Follower Relationship Dynamics Among Us Emergency Management-Related Organizations During a Colorado Wildfire.” *Social Network Analysis of Disaster Response, Recovery, and Adaptation*.

Aral, Sinan, Van Alstyne, M. (2011). “The diversity-bandwidth trade-off.” *Am. J. Sociol. 117, 90–171.*, University of Chicago Press Chicago, IL, 117(1), 90–171.

Asikainen, A., Iñiguez, G., Ureña-Carrión, J., Kaski, K., and Kivelä, M. (2020). “Cumulative effects of triadic closure and homophily in social networks.” *Science Advances*, American Association for the Advancement of Science, 6(19), eaax7310.

Baer, W. C. (1997). “General plan evaluation criteria: An approach to making better plans.” *Journal of the American Planning Association*, 63(3), 329–344.

Bahadorestani, A., Naderpajouh, N., and Sadiq, R. (2020). “Planning for sustainable stakeholder engagement based on the assessment of conflicting interests in projects.” *Journal of Cleaner Production*, 242.

Balland, P. A. (2012). “Proximity and the Evolution of Collaboration Networks: Evidence from Research and Development Projects within the Global Navigation Satellite System (GNSS) Industry.” *Regional Studies*, 46(6), 741–756.

Barima, O. K. B. (2010). “Examination of the best, analogous, competing terms to describe value in construction projects.” *International Journal of Project*

Management, 28(3), 195–200.

Barranco, O., Lozares, C., and Muntanyola-Saura, D. (2019). “Heterophily in social groups formation: a social network analysis.” *Quality and Quantity*, Springer Netherlands, 53(2), 599–619.

Bastos, M., McRoberts, N., Piccardi, C., Lubell, M., and Levy, M. (2017). “Core-periphery or decentralized? Topological shifts of specialized information on Twitter.” *Social Networks*, 52, 282–293.

Beatley, T. (2012). *Coastal Resilience: Best Practices for Calamitous Times*. Island Press.

Berardo, R., and Lubell, M. (2016). “Understanding What Shapes a Polycentric Governance System.” *Public Administration Review*, 76(5), 738–751.

Berke, P. (2019). “Why is Houston so Vulnerable to Flooding?” *Retrieved from: https://hazards.colorado.edu/news/research-counts/part-i-why-is-houston-so-vulnerable-to-flooding*.

Berke, P., Newman, G., Lee, J., Combs, T., Kolosna, C., and Salvesen, D. (2015). “Evaluation of Networks of Plans and Vulnerability to Hazards and Climate Change: A Resilience Scorecard.” *Journal of the American Planning Association*, Taylor & Francis, 81(4), 287–302.

Berke, P. R., and Campanella, T. J. (2006). “Planning for Postdisaster Resiliency.” *The Annals of the American Academy of Political and Social Science*, 604(1), 192–207.

Berke, P. R., and Conroy, M. M. (2000). “Are we planning for sustainable development? An evaluation of 30 comprehensive plans.” *Journal of the American Planning*

Association, 66(1), 21–33.

Berke, P. R., Kartez, J., and Wenger, D. (1993). “Recovery after Disaster: Achieving Sustainable Development, Mitigation and Equity.” *Disasters*, 17(2), 93–109.

Berke, P. R., Malecha, M. L., Yu, S., Lee, J., and Masterson, J. H. (2019). “Plan integration for resilience scorecard: evaluating networks of plans in six US coastal cities.” *Journal of Environmental Planning and Management*, 62(5), 901–920.

Berke, P., and Smith, G. (2009). “Hazard Mitigation, Planning, and Disaster Resiliency: Challenges and Strategic Choices for the 21 st Century.” *Building Safer Communities. Risk Governance, Spatial Planning and Responses to Natural Hazards*, 1–20.

Berz, G., Kron, W., Loster, T., Rauch, E., Schimetschek, J., Schmieder, J., Siebert, A., Smolka, A., and Wirtz, A. (2001). “World map of natural hazards - a global view of the distribution and intensity of significant exposures.” *Natural Hazards*, 23(2–3), 443–465.

Biesenthal, C., Clegg, S., Mahalingam, A., and Sankaran, S. (2018). “Applying institutional theories to managing megaprojects.” *International Journal of Project Management*, 36(1), 43–54.

Binkovitz, L. (2020). “Toward Modern Mobility.” *American Planning Association*.

Blackburn, J. (2020). “At Water’s Edge.” *American Planning Association*.

Blackburn, J. B. (2017). *A Texan plan for the Texas coast (Vol. 31)*. Texas A&M University Press.

Blitzstein, J., and Diaconis, P. (2011). “A sequential importance sampling algorithm for generating random graphs with prescribed degrees." *Internet Mathematics*, Taylor and Francis Inc., 6(4), 489–522.

Boburg, S., and Reinhard, B. (2017). "Houston's 'wild west' growth: how the city's development may have contributed to devastating flooding." *The Washington Post 29*.

Bodin, Ö. (2017). "Collaborative environmental governance: Achieving collective action in social-ecological systems." *Science*, 357(6352).

Bodin, Ö., and Crona, B. I. (2009). "The role of social networks in natural resource governance: What relational patterns make a difference?" *Global Environmental Change*.

Bomiriha, R. (2014). *Topics in Exponential Random Graph Modeling*. *Pennsylvania State University*.

Borgatti, S. P. (1995). "Centrality and AIDS." *Connections*, 18(1), 112–114.

Borgatti, S. P. (2005). "Centrality and network flow." *Social Networks*, Elsevier, 27(1), 55–71.

Borgatti, S. P., and Everett, M. G. (2000). "Models of core/periphery structures." *Social Networks*, Elsevier, 21(4), 375–395.

Bourbousson, J., R'Kiouak, M., and Eccles, D. W. (2015). "The dynamics of team coordination: A social network analysis as a window to shared awareness." *European Journal of Work and Organizational Psychology*.

Bourgeois, M., and Friedkin, N. E. (2001). "The distant core: Social solidarity, social distance and interpersonal ties in core-periphery structures." *Social Networks*, 23(4), 245–260.

Boyd, E., and Juhola, S. (2015). “Adaptive climate change governance for urban resilience.” *Urban Studies*, SAGE Publications Ltd, 52(7), 1234–1264.

Boyd, J. P., and Jonas, K. J. (2001). “Are social equivalences ever regular?: Permutation and exact tests.” *Social Networks*, 23(2), 87–123.

Brody, S. D. (2003). “Implementing the principles of ecosystem management through local land use planning.” *Population and Environment*, 24(6), 511–540.

Brody, S. D., Bernhardt, S. P., Zahran, S., and Kang, J. E. (2009). “Evaluating local flood mitigation strategies in texas and florida.” *Built Environment*, Alexandrine Press, 35(4), 492–515.

Brody, S., Kim, H., and Gunn, J. (2013). “Examining the Impacts of Development Patterns on Flooding on the Gulf of Mexico Coast.” *Urban Studies*, 50(4), 789–806.

Broekel, T., and Hartog, M. (2013). “Explaining the Structure of Inter-Organizational Networks using Exponential Random Graph Models.” *Industry and Innovation*, 20(3), 277–295.

Buitelaar, E. (2009). “Zoning, more than just a tool: Explaining Houston’s regulatory practice.” *European Planning Studies*, 17(7), 1049–1065.

Burby, R. J. (1998). *Cooperating with nature : confronting natural hazards with land use planning for sustainable communities*. *Natural hazards and disasters*.

Burby, R. J. (2003). “Making plans that matter: Citizen involvement and government action.” *Journal of the American Planning Association*, 69(1), 33–49.

Burby, R. J., Beatley, T., Berke, P. R., Deyle, R. E., French, S. P., Godschalk, D. R., Kaiser, E. J., Kartez, J. D., May, P. J., Olshansky, R., Paterson, R. G., and Platt, R. H. (1999). "Unleashing the power of planning to create Disaster-Resistant communities." *Journal of the American Planning Association*, 65(3), 247–258.

Burby, R. J., May, P. J., Berke, P. R., Dalton, L. C., French, S. P., and Kaiser, E. J. (1998). *Making Governments Plan: State Experiments in Managing Land Use*. *CrossRef Listing of Deleted DOIs*.

Burt, R. S. (2004). "Structural Holes and Good Ideas." *American Journal of Sociology,* The University of Chicago Press, 110(2), 349–399.

Bush, G. P. (2019). "TEXAS COASTAL RESILIENCY MASTER PLAN." *Texas General Land Office*.

Callaway, D. S., Newman, M. E. J., Strogatz, S. H., and Watts, D. J. (2000). "Network robustness and fragility: percolation on random graphs." *Physical Review Letters*, 85(25), 5468–5471.

Camarinha-Matos, L. M., and Macedo, P. (2010). "A conceptual model of value systems in collaborative networks." *Journal of Intelligent Manufacturing*, 21(3), 287–299.

Campanella, T. J. (2006). "Urban resilience and the recovery of new orleans." *Journal of the American Planning Association*, 72(2), 141–146.

Campbell, S. (1996). "Green Cities, Growing Cities, Just Cities?: Urban planning and the contradictions of sustainable development." *Journal of the American Planning Association*, 62(3), 296–312.

Cardillo, A., Zanin, M., Gómez-Gardeñes, J., Romance, M., García del Amo, A. J., and Boccaletti, S. (2013). "Modeling the multi-layer nature of the European Air

Transport Network: Resilience and passengers re-scheduling under random failures." *European Physical Journal: Special Topics*.

Carley, K. M. (2001). "Summary of Key Measures for Characterizing Organizational Architectures." *Unpublished Document: CMU*, 1–10.

Carley, K. M., Pfeffer, J., Reminga, J., Storrick, J., and Columbus, D. (2013). *ORA user's guide 2013*.

Chelleri, L., Waters, J. J., Olazabal, M., and Minucci, G. (2015). "Resilience trade-offs: addressing multiple scales and temporal aspects of urban resilience." *Environment and Urbanization*, 27(1), 181–198.

Chen, Y. Z., Huang, Z. G., Zhang, H. F., Eisenberg, D., Seager, T. P., and Lai, Y. C. (2015). "Extreme events in multilayer, interdependent complex networks and control." *Scientific Reports*, 5.

Cheng, A. S., and Fleischmann, K. R. (2010). "Developing a meta-inventory of human values." *Proceedings of the ASIST Annual Meeting*, 112–118.

Chung, F., and Lu, L. (2002). "Connected Components in Random Graphs with Given Expected Degree Sequences." *Annals of Combinatorics*, Birkhäuser Verlag, 6(2), 125–145.

Clark-Ginsberg, A. (2020). "Disaster risk reduction is not 'everyone's business': Evidence from three countries." *International Journal of Disaster Risk Reduction*, 43.

Coates, T., and Tapsell, S. (2019). "Planning for an uncertain future: the challenges of a locally based collaborative approach to coastal development decisions."

Environmental Science and Policy, 101, 24–31.

Comfort, L. K. (2005). “Risk, Security, and Disaster Management.” *Annual Review of Political Science,* 8(1), 335–356.

Creswick, N., and Westbrook, J. I. (2010). “Social network analysis of medication advice-seeking interactions among staff in an Australian hospital.” *International Journal of Medical Informatics,* Elsevier, 79(6), e116--e125.

Crucitti, P., Latora, V., and Marchiori, M. (2004). “A topological analysis of the Italian electric power grid.” *Physica A: Statistical Mechanics and its Applications,* 92–97.

Cucuringu, M., Rombach, P., Lee, S. H., and Porter, M. A. (2016). “Detection of core-periphery structure in networks using spectral methods and geodesic paths.” *European Journal of Applied Mathematics*, Cambridge University Press, 27(6), 846–887.

Davis, C. A., Mostafavi, A., and Wang, H. (2018). “Establishing Characteristics to Operationalize Resilience for Lifeline Systems.” *Natural Hazards Review,* 19(4).

Davlasheridze, M., Atoba, K. O., Brody, S., Highfield, W., Merrell, W., Ebersole, B., Purdue, A., and Gilmer, R. W. (2019). “Economic impacts of storm surge and the cost-benefit analysis of a coastal spine as the surge mitigation strategy in Houston-Galveston area in the USA.” *Mitigation and Adaptation Strategies for Global Change*, 24(3), 329–354.

Dempwolf, C., and Lyles, L. (2010). “The Uses of Social Network Analysis in Planning.” *Journal of Planning Literature,* Sage Publications Sage CA: Los Angeles, CA, 17(1), 351–359.

Dey, A. K., Gel, Y. R., and Poor, H. V. (2019a). “What network motifs tell us about resilience and reliability of complex networks.” *Proceedings of the National Academy of Sciences of the United States of America*, 116(39), 19368–19373.

Dey, A. K., Gel, Y. R., and Poor, H. V. (2019b). “What network motifs tell us about resilience and reliability of complex networks.” *Proceedings of the National Academy of Sciences of the United States of America*, PNAS, 116(39), 19368–19373.

De Domenico, M., Porter, M. A., and Arenas, A. (2015). “MuxViz: A tool for multilayer analysis and visualization of networks.” *Journal of Complex Networks,* 3(2), 159–176.

Dong, S., Li, Q., Farahmand, H., Mostafavi, A., Berke, P. R., and Vedlitz, A. (2020). “Institutional Connectedness in Resilience Planning and Management of Interdependent Infrastructure Systems.” *Journal of Management in Engineering,* 36(6), 04020075.

Dong, S., Mostafizi, A., Wang, H., and Song, X. (2019a). “A Network-of-Networks Percolation Analysis of Cascading Failures in Spatially Co-located Road-Sewer Infrastructure Networks.” *Physica A: Statistical Mechanics and Its Application*.

Dong, S., Wang, H., Mostafizi, A., Gao, J., and Li, X. (2019b). “Measuring the topological robustness of transportation networks to disaster-induced failures: A percolation approach.” *Journal of Infrastructure System*.

Dong, S., Wang, H., Mostfavi, A., and Gao, J. (2019c). “Robust component characterization of hazards-induced failure disrupted access to critical facilities through percolation." *Jounal of Royal Society Interface*.

Doreian, P. (1985). "Structural equivalence in a psychology journal network." *Journal of the American Society for Information Science*, Wiley Online Library, 36(6), 411–417.

Doreian, P., and Conti, N. (2012). "Social context, spatial structure and social network structure." *Social Networks,* 34(1), 32–46.

Dueñas-Osorio, L., Craig, J. I., and Goodno, B. J. (2007). "Seismic response of critical interdependent networks." *Earthquake Engineering and Structural Dynamics,* 36(2), 285–306.

Dunn, S., Wilkinson, S., Alderson, D., Fowler, H., and Galasso, C. (2018). "Fragility Curves for Assessing the Resilience of Electricity Networks Constructed from an Extensive Fault Database." *Natural Hazards Review,* American Society of Civil Engineers, 19(1), 04017019.

Dyckman, C. S. (2018). "Planning without the planners: South Carolina's Section 319 local watershed planning process." *Environmental Science and Policy*, 89, 126–141.

Echeverría, J. (2003). "Science, technology, and values: Towards an axiological analysis of techno-scientific activity." *Technology in Society*, 25(2), 205–215.

Eisenberg, D. A., Park, J., and Seager, T. P. (2020). "Linking Cascading Failure Models and Organizational Networks to Manage Large-Scale Blackouts in South Korea." *Journal of Management in Engineering*, 36(5), 04020067.

El-Gohary, N. (2010). "Model-Based Automated Value Analysis of Building Projects."

Analysis.

El-Gohary, N. M., and Qari, A. (2010). "Towards a formal axiology for sustainable infrastructure development." *Proceedings of the ASCE International Conference on Computing in Civil and Building Engineering*, 2006–2007.

Endter-Wada, J., Kettenring, K. M., and Sutton-Grier, A. (2020). "Protecting wetlands for people: Strategic policy action can help wetlands mitigate risks and enhance resilience." *Environmental Science and Policy*, 108, 37–44.

Everitt, B. S. (2018). "Cluster analysis." *Multivariate Analysis for the Behavioral Sciences*, CRC Press, 341–363.

Fan, C., and Mostafavi, A. (2019). "Metanetwork Framework for Performance Analysis of Disaster Management System-of-Systems." *IEEE Systems Journal*, 1–12.

Fan, C., Zhang, C., and Mostafavi, A. (2018). "Meta-network framework for analyzing disaster management system-of-systems." *2018 13th System of Systems Engineering Conference, SoSE 2018*, 372–378.

Farahmand, H., Dong, S., Mostafavi, A., Berke, P. R., Woodruff, S. C., Hannibal, B., and Vedlitz, A. (2020). "Institutional congruence for resilience management in interdependent infrastructure systems." *International Journal of Disaster Risk Reduction*, 46, 101515.

Fastiggi, M., Meerow, S., and Miller, T. R. (2021). "Governing urban resilience: Organisational structures and coordination strategies in 20 North American city governments." *Urban Studies*, SAGE Publications Ltd, 58(6), 1262–1285.

Feiock, R. C. (2013). "The institutional collective action framework." *Policy Studies*

Journal, Wiley Online Library, 41(3), 397–425.

Finn, D., Hopkins, L. D., and Wempe, M. (2007). “The information system of plans approach: Using and making plans for landscape protection.” *Landscape and Urban Planning*, 81(1–2), 132–145.

Ford, R. M., Rawluk, A., and Williams, K. J. H. (2019). “Managing values in disaster planning: Current strategies, challenges and opportunities for incorporating values of the public.” *Land Use Policy*, 81, 131–142.

Forester, J. (2013). *Critical theory, public policy, and planning practice*. SUNY Press.

Freeman, L. C. (1978a). “Centrality in social networks conceptual clarification.” *Social Networks*, 1(3), 215–239.

Freeman, L. C. (1978b). “Centrality in social networks conceptual clarification.” *Social Networks*, North-Holland, 1(3), 215–239.

Freeman, R. E. (2010). *Strategic management: A stakeholder approach*. *Cambridge university press*.

Fulton, W. (2020). “The ‘Z’ Word.” *American Planning Association*.

Gajewski, S., Bell, H., Lein, L., and Angel, R. J. (2011). “Complexity and instability: The response of nongovernmental organizations to the recovery of Hurricane Katrina survivors in a host community.” *Nonprofit and Voluntary Sector Quarterly*, 40(2), 389–403.

Gao, S., Frejinger, E., and Ben-Akiva, M. (2010). “Adaptive route choices in risky traffic networks: A prospect theory approach.” *Transportation Research Part C: Emerging Technologies*, Elsevier, 18(5), 727–740.

Gerber, E. R., Henry, A. D., and Lubell, M. (2013). “Political homophily and collaboration in regional planning networks.” *American Journal of Political Science*, 57(3), 598–610.

GIAQUINTO, M., and ABELLI, G. (1964). *Valore Diagnostico Dell’Amnioscopia. Attualità di ostetricia e ginecologia*.

Gibbons, D. E. (2004). “Network structure and innovation ambiguity effects on diffusion in dynamic organizational fields.” *Academy of Management Journal*, 47(6), 938–951.

Godschalk, D. R. (2003). “Urban Hazard Mitigation: Creating Resilient Cities.” *Natural Hazards Review*, 4(3), 136–143.

Godschalk, D. R. (2004). “Land use planning challenges: Coping with conflicts in visions of sustainable development and livable communities.” *Journal of the American Planning Association*, 70(1), 5–13.

Godschalk, D. R., Kaiser, E. J., and Berke, P. R. (1999). “Integrating hazard mitigation and local land-use planning.” *APA Planning Advisory Service Reports*, (480–481), 57–81.

Gómez, S., De Domenico, M., Omodei, E., Albert, S. R., and Arenas, A. (2018). “Multilayer networks.” *Multiplex and Multilevel Networks*, 2(3), 1–30.

Goodman, R. M., Speers, M. A., McLeroy, K., Fawcett, S., Kegler, M., Parker, E., Smith, S. R., Sterling, T. D., and Wallerstein, N. (1998). “Identifying and Defining the Dimensions of Community Capacity to Provide a Basis for Measurement.” *Health Education and Behavior*.

Gorochowski, T. E., Grierson, C. S., and Di Bernardo, M. (2018). “Organization of feed-forward loop motifs reveals architectural principles in natural and engineered networks.” *Science Advances*, American Association for the Advancement of Science, 4(3), eaap9751.

Granovetter, M. (1983). “The Strength of Weak Ties: A Network Theory Revisited.” *Sociological Theory*, JSTOR, 1, 201.

Graversgaard, M., Jacobsen, B. H., Kjeldsen, C., and Dalgaard, T. (2017). “Stakeholder engagement and knowledge co-creation in water planning: Can public participation increase cost-effectiveness?” *Water (Switzerland)*, 9(3).

Gunderson, L. H. (2001). *Panarchy: Understanding Transformations in Human and Natural Systems. Island press.*

Habib, S. B. (1979). “The Critical Theory of Jurgen Habermas.” *Telos*, 1979(40), 177–187.

Hackett, A., Cellai, D., Gómez, S., Arenas, A., and Gleeson, J. P. (2016). “Bond percolation on multiplex networks.” *Physical Review X*, 6(2).

Hamilton, M., Lubell, M., and Namaganda, E. (2018). “Cross-level linkages in an ecology of climate change adaptation policy games.” *Ecology and Society*, 23(2).

Hannibal, B., and Ono, H. (2017). “Relationships of collapse: Network brokerage, opportunism and fraud in financial markets.” *International Journal of Social Economics*, 44(12), 2097–2111.

Harris County Flood Control District. (2017). “Federal Briefing.” *Https://Www.Hcfcd.Org/Media/2237/Hcfcd-Federal-Briefing-2017_Final.Pdf.*

Hawe, P., and Ghali, L. (2008). “Use of social network analysis to map the social relationships of staff and teachers at school.” *Health Education Research*, Oxford University Press, 23(1), 62–69.

Healey, P. (1992). “Planning through debate: the communicative turn in planning theory.” *Town Planning Review*, 63(2), 143–162.

Heaney, M. T., and McClurg, S. D. (2009). “Social Networks and American Politics: Introduction to the Special Issue.” *American Politics Research*, 37(5), 727–741.

Holme, P. (2005). “Core-periphery organization of complex networks.” *Physical Review E - Statistical, Nonlinear, and Soft Matter Physics*, APS, 72(4), 46111.

Hopkins, L. D., and Knaap, G. J. (2018). “Autonomous planning: Using plans as signals.” *Planning Theory*, 17(2), 274–295.

Hughes, T. P., Baird, A. H., Bellwood, D. R., Card, M., Connolly, S. R., Folke, C., Grosberg, R., Hoegh-Guldberg, O., Jackson, J. B. C., Kleypas, J., Lough, J. M., Marshall, P., Nyström, M., Palumbi, S. R., Pandolfi, J. M., Rosen, B., and Roughgarden, J. (2003). “Climate change, human impacts, and the resilience of coral reefs.” *Science*.

Hunter, D. R., Handcock, M. S., Butts, C. T., Goodreau, S. M., and Morris, M. (2008). “ergm: A package to fit, simulate and diagnose exponential-family models for networks.” *Journal of Statistical Software*, 24(3).

Iii, H. C., Riley, S. J., Winterstein, S. R., Hiller, T. L., Lischka, S. A., and Burroughs, J. P. (2011). “Changing landscapes for white-tailed deer management in the 21st century: Parcelization of land ownership and evolving stakeholder values in

Michigan.” *Wildlife Society Bulletin*, 35(3), 168–176.

Innes, J. E., and Booher, D. E. (2004). “Reframing public participation: Strategies for the 21st century.” *Planning Theory and Practice*.

Ip, W. H., and Wang, D. (2011). “Resilience and friability of transportation networks: Evaluation, analysis and optimization.” *IEEE Systems Journal*, IEEE, 5(2), 189–198.

Jackson, M. O. (2010). *Social and Economic Networks*. *Social and Economic Networks*.

van der Jagt, A. P. N., Szaraz, L. R., Delshammar, T., Cvejić, R., Santos, A., Goodness, J., and Buijs, A. (2017). “Cultivating nature-based solutions: The governance of communal urban gardens in the European Union.” *Environmental Research*, 159, 264–275.

Jahani, H., and El-Gohary, N. (2012). “Value-sensitive construction: Value discovery in building projects.” *Construction Research Congress 2012: Construction Challenges in a Flat World, Proceedings of the 2012 Construction Research Congress*, 797–807.

Janssen, M. A., Bodin, Ö., Anderies, J. M., Elmqvist, T., Ernstson, H., McAllister, R. R. J., Olsson, P., and Ryan, P. (2006). “Toward a network perspective of the study of resilience in social-ecological systems.” *Ecology and Society*, JSTOR, 11(1).

Johnson, T. L., Bielicki, J. M., Dodder, R. S., Hilliard, M. R., Ozge Kaplan, P., and Andrew Miller, C. (2013). “Advancing sustainable bioenergy: Evolving stakeholder interests and the relevance of research.” *Environmental Management*, 51(2), 339–353.

Kaluza, P., Vingron, M., and Mikhailov, A. S. (2008). “Self-correcting networks: Function, robustness, and motif distributions in biological signal processing.” *Chaos*, 18(2).

Kapucu, N. (2005). “Interorganizational Coordination in Dynamic Context: Networks in Emergency Response Management.” *Connections*, 26(2), 33–48.

Kapucu, N., and Van Wart, M. (2006). “The evolving role of the public sector in managing catastrophic disasters: Lessons learned.” *Administration and Society*.

Kimura, D., and Hayakawa, Y. (2008). “Coevolutionary networks with homophily and heterophily.” *Physical Review E - Statistical, Nonlinear, and Soft Matter Physics*, 78(1).

Kinney, R., Crucitti, P., Albert, R., and Latora, V. (2005). “Modeling cascading failures in the North American power grid.” *European Physical Journal B*, 46(1), 101–107.

Koetse, M. J., and Rietveld, P. (2009). “The impact of climate change and weather on transport: An overview of empirical findings.” *Transportation Research Part D: Transport and Environment*, Elsevier, 14(3), 205–221.

Kossinets, G., and Watts, D. J. (2009). “Origins of homophily in an evolving social network.” *American Journal of Sociology*, 115(2), 405–450.

Kotani, H., and Yokomatsu, M. (2016). “Natural disasters and dynamics of ‘a paradise built in hell’: a social network approach.” *Natural Hazards*, 84(1), 309–333.

Krackhardt, D., and Carley, K. M. (1998). “PCANS model of structure in organizations.” *Research report series / Carnegie Mellon University Institute for Complex Engineered Systems*, (88-07–98), 7 p.

Krippendorff, K. (2011). “Computing Krippendorff’s alpha-reliability.”

Larocca, S. (2014). “Modeling the Reliability and Robustness of Critical Infrastructure Networks.”

Larocca, S., Johansson, J., Hassel, H., and Guikema, S. (2015). “Topological Performance Measures as Surrogates for Physical Flow Models for Risk and Vulnerability Analysis for Electric Power Systems.” *Risk Analysis*.

Larsen, A. G., and Ellersgaard, C. H. (2017). “Identifying power elites—k-cores in heterogeneous affiliation networks.” *Social Networks*, 50, 55–69.

Latora, V., and Marchiori, M. (2001). “Efficient behavior of small-world networks.” *Physical Review Letters*, 87(19), 198701-1-198701–4.

Lazega, E., and Burt, R. S. (1995a). *Structural Holes: The Social Structure of Competition*. *Revue Française de Sociologie*, Harvard University Press, Cambridge.

Lazega, E., and Burt, R. S. (1995b). “Structural Holes: The Social Structure of Competition.” *Revue Française de Sociologie*, Harvard university press, 36(4), 779.

Li, Q., Dong, S., and Mostafavi, A. (2019). “Modeling of inter-organizational coordination dynamics in resilience planning of infrastructure systems: A multilayer network simulation framework.” *PLoS ONE*, Public Library of Science, 14(11).

Li, Q., Dong, S., and Mostafavi, A. (2020a). “Metanetwork Framework for Analysis of Actor-Plan-Task-Infrastructure Networks in Resilience Planning and Management.” *Natural Hazards Review*, 21(2).

Li, Q., Dong, S., and Mostafavi, A. (2020b). “Community detection in actor collaboration networks of resilience planning and management in interdependent infrastructure systems." *Construction Research Congress 2020: Infrastructure Systems and Sustainability - Selected Papers from the Construction Research Congress 2020*, American Society of Civil Engineers (ASCE), 675–683.

Li, Q., Hannibal, B., Mostafavi, A., Berke, P., Woodruff, S., and Vedlitz, A. (2020c). "Examining of the actor collaboration networks around hazard mitigation: a hurricane harvey study." *Natural Hazards*, 103(3), 3541–3562.

Lomi, A., and Pallotti, F. (2012). "Relational collaboration among spatial multipoint competitors." *Social Networks*, 34(1), 101–111.

Long, J. C., Cunningham, F. C., and Braithwaite, J. (2013). "Bridges, brokers and boundary spanners in collaborative networks: A systematic review." *BMC Health Services Research*, 13(1).

Longstaff, P. (2005). *Security, Resilience, and Communication in Unpredictable Environments Such as Terrorism*. *Natural Disasters and Complex Technology*.

Lozares, C., Verd, J. M., Cruz, I., and Barranco, O. (2014). "Homophily and heterophily in personal networks. From mutual acquaintance to relationship intensity." *Quality and Quantity*, Kluwer Academic Publishers, 48(5), 2657–2670.

Lyles, L. W., Berke, P., and Smith, G. (2014a). "Do planners matter? Examining factors driving incorporation of land use approaches into hazard mitigation plans." *Journal of Environmental Planning and Management*, 57(5), 792–811.

Lyles, W., Berke, P., and Smith, G. (2014b). "A comparison of local hazard mitigation plan quality in six states, USA." *Landscape and Urban Planning*, 122, 89–99.

Lyles, W., and Stevens, M. (2014). “Plan Quality Evaluation 1994–2012: Growth and Contributions, Limitations, and New Directions.” *Journal of Planning Education and Research*, SAGE Publications Sage CA: Los Angeles, CA, 34(4), 433–450.

Macedo, P., Sapateiro, C., and Filipe, J. (2006). “Distinct approaches to value system in collaborative networks environments.” *IFIP International Federation for Information Processing*, 111–120.

Magsino, S. L. (2009). *Applications of Social Network Analysis for Building Community Disaster Resilience*. *Applications of Social Network Analysis for Building Community Disaster Resilience*.

Malecha, M. L., Brand, A. D., and Berke, P. R. (2018). “Spatially evaluating a network of plans and flood vulnerability using a Plan Integration for Resilience Scorecard: A case study in Feijenoord District, Rotterdam, the Netherlands.” *Land Use Policy*, Elsevier, 78, 147–157.

Mannarini, T., and Talò, C. (2013). “Evaluating public participation: Instruments and implications for citizen involvement.” *Community Development*, 44(2), 239–256.

Masterson, J. H., Peacock, W. G., Van Zandt, S. S., Grover, H., Schwarz, L. F., and Cooper, J. T. (2014a). *Planning for Community Resilience: A handbook for reducing vulnerability to disasters*. *Washington, DC: Island Press*.

Masterson, J. H., Peacock, W. G., Van Zandt, S. S., Grover, H., Schwarz, L. F., and Cooper, J. T. (2014b). *Planning for Community Resilience*. *Planning for Community Resilience*, Island press.

Matinheikki, J., Aaltonen, K., and Walker, D. (2019). “Politics, public servants, and profits: Institutional complexity and temporary hybridization in a public infrastructure alliance project." *International Journal of Project Management*, 37(2), 298–317.

Matinheikki, J., Artto, K., Peltokorpi, A., and Rajala, R. (2016). "Managing inter-organizational networks for value creation in the front-end of projects." *International Journal of Project Management*, 34(7), 1226–1241.

Matinheikki, J., Pesonen, T., Artto, K., and Peltokorpi, A. (2017). "New value creation in business networks: The role of collective action in constructing system-level goals." *Industrial Marketing Management*, 67, 122–133.

Mattsson, L. ., and Jenelius, E. (2015). "Vulnerability and resilience of transport systems - A discussion of recent research." *Transportation Research Part A: Policy and Practice*.

Matyas, C. J., and Silva, J. A. (2013). "Extreme weather and economic well-being in rural Mozambique." *Natural Hazards*, 66(1), 31–49.

McAllister, R. R. J., Taylor, B. M., and Harman, B. P. (2015). "Partnership Networks for Urban Development: How Structure is Shaped by Risk." *Policy Studies Journal*, 43(3), 379–398.

METRO. (1969). "Regional population growth." *Statistical bulletin (Metropolitan Life Insurance Company)*.

Milallos, M. (2013). *Building Resilience, Social Capital in Post-Disaster Recovery: Daniel Aldrich (Chicago: The University of Chicago Press, 2012)*. *Journal of Contemporary Asia*, University of Chicago Press.

Mills, M., Álvarez-Romero, J. G., Vance-Borland, K., Cohen, P., Pressey, R. L., Guerrero, A. M., and Ernstson, H. (2014). “Linking regional planning and local action: Towards using social network analysis in systematic conservation planning.” *Biological Conservation*.

Milo, R., Shen-Orr, S., Itzkovitz, S., Kashtan, N., Chklovskii, D., and Alon, U. (2002). “Network Motifs: Simple Building Blocks of Complex Networks.” *Science*, 298(5594), 824–827.

Morrissey, J. (2000). “Indicators of citizen participation: Lessons from learning teams in rural EZ/EC communities.” *Community Development Journal*, 35(1), 59–74.

Murnane, R. J. (2006). “Catastrophe risk models for wildfires in the Wildland-Urban interface: What insurers need.” *Natural Hazards Review*, 7(4), 150–156.

N. Lam, N. S., Reams, M., Li, K., Li, C., and Mata, L. P. (2016). “Measuring Community Resilience to Coastal Hazards along the Northern Gulf of Mexico.” *Natural Hazards Review*, 17(1), 04015013.

Naderpajouh, N., Yu, D. J., Aldrich, D. P., Linkov, I., and Matinheikki, J. (2018). “Engineering meets institutions: an interdisciplinary approach to the management of resilience.” *Environment Systems and Decisions*, 38(3), 306–317.

National Research Council. (2012). *Disaster resilience: A national imperative*. *The National Academies Press*.

Neuman, M., and Smith, S. (2010). “City planning and infrastructure: Once and future partners.” *Journal of Planning History*, 9(1), 21–42.

Newman, M. (2018). *Networks*. *Oxford university press*.

Newman, M. E. J. (2003a). “The structure and function of complex networks.” *SIAM Review*.

Newman, M. E. J. (2003b). “Mixing patterns in networks.” *Physical Review E - Statistical Physics, Plasmas, Fluids, and Related Interdisciplinary Topics*, APS, 67(2), 13.

NOAA & NHC. (2018). “Costliest U.S. tropical cyclones tables updated.” *NOAA Technical Memorandum NWS NHC-6*, 3.

Nohrstedt, D., and Bodin, Ö. (2019). “Collective Action Problem Characteristics and Partner Uncertainty as Drivers of Social Tie Formation in Collaborative Networks.” *Policy Studies Journal*.

Norris, F. H., Stevens, S. P., Pfefferbaum, B., Wyche, K. F., and Pfefferbaum, R. L. (2008). “Community resilience as a metaphor, theory, set of capacities, and strategy for disaster readiness.” *American Journal of Community Psychology*, 41(1–2), 127–150.

Nowell, H. K., Horner, M. W., and Widener, M. J. (2015). “Impacts of Disrupted Road Networks in Siting Relief Facility Locations: Case Study for Leon County, Florida.” *Natural Hazards Review*, American Society of Civil Engineers, 16(3), 04014032.

Nutters, H. M., and Pinto da Silva, P. (2012). “Fishery stakeholder engagement and marine spatial planning: Lessons from the Rhode Island Ocean SAMP and the Massachusetts Ocean Management Plan.” *Ocean and Coastal Management*, 67, 9–18.

Olsson, P., Gunderson, L. H., Carpenter, S. R., Ryan, P., Lebel, L., Folke, C., and Holling, C. S. (2006). “Shooting the rapids: Navigating transitions to adaptive governance of social-ecological systems.” *Ecology and Society*.

Opdyke, A., Lepropre, F., Javernick-Will, A., and Koschmann, M. (2017). “Inter-organizational resource coordination in post-disaster infrastructure recovery.” *Construction Management and Economics*, 35(8–9), 514–530.

Opsahl, T., Agneessens, F., and Skvoretz, J. (2010). “Node centrality in weighted networks: Generalizing degree and shortest paths.” *Social Networks*, Elsevier, 32(3), 245–251.

Palmisano, F., Vitone, C., and Cotecchia, F. (2018). “Assessment of Landslide Damage to Buildings at the Urban Scale.” *Journal of Performance of Constructed Facilities*, American Society of Civil Engineers, 32(4), 4018055.

Palttala, P., Boano, C., Lund, R., and Vos, M. (2012). “Communication Gaps in Disaster Management: Perceptions by Experts from Governmental and Non-Governmental Organizations.” *Journal of Contingencies and Crisis Management*, 20(1), 2–12.

Paterson, S. K., Pelling, M., Nunes, L. H., de Araújo Moreira, F., Guida, K., and Marengo, J. A. (2017). “Size does matter: City scale and the asymmetries of climate change adaptation in three coastal towns.” *Geoforum*, Elsevier Ltd, 81, 109–119.

Patterson, T. (2017). “How Houston’s layout may have made its flooding worse.” *CNN*.

Phelps, C., Heidl, R., and Wadhwa, A. (2012). “Knowledge, Networks, and Knowledge Networks: A Review and Research Agenda.” *Journal of Management*, 38(4), 1115–1166.

Qian, Z. (2010). “Without zoning: Urban development and land use controls in Houston.” *Cities*, 27(1), 31–41.

Rajput, A. A., Li, Q., Zhang, C., and Mostafavi, A. (2020). “Temporal network analysis of inter-organizational communications on social media during disasters: A study of Hurricane Harvey in Houston.” *International Journal of Disaster Risk Reduction*, 46(Under Review).

Rasoulkhani, K., Logasa, B., Reyes, M. P., and Mostafavi, A. (2017). “Agent-based Modeling Framework for Simulation of Complex Adaptive Mechanisms Underlying Household Water Conservation Technology Adoption.” *The 2017 Winter Simulation Conference*, IEEE, 1109–1120.

Rasoulkhani, K., and Mostafavi, A. (2018a). “Resilience as an emergent property of human-infrastructure dynamics: A multi-agent simulation model for characterizing regime shifts and tipping point behaviors in infrastructure systems.” *PLoS ONE*, 13(11), e0207674.

Rasoulkhani, K., and Mostafavi, A. (2018b). “Resilience as an emergent property of human-infrastructure dynamics: A multi-agent simulation model for characterizing regime shifts and tipping point behaviors in infrastructure systems.” *PLoS ONE*, 13(11), e0207674.

Reed, M. S. (2008). “Stakeholder participation for environmental management: A literature review.” *Biological Conservation*.

Rittel, H. W. J., and Webber, M. M. (1973). “Dilemmas in a general theory of planning.” *Policy Sciences*, 4(2), 155–169.

Rivera, M. T., Soderstrom, S. B., and Uzzi, B. (2010). “Dynamics of dyads in social networks: Assortative, relational, and proximity mechanisms.” *Annual Review of Sociology*, 36, 91–115.

Robins, G., and Alexander, M. (2004). “Small Worlds Among Interlocking Directors: Network Structure and Distance in Bipartite Graphs.” *Computational & Mathematical Organization Theory*, 10(1), 69–94.

Robins, G., Pattison, P., Kalish, Y., and Lusher, D. (2007). “An introduction to exponential random graph (p*) models for social networks.” *Social Networks*, 29(2), 173–191.

Robins, G., Pattison, P., and Wasserman, S. (1999). “Logit models and logistic regressions for social networks: III. Valued relations.” *Psychometrika*, 64(3), 371–394.

Rombach, M. P., Porter, M. A., Fowler, J. H., and Mucha, P. J. (2014). “Core-Periphery Structure in Networks.” *SIAM Journal on Applied mathematics*, SIAM, 74(1), 167–190.

Ros, M., Schwartz, S. H., and Surkiss, S. (1999). “Basic individual values, work values, and the meaning of work.” *Applied Psychology*, 48(1), 49–71.

Rossa, F. Della, Dercole, F., and Piccardi, C. (2013). “Profiling core-periphery network structure by random walkers.” *Scientific Reports*, Nature Publishing Group, 3, 1–5.

Rubinov, M., and Sporns, O. (2010). “Complex network measures of brain connectivity: Uses and interpretations.” *NeuroImage*, 52(3), 1059–1069.

Sadri, A. M., Ukkusuri, S. V., Lee, S., Clawson, R., Aldrich, D., Nelson, M. S., Seipel, J., and Kelly, D. (2018). “The role of social capital, personal networks, and emergency responders in post-disaster recovery and resilience: a study of rural communities in Indiana.” *Natural Hazards*, 90(3), 1377–1406.

Sallenger, A. H., Doran, K. S., and Howd, P. A. (2012). “Hotspot of accelerated sea-level rise on the Atlantic coast of North America.” *Nature Climate Change,* Nature Publishing Group, 2(12), 884–888.

Sandercock, L. (2017). “Towards a Planning Imagination for the 21St Century.” *Contemporary Movements in Planning Theory: Critical Essays in Planning Theory: Volume 3,* 413–421.

Saracco, F., Di Clemente, R., Gabrielli, A., and Squartini, T. (2015). “Randomizing bipartite networks: The case of the World Trade Web.” *Scientific Reports,* 5.

Saracco, F., Di Clemente, R., Gabrielli, A., and Squartini, T. (2016). “Detecting early signs of the 2007-2008 crisis in the world trade.” *Scientific Reports,* 6.

Schilling, M. A., and Phelps, C. C. (2007). “Interfirm collaboration networks: The impact of large-scale network structure on firm innovation.” *Management Science,* 53(7), 1113–1126.

Schneider, C. M., Belik, V., Couronné, T., Smoreda, Z., and González, M. C. (2013). “Unravelling daily human mobility motifs.” *Journal of the Royal Society Interface,* Royal Society, 10(84).

Scholz, J. T., Berardo, R., and Kile, B. (2008). “Do networks solve collective action problems? Credibility, search, and collaboration.” *Journal of Politics*, Cambridge University Press New York, USA, 70(2), 393–406.

Schreiber, C., and Carley, K. M. (2005). “Ineffective Organizational Practices at NASA: A Dynamic Network Analysis.” *SSRN Electronic Journal*.

Schrock, G., Bassett, E. M., and Green, J. (2015). “Pursuing Equity and Justice in a Changing Climate: Assessing Equity in Local Climate and Sustainability Plans in U.S. Cities.” *Journal of Planning Education and Research*, 35(3), 282–295.

Schwartz, S. H. (2012). “An Overview of the Schwartz Theory of Basic Values.” *Online Readings in Psychology and Culture*, 2(1).

Schweinberger, M., Petrescu-Prahova, M., and Vu, D. Q. (2014). “Disaster response on September 11, 2001 through the lens of statistical network analysis.” *Social Networks*, 37(1), 42–55.

Scott, J., Carrington, P., Borgatti, S. P., and Halgin, D. S. (2015). “Analyzing Affiliation Networks.” *The SAGE Handbook of Social Network Analysis*, Sage Thousand Oaks, CA, 1, 417–433.

Scott, W. R. (2013). “Institutions and organizations: Ideas, interests, and identities.” *Sage publications*, Sage publications.

Shalizi, C. R., and Thomas, A. C. (2011). “Homophily and contagion are generically confounded in observational social network studies.” *Sociological Methods and Research*, 40(2), 211–239.

Shelton, K. (2017). *Power Moves: Transportation, Politics, and Development in Houston*. University of Texas Press.

Shen, Q., Huang, W., and Qi, D. (2018). “Integrated modeling of Typhoon Damrey’s effects on sediment resuspension and transport in the north passage of Changjiang

Estuary, China." *Journal of Waterway, Port, Coastal and Ocean Engineering*, American Society of Civil Engineers, 144(6), 04018015.

Shilcutt, K., and Asgarian, R. (2017). "The Deliberate Flooding of West Houston." *Issue of Houstonia*, https://www.houstoniamag.com/news-and-city-life/20.

Shutters, S. T., Muneepeerakul, R., and Lobo, J. (2015). "Quantifying urban economic resilience through labour force interdependence." *Palgrave Communications*.

Siegel, J. M. (2000). "Emotional injury and the Northridge, California earthquake." *Natural Hazards Review*, 1(4), 204–211.

Da Silva, M. R., Ma, H., and Zeng, A. P. (2008). "Centrality, network capacity, and modularity as parameters to analyze the core-periphery structure in metabolic networks." *Proceedings of the IEEE*, IEEE, 96(8), 1411–1420.

Soldz, S., and Andersen, L. L. (2012). "Expanding subjectivities: Introduction to the special issue on 'New Directions in Psychodynamic Research.'" *Journal of Research Practice*, American Society of Civil Engineers, 8(2), 123–132.

Solé-Ribalta, A., Gómez, S., and Arenas, A. (2016). "Congestion Induced by the Structure of Multiplex Networks." *Physical Review Letters*.

Srivastava, P., and Mostafavi, A. (2018). "Challenges and opportunities of crowdsourcing and participatory planning in developing infrastructure systems of smart cities." *Infrastructures*.

Stevens, M. R., Lyles, W., and Berke, P. R. (2014). "Measuring and Reporting Intercoder Reliability in Plan Quality Evaluation Research." *Journal of Planning Education and Research*, 34(1), 77–93.

Sutley, E. J., van de Lindt, J. W., and Peek, L. (2017). "Community-Level Framework for Seismic Resilience. I: Coupling Socioeconomic Characteristics and Engineering Building Systems." *Natural Hazards Review*, 18(3), 04016014.

Taeby, M., and Zhang, L. (2018). "Stakeholder Value Systems on Disaster Resilience of Residential Buildings." *ICCREM 2018: Construction Enterprises and Project Management - Proceedings of the International Conference on Construction and Real Estate Management 2018*, 10–17.

Taeby, M., and Zhang, L. (2019). "Exploring Stakeholder Views on Disaster Resilience Practices of Residential Communities in South Florida." *Natural Hazards Review*, 20(1).

Taylor, O. S., Lee, T. A. I., and Lester, A. P. (2015). "Hazard and Risk Potential of Unconventional Hydrocarbon Development-Induced Seismicity within the Central United States." *Natural Hazards Review*, American Society of Civil Engineers, 16(4), 4015008.

Therrien, M. C., Jutras, M., and Usher, S. (2019). "Including quality in Social network analysis to foster dialogue in urban resilience and adaptation policies." *Environmental Science and Policy*, 93, 1–10.

Tompkins, E. L., Few, R., and Brown, K. (2008). "Scenario-based stakeholder engagement: Incorporating stakeholders preferences into coastal planning for climate change." *Journal of Environmental Management*, 88(4), 1580–1592.

Traud, A. L., Kelsic, E. D., Mucha, P. J., and Porter, M. A. (2011). "Comparing community structure to characteristics in online collegiate social networks." *SIAM*

Review, 53(3), 526–543.

Traud, A. L., Mucha, P. J., and Porter, M. A. (2012). "Social structure of Facebook networks." *Physica A: Statistical Mechanics and its Applications*, 391(16), 4165–4180.

Ulanowicz, R. E., Goerner, S. J., Lietaer, B., and Gomez, R. (2009). "Quantifying sustainability: Resilience, efficiency and the return of information theory." *Ecological Complexity*, 6(1), 27–36.

Urban, W. M., and Perry, R. B. (1927). "General Theory of Value: Its Meaning and Basic Principles Construed in Terms of Interest." *The Journal of Philosophy*, 24(4), 104.

Uzzi, B. (1997). "Social structure and competition in interfirm networks: The paradox of embeddedness." *Administrative Science Quarterly*, JSTOR, 42(1), 35–67.

Uzzi, B., and Spiro, J. (2005). "Collaboration and creativity: The small world problem." *American Journal of Sociology*, 111(2), 447–504.

Van Vliet, M. T. H., Yearsley, J. R., Ludwig, F., Vögele, S., Lettenmaier, D. P., and Kabat, P. (2012). "Vulnerability of US and European electricity supply to climate change." *Nature Climate Change*, Nature Publishing Group, 2(9), 676–681.

Wagenaar, H., and Wilkinson, C. (2015). "Enacting Resilience: A Performative Account of Governing for Urban Resilience." *Urban Studies*, SAGE Publications Ltd, 52(7), 1265–1284.

Walker, B., and Salt, D. (2012). *Resilience thinking : sustaining ecosystems and people in a changing world*. Island Press.

Wang, P., Sharpe, K., Robins, G. L., and Pattison, P. E. (2009). “Exponential random graph (p *) models for affiliation networks.” *Social Networks*, 31(1), 12–25.

Ward, P. S., and Pede, V. O. (2015). “Capturing social network effects in technology adoption: The spatial diffusion of hybrid rice in Bangladesh.” *Australian Journal of Agricultural and Resource Economics*, Wiley Online Library, 59(2), 225–241.

Watson, R., Wilson, H. N., Smart, P., and Macdonald, E. K. (2018). “Harnessing Difference: A Capability-Based Framework for Stakeholder Engagement in Environmental Innovation.” *Journal of Product Innovation Management*, 35(2), 254–279.

Watts, D. J., and Strogatz, S. H. (1998). “Collective dynamics of ‘small-world’ networks.” *Nature*, Nature Publishing Group, 393(6684), 440–442.

Welborn, D. M., May, P. J., Burby, R. J., Ericksen, N. J., Handmer, J. W., Dixon, J. E., Michaels, S., and Smith, D. I. (1997). “Environmental Management and Governance: Intergovernmental Approaches to Hazards and Sustainability.” *CrossRef Listing of Deleted DOIs*, 27(2), 211.

Wiesmeth, H. (2018). “Stakeholder engagement for environmental innovations.” *Journal of Business Research*.

Wiki. (2019). “Disasters in Houston.” *Retrieved from: https://en.wikipedia.org/wiki/Timeline_of_Houston*.

Willigers, B. J. A., Bratvold, R. B., and Hausken, K. (2009). “A game theoretic approach to conflicting and evolving stakeholder preferences in the EandP industry.” *SPE Economics and Management*, 1(1), 19–26.

Wimmer, A., and Lewis, K. (2010). “Beyond and Below Racial Homophily: ERG Models of a Friendship Network Documented on Facebook.” *American Journal of Sociology*.

Woodruff, S. C. (2018). “Coordinating Plans for Climate Adaptation.” *Journal of Planning Education and Research*, SAGE Publications Inc., (DOI: 10.1177/0739456X18810131).

Woodruff, S. C., and Regan, P. (2019). “Quality of national adaptation plans and opportunities for improvement.” *Mitigation and Adaptation Strategies for Global Change*, 24(1), 53–71.

Woodruff, S. C., and Stults, M. (2016). “Numerous strategies but limited implementation guidance in US local adaptation plans.” *Nature Climate Change*, 6(8), 796–802.

Zambrano Leal, A. (2012). “Sociedad de control y profesión docente. Las imposturas de un discurso y la exigencia de una nueva realidad.” *Antimicrobial Agents and Chemotherapy*, (95), 45–52.

Zanin, M., Sun, X., and Wandelt, S. (2018). “Studying the Topology of Transportation Systems through Complex Networks: Handle with Care.” *Journal of Advanced Transportation*, 2018.

Zhang, L., and El-Gohary, N. M. (2016). “Discovering Stakeholder Values for Axiology-Based Value Analysis of Building Projects.” *Journal of Construction Engineering and Management*, 142(4).

Zhang, W., Villarini, G., Vecchi, G. A., and Smith, J. A. (2018). “Urbanization exacerbated the rainfall and flooding caused by hurricane Harvey in Houston." *Nature*, 563(7731), 384–388.

Zhang, X., Martin, T., and Newman, M. E. J. (2015). "Identification of core-periphery structure in networks." *Physical Review E - Statistical, Nonlinear, and Soft Matter Physics*, APS, 91(3), 32803.

Zhou, T., Ren, J., Medo, M., and Zhang, Y. C. (2007). "Bipartite network projection and personal recommendation." *Physical Review E - Statistical, Nonlinear, and Soft Matter Physics*, 76(4).

Zhu, J., and Mostafavi, A. (2016). "Metanetwork framework for integrated performance assessment under uncertainty in construction projects." *Journal of Computing in Civil Engineering*, 31(1), 04016042.

Zhu, J., and Mostafavi, A. (2018). "Enhancing resilience in disaster response: A meta-network analysis approach." *Construction Research Congress 2018: Safety and Disaster Management - Selected Papers from the Construction Research Congress 2018*, 553–562.

APPENDIX A

SUPPLEMENTARY TABLES

Table 24 Degree Centrality at Weekly Collaboration Level.

No.	Indegree (Weekly)	Actors in the survey roster	Infrastructure sector
1	32	Harris County	Regional governance
2	31	City of Houston	Regional governance
3	22	Texas Department of Transportation	Transportation
4	16	City of Houston Department of Public Work and Engineering	Regional governance
5	15	Houston-Galveston Area Council	Regional governance
No.	**Outdegree (Weekly)**	**Survey respondents**	**Infrastructure Sector**
1	36	Harris County Flood Control District	Flood control
2	34	Harris County Office of Homeland Security and Emergency Management	Emergency Response
3	25	H-GAC Community and Environmental Planning	Community development
4	23	Harris County Engineering Department	Community development
5	23	H-GAC Public Services Department	Community development
6	20	Harris County Judges Office	Regional governance
7	15	Blueprint Houston	Community development
8	15	H-GAC The Gulf Coast Economic Development District	Community development
9	15	Private company[††]	Community development
10	12	City of Clear Lake Department of Engineering	Community development

---

[††] The name of the company cannot be disclosed due to the privacy policy.

Table 25 Degree Centrality at Monthly Collaboration Level.

No.	Indegree (Monthly)	Actors in the survey roster	Infrastructure sector
1	59	Harris County	Regional governance
2	49	City of Houston	Regional governance
3	39	Harris County Office of Emergency Management	Emergency response
4	35	Harris County Flood Control District	Flood control
5	34	Houston-Galveston Area Council	Regional governance

No.	Outdegree (Monthly)	Survey respondents	Infrastructure Sector
1	52	Harris County Engineering Department	Community development
2	51	H-GAC Community and Environmental Planning	Community development
3	50	H-GAC Public Services Department	Community development
4	46	Harris County Flood Control District	Flood control
5	45	Harris County Office of Homeland Security and Emergency Management	Emergency response
6	34	Blueprint Houston	Community development
7	34	City of Clear Lake Department of Engineering	Community development
8	21	Harris County Judges Office	Regional governance
9	28	City of Seabrook Mayor’s Office	Comprehensive
10	28	LJA Engineering and Texas Floodplain Management Association	Flood control

Table 26 Potential Boundary Spanners at Weekly Collaboration.

Betweenness	Actors in the survey roster	Infrastructure sector
0.1350	Harris County	Regional governance
0.1300	City of Houston	Regional governance
0.0640	Texas Department of Transportation	Transportation
0.0531	City of Houston Department of Public Work and Engineering	Regional governance
0.0461	Federal Emergency Management Agency	Emergency response
Betweenness	**Survey respondents**	**Infrastructure Sector**
0.1873	Harris County Office of Homeland Security and Emergency Management	Emergency Response
0.1564	Harris County Flood Control District	Flood Control
0.0822	H-GAC Community and Environmental Planning	Community development
0.0747	H-GAC Public Services Department	Community development
0.0734	Harris County Engineering Department	Community development
0.0518	Blueprint Houston	Community development
0.0460	Center of Houston's Future	Community development
0.0404	Harris County Judges Office	Regional governance
0.0352	City of Houston Parks and Recreation Department	Community development
0.0305	Private company	Community development

Table 27 Potential Boundary Spanners at Monthly Collaboration.

Betweenness	Actors in the survey roster	Infrastructure sector
0.1278	Harris County	Regional governance
0.0869	City of Houston	Regional governance
0.0640	Harris County Office of Emergency Management	Emergency response
0.0441	United Way of Greater Houston	Community development
0.0403	Houston-Galveston Area Council	Regional governance
Betweenness	**Survey respondents**	**Infrastructure Sector**
0.0833	H-GAC Public Services Department	Community development
0.0776	Harris County Office of Homeland Security and Emergency Management	Emergency Response
0.0740	Harris County Engineering Department	Community development
0.0689	H-GAC Community and Environmental Planning	Community development
0.0646	Harris County Flood Control District	Flood control
0.0424	Houston Wilderness	Environmental conservation
0.0363	Blueprint Houston	Community development
0.0328	City of Clear Lake Department of Engineering	Community development
0.0256	Bayou Preservation Association	Environmental conservation
0.0219	Harris County Judges Office	Regional governance

Table 28 Infrastructure Sectors of Core Nodes at Weekly Collaboration.

	Core nodes: 38		
Infrastructure sectors	**Actors in the roster**	**Respondents**	**Percentage**
Transportation	9	3	31.60%
Community development	3	8	28.90%
Food control	1	2	7.90%
Emergency response	3	2	13.20%
Environmental conservation	0	1	2.60%
Regional governance	3	3	15.80%
Sum	**19**	**19**	**100.00%**

Table 29 Infrastructure Sectors of Core Nodes at Monthly Collaboration.

	Core nodes: 51		
Infrastructure sectors	**Actors in the roster**	**Respondents**	**Percentage**
Transportation	10	1	21.57%
Community development	5	13	35.29%
Food control	2	2	7.84%
Emergency response	4	2	11.76%
Environmental conservation	1	1	3.92%
Regional governance	5	5	19.61%
Sum	**27**	**24**	**100.00%**

Table 30 Policy Preference Satisfaction Matrix.

Categories **Policy**	**FC/GO**	**FC/NGO**	**ER/GO**	**…**	**EC/GO**	**EC/NGO**
P1	A_{11}	A_{12}	A_{13}	A_{1j}	$A_{1,9}$	$A_{1,10}$
P2	A_{21}	A_{22}	A_{23}	A_{2j}	A_{29}	$A_{2,10}$
…	$A_{i,1}$	A_{i2}	A_{i3}	A_{ij}	A_{i9}	$A_{i,10}$
P16	$A_{16,1}$	$A_{16,2}$	$A_{16,3}$	$A_{16,j}$	$A_{16,9}$	$A_{16,10}$

Liner Transformation

$$A_{ij} = \frac{(R_o - 1)}{(5 - 1)} \times 10 \tag{A1}$$

In Equation A1, R_o means the average policy ratings before transformation

Table 31 Policy Preference Aggregation Based on Obtained Scores.

Policy \ Categories	FC/GO	FC/NGO	…	Sum	Percent
P1	A_{11}	A_{12}	A_{1j}	$P_{a1} = \sum_{j=1}^{10} A_{1j}$	$P_{a1}/100$
P2	A_{21}	A_{22}	A_{2j}	$P_{a2} = \sum_{j=1}^{10} A_{2j}$	$P_{a2}/100$
…	A_{i1}	A_{i2}	A_{ij}	$P_{ai} = \sum_{j=1}^{10} A_{ij}$	$P_{ai}/100$
Sum	$S_{a1} = \sum_{i=1}^{16} A_{i1}$	$S_{a2} = \sum_{i=1}^{16} A_{i2}$	$S_{aj} = \sum_{i=1}^{16} A_{ij}$		
Percent	$S_{a1}/160$	$S_{a2}/160$	$S_{aj}/160$		

Note: S_a represents stakeholder aggregation and P_a represents policy aggregation. The policy preference aggregations are only based on the transformed average level of policy support, and variances do not have the aggregations.

Policy-based plan integration index: D_{AB}

$$D_{AB} = 2 \times \frac{\frac{N_O}{N_A} \times \frac{N_O}{N_B}}{\left(\frac{N_O}{N_A} + \frac{N_O}{N_B}\right)} \tag{A2}$$

In Equation A2, N_A and N_B represent the number of incorporated survey policy actions in plans A and B. N_O represents the number of policy actions included in both plans A and B.

Table 32 Policy Preference Satisfaction Matrix of Variance in Level of Policy Support.

Policy	FC/G	FC/N	ER/G	ER/N	TT/G	TT/N	CD/G	CD/N	EC/G	EC/N
P1	0.86	0.89	0.72	0.79	0.48	0.22	0.52	0.87	0.16	0.56
P2	0.49	0.25	0.57	0.40	0.12	0.00	0.82	0.71	0.40	0.61
P3	0.46	0.25	0.52	0.77	0.61	0.89	0.73	0.52	0.24	0.41
P4	0.55	0.25	0.49	0.46	0.75	0.22	0.57	0.59	0.24	0.44
P5	0.45	1.56	0.55	0.70	0.24	0.22	0.57	0.61	0.64	0.84
P6	0.52	0.00	0.74	0.52	0.24	0.22	0.65	0.53	0.64	0.89
P7	0.64	0.00	0.57	0.62	0.20	0.67	0.47	0.43	1.04	0.69
P8	0.52	0.00	0.50	0.49	0.41	0.89	0.50	0.42	0.40	0.29
P9	0.84	0.22	0.47	0.84	0.69	0.22	0.88	0.62	0.24	0.44
P10	0.38	0.22	0.46	0.64	0.36	0.67	0.50	0.45	0.19	0.76
P11	0.92	0.00	0.44	0.64	0.41	0.67	0.48	0.44	0.00	0.76
P12	0.63	0.22	0.75	0.54	0.69	0.00	0.62	0.92	0.19	0.54
P13	0.96	0.22	0.87	0.49	0.53	0.22	0.71	1.00	0.69	0.69
P14	0.55	1.56	0.80	0.74	0.36	0.22	0.80	1.17	0.00	0.89
P15	0.37	0.89	0.72	0.99	0.61	0.67	0.58	0.73	0.00	0.41
P16	1.23	0.22	0.94	0.71	0.78	0.22	0.60	0.89	0.64	0.60

Table 33 Results of Plan Evaluation and Policy Preference Aggregation for the CIP.

Policy	FC/G	FC/N	ER/G	ER/N	TT/G	TT/N	CD/G	CD/N	EC/G	EC/N	Sum	PCT
P4	7.14	8.75	7.34	7.50	7.50	6.67	7.96	7.58	8.50	9.00	77.94	77.9%
P5	5.54	6.67	5.71	5.96	6.43	6.67	6.35	6.75	8.50	6.50	65.07	65.1%
P8	6.73	10.00	7.45	8.08	7.14	6.67	7.43	7.65	7.50	7.25	75.90	75.9%
P9	7.14	8.33	7.61	7.31	7.14	5.83	7.24	7.34	9.00	8.50	75.45	75.4%
P10	7.83	8.33	8.24	8.08	7.81	7.50	8.09	7.95	8.13	7.00	78.97	79.0%
P11	7.32	10.00	7.93	8.08	7.14	7.50	7.83	8.18	7.50	7.00	78.48	78.5%
P16	8.00	8.33	7.22	6.35	6.79	5.83	7.70	6.67	8.50	7.50	72.88	72.9%
Sum	49.71	60.42	51.49	51.35	49.96	46.67	52.60	52.13	57.63	52.75		
PCT	31.1%	37.8%	32.2%	32.1%	31.2%	29.2%	32.9%	32.6%	36.0%	33.0%		

Table 34 Results of Plan Evaluation and Policy Preference Aggregation for the RCP.

Policy	**FC/G**	**FC/N**	**ER/G**	**ER/N**	**TT/G**	**TT/N**	**CD/G**	**CD/N**	**EC/G**	**EC/N**	**Sum**	**PCT**
P1	7.50	8.33	7.61	8.08	8.44	5.83	8.22	7.92	9.50	8.00	79.43	79.4%
P4	7.14	8.75	7.34	7.50	7.50	6.67	7.96	7.58	8.50	9.00	77.94	77.9%
P9	7.14	8.33	7.61	7.31	7.14	5.83	7.24	7.34	9.00	8.50	75.45	75.4%
P10	7.83	8.33	8.24	8.08	7.81	7.50	8.09	7.95	8.13	7.00	78.97	79.0%
P14	7.86	6.67	7.34	7.29	7.81	5.83	7.57	6.81	10.00	7.25	74.43	74.4%
P15	9.11	8.33	7.99	7.31	7.19	7.50	8.29	7.26	10.00	8.25	81.22	81.2%
P16	8.00	8.33	7.22	6.35	6.79	5.83	7.70	6.67	8.50	7.50	72.88	72.9%
Sum	54.58	57.08	53.35	51.91	52.68	45.00	55.07	51.53	63.63	55.50		
PCT	34.1%	35.7%	33.3%	32.4%	32.9%	28.1%	34.4%	32.2%	39.8%	34.7%		

Table 35 Policy Preference Evaluation in the RTP.

Policy	**FC/G**	**FC/N**	**ER/G**	**ER/N**	**TT/G**	**TT/N**	**CD/G**	**CD/N**	**EC/G**	**EC/N**	**Sum**	**PCT**
P4	7.14	8.75	7.34	7.50	7.50	6.67	7.96	7.58	8.50	9.00	77.94	77.9%
PCT	4.5%	5.5%	4.6%	4.7%	4.7%	4.2%	5.0%	4.7%	5.3%	5.6%		

Table 36 Policy Preference Evaluation in the HMP.

Policy	FC/G	FC/N	ER/G	ER/N	TT/G	TT/N	CD/G	CD/N	EC/G	EC/N	Sum	PCT
P1	7.50	8.33	7.61	8.08	8.44	5.83	8.22	7.92	9.50	8.00	79.43	79.4%
P2	8.33	8.75	6.68	6.15	5.36	5.00	7.84	6.42	7.50	6.75	68.78	68.8%
P3	7.33	8.75	7.61	7.50	7.19	8.33	7.96	7.50	9.00	8.25	79.42	79.4%
P4	7.14	8.75	7.34	7.50	7.50	6.67	7.96	7.58	8.50	9.00	77.94	77.9%
P8	6.73	10.00	7.45	8.08	7.14	6.67	7.43	7.65	7.50	7.25	75.90	75.9%
P9	7.14	8.33	7.61	7.31	7.14	5.83	7.24	7.34	9.00	8.50	75.40	75.4%
P10	7.83	8.33	8.24	8.08	7.81	7.50	8.09	7.95	8.13	7.00	78.97	79.0%
P11	7.32	10.00	7.93	8.08	7.14	7.50	7.83	8.18	7.50	7.00	78.48	78.5%
P14	7.86	6.67	7.34	7.29	7.81	5.83	7.57	6.81	10.00	7.25	74.43	74.4%
P15	9.11	8.33	7.99	7.31	7.19	7.50	8.29	7.26	10.00	8.25	81.22	81.2%
P16	8.00	8.33	7.22	6.35	6.79	5.83	7.70	6.67	8.50	7.50	72.88	72.9%
Sum	84.30	94.58	83.01	81.71	79.51	72.50	86.13	81.28	95.13	84.75		
PCT	52.7%	59.1%	51.9%	51.1%	49.7%	45.3%	53.8%	50.8%	59.5%	53.0%		

Table 37 Degree of Policy Consistency between Examined Plans.

No. of included policy in Plan A	No. of included policy in Plan B	No. of same policy included in plans A and B	Value Consistency Index: D_{AB}
HMP, 11	RTP, 1	1	16.7%
HMP, 11	CIP, 7	6	66.7%
HMP, 11	RCP, 7	7	77.7%
CIP, 7	RTP, 1	1	25%
CIP, 7	RCP, 7	4	57.1%
RCP, 7	RTP, 1	1	25%

Table 38 Data Extraction from the 2040 Regional Transportation Plan (RTP).

Stakeholders	Plans/Policies	Tasks/Projects	Infrastructures
Houston-Galveston Area Council (H–GAC)	2040 Regional Transportation Plan (RTP)	Expand roadway network	BW8
Toll Road Authority of Counties	Transportation Improvement Plan (TIP)	Enhance state of good repair	SH99
TxDOT	Clean Water Act	Wetland mitigation process	IH10E
USACE			IH10W
Texas Parks and Wildlife Department (TPWD)			IH45N
Congestion Management Press			IH45S
			IH610
			IH69 Southwest
			SH249
			SH288
			US59N
			US290

Table 39 Data Extraction from the Capital Improvement Program (CIP).

Stakeholders	Plans/Policies	Tasks/Projects	Infrastructures
Harris County Flood Control District (HCFCD)	Capital Improvement Plan	Floodway Right-Of-Way Acquisition on Armand Bayou	Houston Ship Channel
USACE	Floodplain acquisition and preservation	Site Stabilization of Red Bluff Stormwater Detention Basin	Armand Bayou
FEMA	Main channel flood damage reduction	Channel Conveyance Improvements along C106-03-00	Little White Oak Bayou
Texas Water Development Board	Tributary flood damage reduction	Channel C147 Flood Risk Reduction Study	White Oak Bayou
National Weather Service	Major maintenance plan	Little White Oak Flood Risk Reduction	Cypress Creek
U.S. Geological Survey	Major partnership damage reduction	Brickhouse Gully Flood Risk Reduction	Little Cypress Creek
	Frontier plan	Excavation of Inwood Stormwater Detention Basin	Spring Creek
	North Canal Bypass Plan	Right-of-Way Acquisition for Long Term Maintenance Site Improvements	Halls Bayou
	The National Flood Insurance Program	Excavation of Homestead Stormwater Detention Basin	Hunting Bayou
	Home Buyout	Bender Environmental Mitigation Bank Site Permitting	South Mayde Creek
		Cypress Creek Overflow Management Study	Horsepen Creek
		Channel Conveyance Improvements Along K163-00-00	Brickhouse Gully
		Little Cypress Creek SubRegional Frontier Program Management	Greens Bayou
		Channel Conveyance Improvements along L112-01-00	Smith Road Channel
		Acquisition of Right-of-way for Mueschke West Stormwater Detention Basin	Cedar Bayou

Table 40 Data Extraction from the Capital Improvement Program (CIP) Continued.

Stakeholders	Plans/Policies	Tasks/Projects	Infrastructures
		Greens Bayou Federal Flood Risk Management Project	Mason Creek
		Halls Ahead Flood Risk Reduction Program Implementation	Langham Creek
		Engineering report to reduce flood risks along channel P118-26-00	Spring Branch Creek
		Smith Road Channel Diversion	Bear Creek
		Design construction of the Lauder Road Stormwater Detention Basin	Lake Creek
		Design project preparation of Hopper Road Stomwater Detention Basin	Buffalo Bayou
		Feasibility study for flood risk reduction in the Cedar Bayou Watershed	Channel B-107-00-00
		Mason Creek Stormwater Detention Basin Revegetation Environmental Enhancements	Channel C-106-03-00
		Management Design Construction associated with Upper Langham Creek Frontier Program	Channel C-147-00-00
		Revegetation of the Langham Creek Corridor	Channel F-210-00-00
		Engineering report of South Mayde Creek	Channel K-160-00-00
		Rehabilitation of channel U102-00-00 to restore conveyance capacity	Channel L-112-01-00
		Rehabilitation of channel U106-00-00 to restore conveyance capacity	Channel P-118-26-00
		Rehabilitation of channel U107-00-00 to restore conveyance capacity	Channel P-118-14-00
		Revegetation of channel U132-00-00 associated with the Upper Langham Creek Frontier	Channel U-102-00-00
		Greenhouse Stormwater Detention Basin Construction	Channel U-106-00-00

Table 41 Data Extraction from the Capital Improvement Program (CIP) Continued.

Stakeholders	Plans/Policies	Tasks/Projects	Infrastructures
		Revegetation of the Greenhouse Stormwater Detention Basin	Channel U-107-00-00
		Design construction of channel along W129-00-00	Channel U-132-00-00
		Spring Branch Creek Stabilization	Channel W-129-00-00
		Flood risk reduction in Cedar Bayou watershed	Sims Bayou
		Construction High Flow Diversion Channel	Red Bluff Stormwater Detention Basin
			Inwood Stormwater Detention Basin
			Homestead Stormwater Detention Basin
			Lauder Road Stormwater Detention Basin
			Hopper Road Stormwater Detention Basin
			Mason Creek Stormwater Detention Basin
			Greenhouse Stormwater Detention Basin
			The Addicks Reservoir
			The Barker Reservoir
			Mueschke West Stormwater Detention

Table 42 Data Extraction from the Gulf-Houston Regional Conservation Plan (RCP).

Stakeholders	Plans/Policies	Tasks/Projects	Infrastructures
Katy Prairie Conservancy	The Gulf-Houston RCP	Katy Prairie Acquisition Restoration Project Phase 1 & 2	Lake Creek
Houston Parks Board	Bayou Greenways Initiative	Clear Creek Linear Park Project	Cypress Creek
Texas Parks & Wildlife Dept.	Prairie Conservation Initiative	Virginia Point Shoreline Protection Estuarine Restoration	Spring Creek
The Nature Conservancy	Galveston Bay Habitat Acquisition Easements Initiative	Coastal Heritage Preserve	Buffalo Bayou
Artist Boat	Galveston Bay Oyster Reefs Migratory Bird Habitat Initiative	Anahuac NWR Coastal Marsh Acquisition	Clear Creek
Coastal Conservation Association of Texas		Hitchcock Prairie West Galveston Bay Conservation Corridor Habit Preservation	San Jacinto River
Armand Bayou Nature Center		Mid Upper Texas Coast Artificial Reef Freeport Artificial Reef Project	Trinity River
Houston Audubon		Galveston Bay Sustainable Oyster Reef Restoration	Katy Prairie Land
Texas Agricultural Land Trust		Oyster Reef Restoration in East Bay	Coastal Wetlands
Galveston Bay Foundation		Armand Prairie Land Acquisition	Galveston Bay
Scenic Galveston		San Bernard Woods Preserve	
The Conservation Fund		Bolivar Peninsula Habitat Acquisition Restoration Enhancement	
Trust for Public Land		Texas Farms Ranch Conservation Program	

Table 43 Correspondent Relationships between the Nodes and Numbers (Actors).

Node Number	Node Name	Node Number	Node Name
1	H GAC	2	Toll Road Authority of Counties
3	TxDOT	4	HCFCD
5	USACE	6	FEMA
7	Texas Water Development Board	8	National Weather Service
9	U.S. Geological Survey	10	Katy Prairie Conservancy
11	Houston Parks Board	12	Texas Parks Wildlife Dept
13	The Nature Conservancy	14	Artist Boat
15	Coastal Conservation Association of Texas	16	Armand Bayou Nature Center
17	Houston Audubon	18	Texas Agricultural Land Trust
19	Galveston Bay Foundation	20	Congestion Management Press
21	City of Houston Fire Dept.	22	Houston Transtar
23	City of Houston City Council	24	Harris County Engineering Dept
25	HUD	26	Houston Dept of Public Works Engineering
27	Scenic Galveston	28	The Conservation Fund
29	Trust for Public Land	30	City of Houston Housing Community Development Dept.

Table 44 Correspondent Relationships between the Nodes and Numbers (Plans and Policies).

Node Number	Node Name	Node Number	Node Name
101	2040 Regional Transportation Plan	102	Clean Water Act
103	Transportation Improvement Plan	104	Capital Improvement Plan
105	Floodplain Acquisition Preservation	106	Main Channel Flood Damage Reduction
107	Tributary Flood Damage Reduction	108	Major Maintenance Plan
109	Major Partnership Damage Reduction	110	Frontier Preservation
111	Cedar Bayou Master Planning Mitigation Evaluation	112	Gulf Houston Regional Conservation Plan
113	Bayou Greenways Initiative	114	Prairie Conservation Initiative
115	Galveston Bay Habitat Acquisition Easements Initiative	116	Galveston Bay Oyster Reefs Migratory Bird Habitat Initiative
117	North Canal Bypass Plan	118	The National Flood Insurance Program
119	Home Buyout		

Table 45 Correspondent Relationships between the Nodes and Numbers (Tasks and Projects).

Node Number	Node Name	Node Number	Node Name
201	Expand roadway network	202	Enhance state of good repair
203	Wetland mitigation process	204	Floodway Right-Of-Way Acquisition on Armand Bayou
205	Site Stabilization of Red Bluff Stormwater Detention Basin	206	Channel Conveyance Improvements along C106-03-00
207	Channel C147 Flood Risk Reduction Study	208	Little White Oak Flood Risk Reduction
209	Brickhouse Gully Flood Risk Reduction	210	Excavation of Inwood Stormwater Detention Basin
211	Right-of-Way Acquisition for Long Term Maintenance Site Improvements	212	Excavation of Homestead Stormwater Detention Basin
213	Bender Environmental Mitigation Bank Site Permitting	214	Cypress Creek Overflow Management Study
215	Channel Conveyance Improvements Along K163-00-00	216	Little Cypress Creek Sub-Regional Frontier Program Management
217	Channel Conveyance Improvements along L112-01-00	218	Acquisition of Right-of-way for Mueschke West Stormwater Detention Basin
219	Greens Bayou Federal Flood Risk Management Project	220	Halls Ahead Flood Risk Reduction Program Implementation
221	Engineering report to reduce flood risks along channel P118-26-00	222	Smith Road Channel Diversion
223	Design construction of the Lauder Road Stormwater Detention Basin	224	Design project preparation of Hopper Road Stomwater Detention Basin
225	Feasibility study for flood risk reduction in the Cedar Bayou Watershed	226	Feasibility study for flood risk reduction in the Cedar Bayou Watershed
227	Management Design Construction associated with Upper Langham Creek Frontier	228	Revegetation of the Langham Creek Corridor
229	Engineering report of South Mayde Creek	230	Rehabilitation of channel U102-00-00 to restore conveyance capacity
231	Rehabilitation of channel U106-00-00 to restore conveyance capacity	232	Rehabilitation of channel U107-00-00 to restore conveyance capacity
233	Rehabilitation of channel U107-00-00 to restore conveyance capacity	234	Greenhouse Stormwater Detention Basin Construction

Table 46 Correspondent Relationships between the Nodes and Numbers (Tasks and Projects) Continued.

Node Number	Node Name	Node Number	Node Name
235	Revegetation of the Greenhouse Stormwater Detention Basin	236	Design construction of channel along W129-00-00
237	Spring Branch Creek Stabilization	238	Flood risk reduction in Cedar Bayou watershed
239	Katy Prairie Acquisition Restoration Project Phase 1&2	240	Clear Creek Linear Park Project
241	Virginia Point Shoreline Protection Estuarine Restoration	242	Coastal Heritage Preserve
243	Anahuac NWR Coastal Marsh Acquisition	244	Hitchcock Prairie West Galveston Bay Conservation Corridor Habit Preservation
245	Mid Upper Texas Coast Artificial Reef	246	Freeport Artificial Reef Project
247	Galveston Bay Sustainable Oyster Reef Restoration	248	Oyster Reef Restoration in East Bay
249	Armand Prairie Land Acquisition	250	San Bernard Woods Preserve
251	Bolivar Peninsula Habitat Acquisition Restoration Enhancement	252	Texas Farms Ranch Conservation Program
253	Boat Operation	254	Fire Vehicle Operation
255	Construction High Flow Diversion Channel		

Table 47 Correspondent Relationships between the Nodes and Numbers (Human Infrastructure).

Node Number	Node Name	Node Number	Node Name
301	BW8	302	SH99
303	IH10E	304	IH10W
305	IH45N	306	IH45S
307	Bender Mitigation Bank	308	IH610
309	IH69 Southwest	310	SH249
311	SH288	312	US59N
313	US290	314	Website of Houston Transtar
315	Cell Network	316	Hydrological Gauges
317	Storm Radar	318	Jersey Village
319	Red Bluff Stormwater Detention Basin	320	Inwood Stormwater Detention Basin
321	Homestead Stormwater Detention Basin	322	Lauder Road Stormwater Detention Basin
323	Hopper Road Stormwater Detention Basin	324	Mason Creek Stormwater Detention Basin
325	Greenhouse Stormwater Detention Basin	326	The Addicks Reservoir
327	The Barker Reservoir	328	Mueschke West Stormwater Detention
329	Freeport		

Table 48 Correspondent Relationships between the Nodes and Numbers (Green Infrastructure).

Node Number	Node Name	Node Number	Node Name
401	Houston Ship Channel	402	Armand Bayou
403	Little White Oak Bayou	404	White Oak Bayou
405	Cypress Creek	406	Little Cypress Creek
407	Spring Creek	408	Halls Bayou
409	Hunting Bayou	410	South Mayde Creek
411	Horsepen Creek	412	Brickhouse Gully
413	Greens Bayou	414	Smith Road Channel
415	Cedar Bayou	416	Mason Creek
417	Langham Creek	418	Spring Branch Creek
419	Bear Creek	420	Lake Creek
421	Buffalo Bayou	422	Clear Creek
423	San Jacinto River	424	Trinity River
425	Katy Prairie Land	426	Coastal Wetlands
427	Galveston Bay	428	Channel B 107 00 00
429	Channel C 106 03 00	430	Channel C 147 00 00
431	Channel F 210 00 00	432	Channel K 160 00 00
433	Channel L 112 01 00	434	Channel P 118 26 00
435	Channel P 118 14 00	436	Channel U 102 00 00
437	Channel U 106 00 00	438	Channel U 107 00 00
439	Channel U 132 00 00	440	Channel W 129 00 00
441	Sims Bayou		

APPENDIX B

SUPPLEMENTARY FIGURES

Place text or figures/tables here.

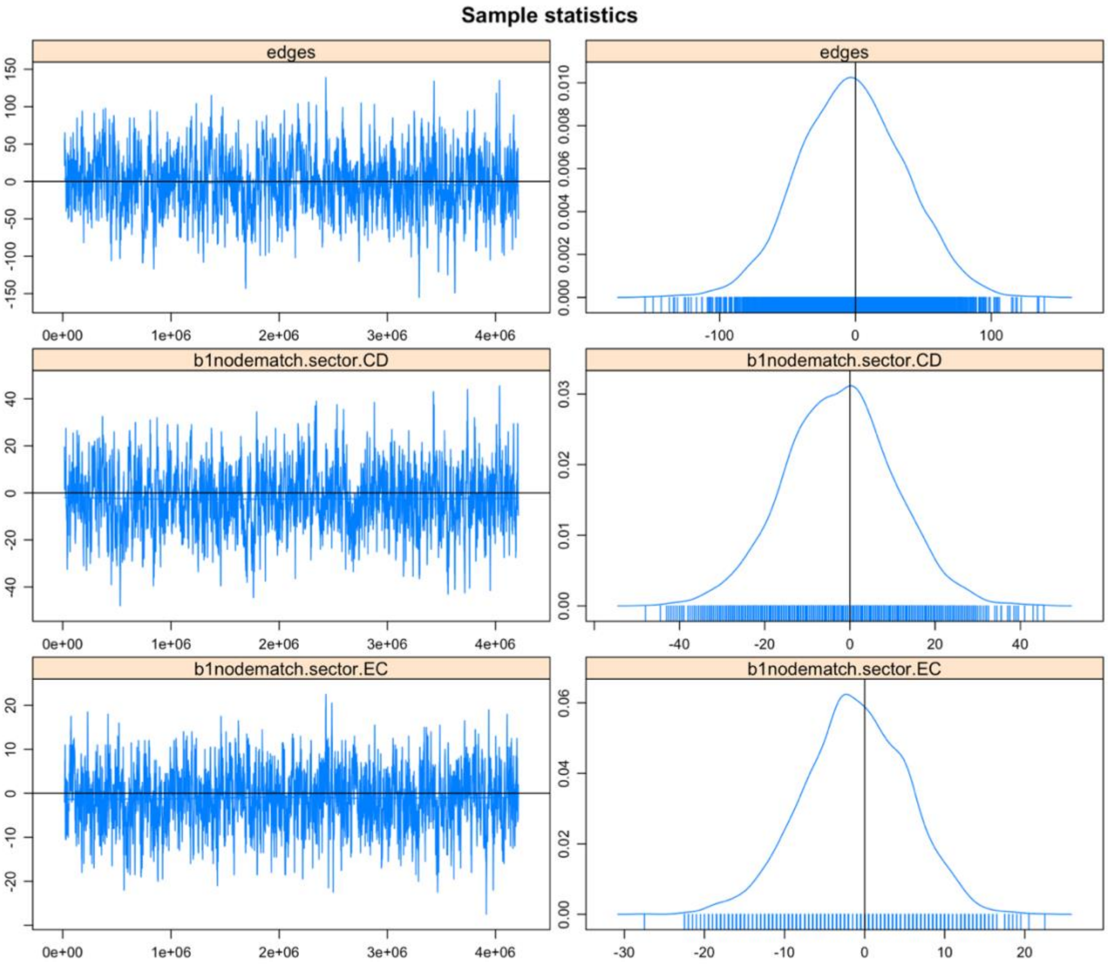


Figure 36 The MCMC diagnostic plots of ERGMs: edges, urban sectors CD and EC.

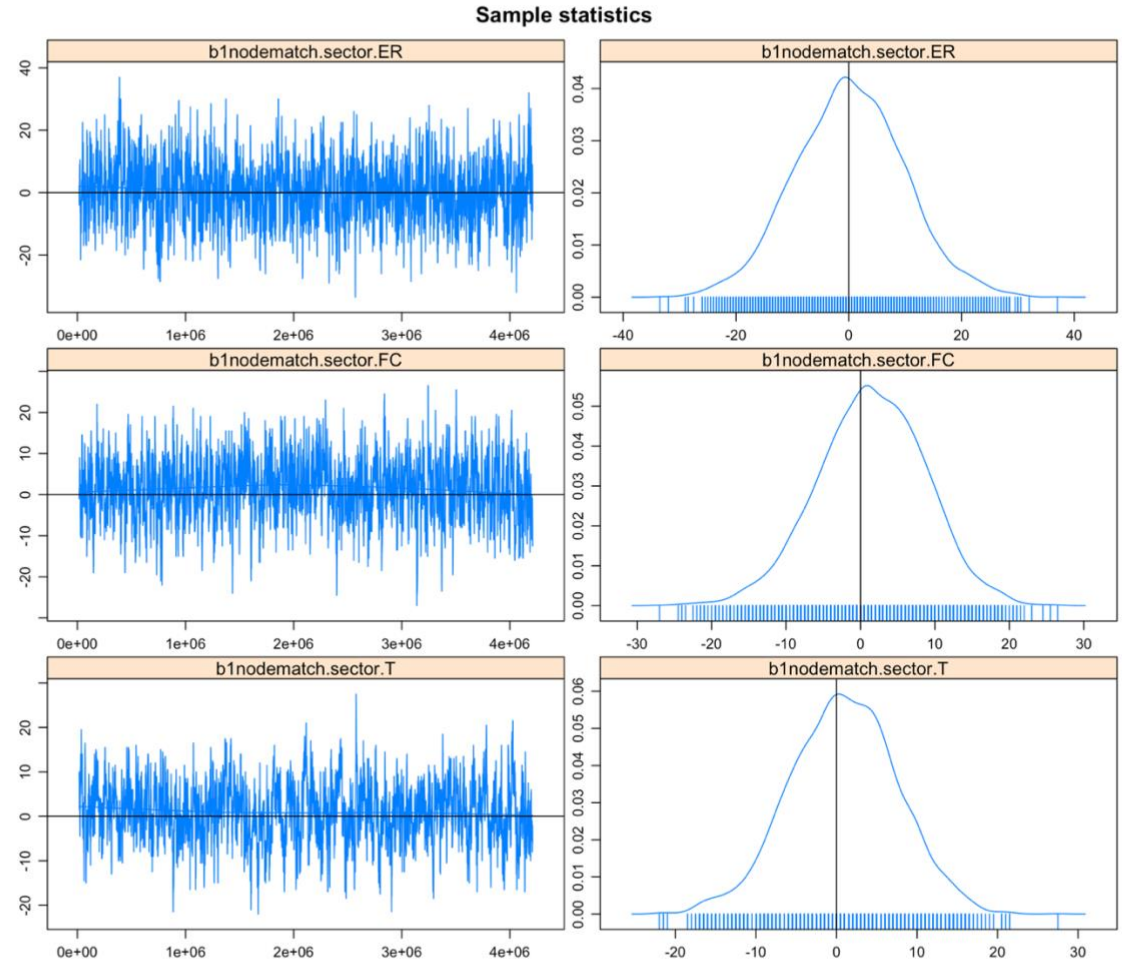


Figure 37 The MCMC diagnostic plots of ERGMs: urban sectors ER, FC and TT.

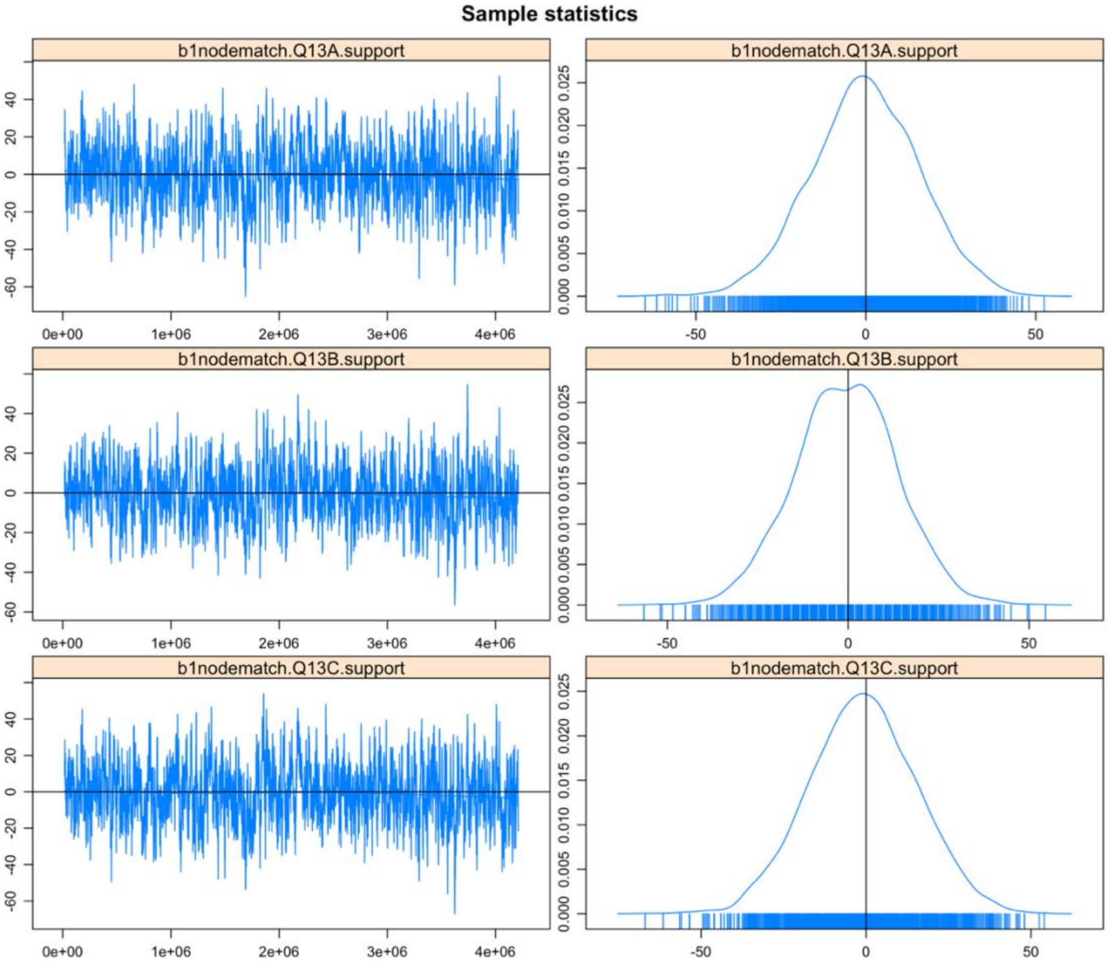


Figure 38 The MCMC diagnostic plots of ERGMs: P1, P2 and P3.

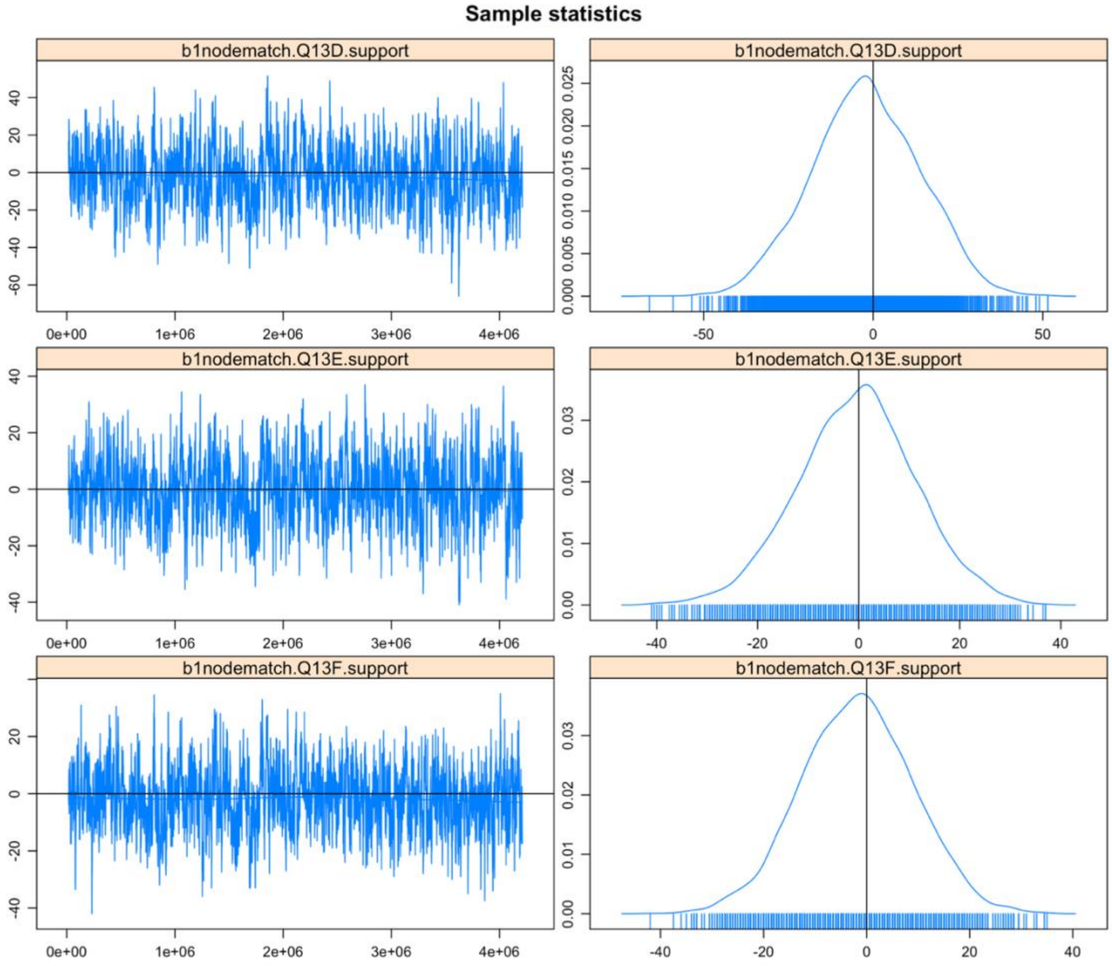


Figure 39 The MCMC diagnostic plots of ERGMs: P4, P5 and P6.

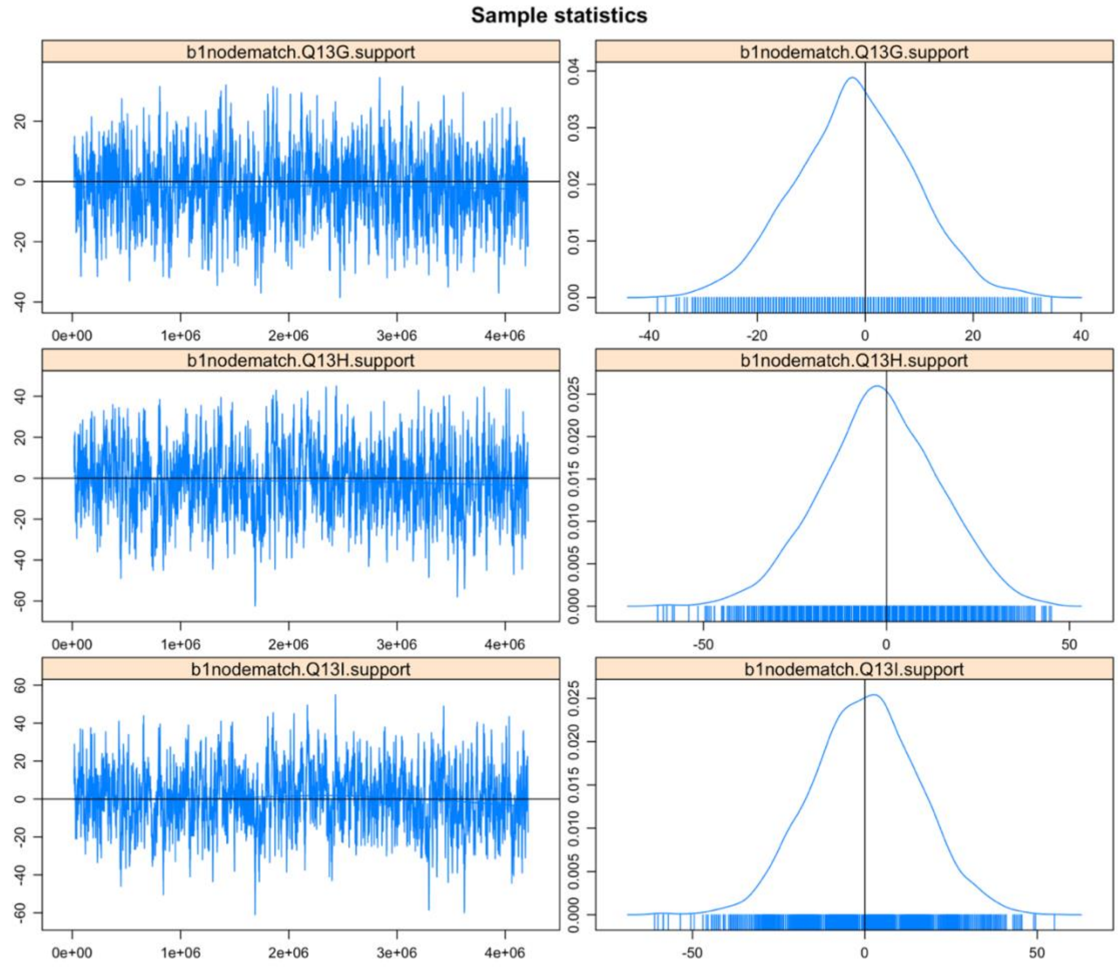


Figure 40 The MCMC diagnostic plots of ERGMs: P7, P8 and P9.

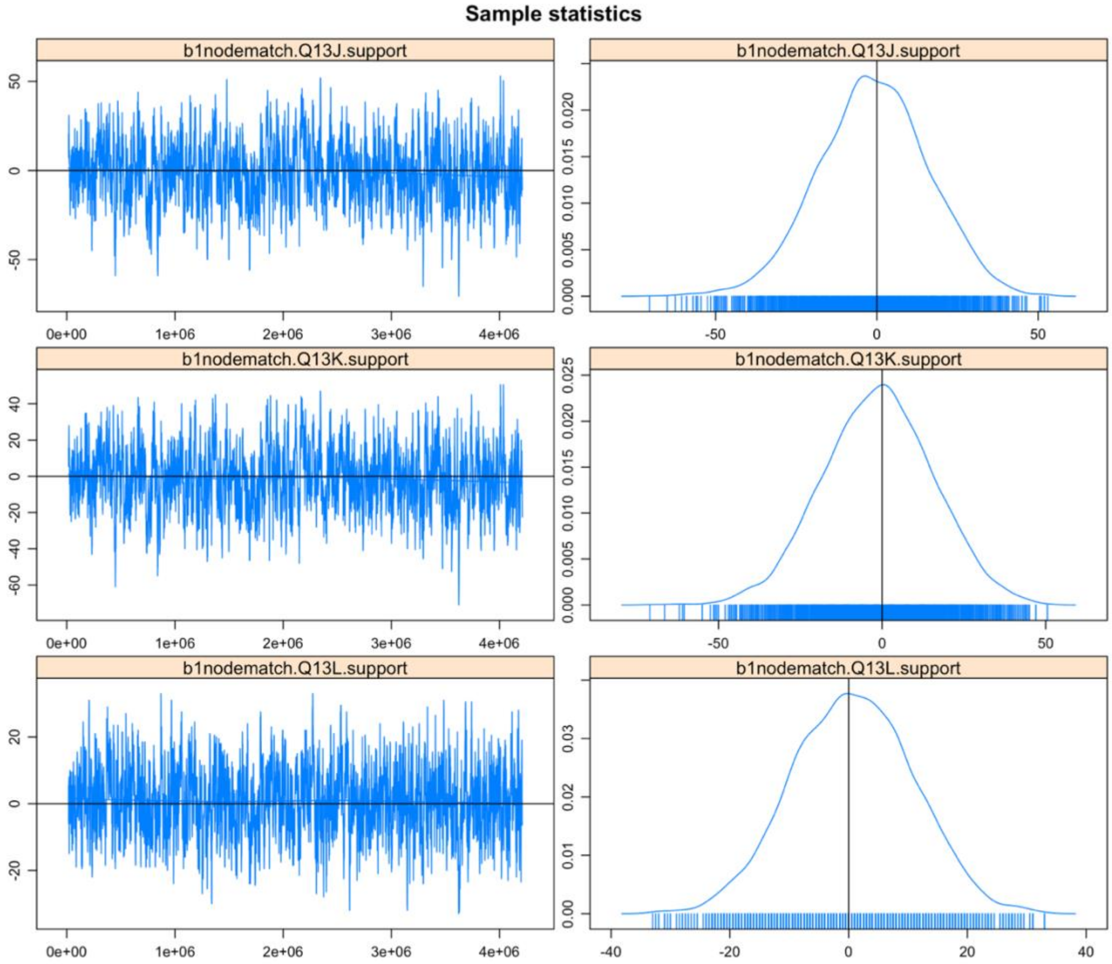


Figure 41 The MCMC diagnostic plots of ERGMs: P10, P11 and P12.

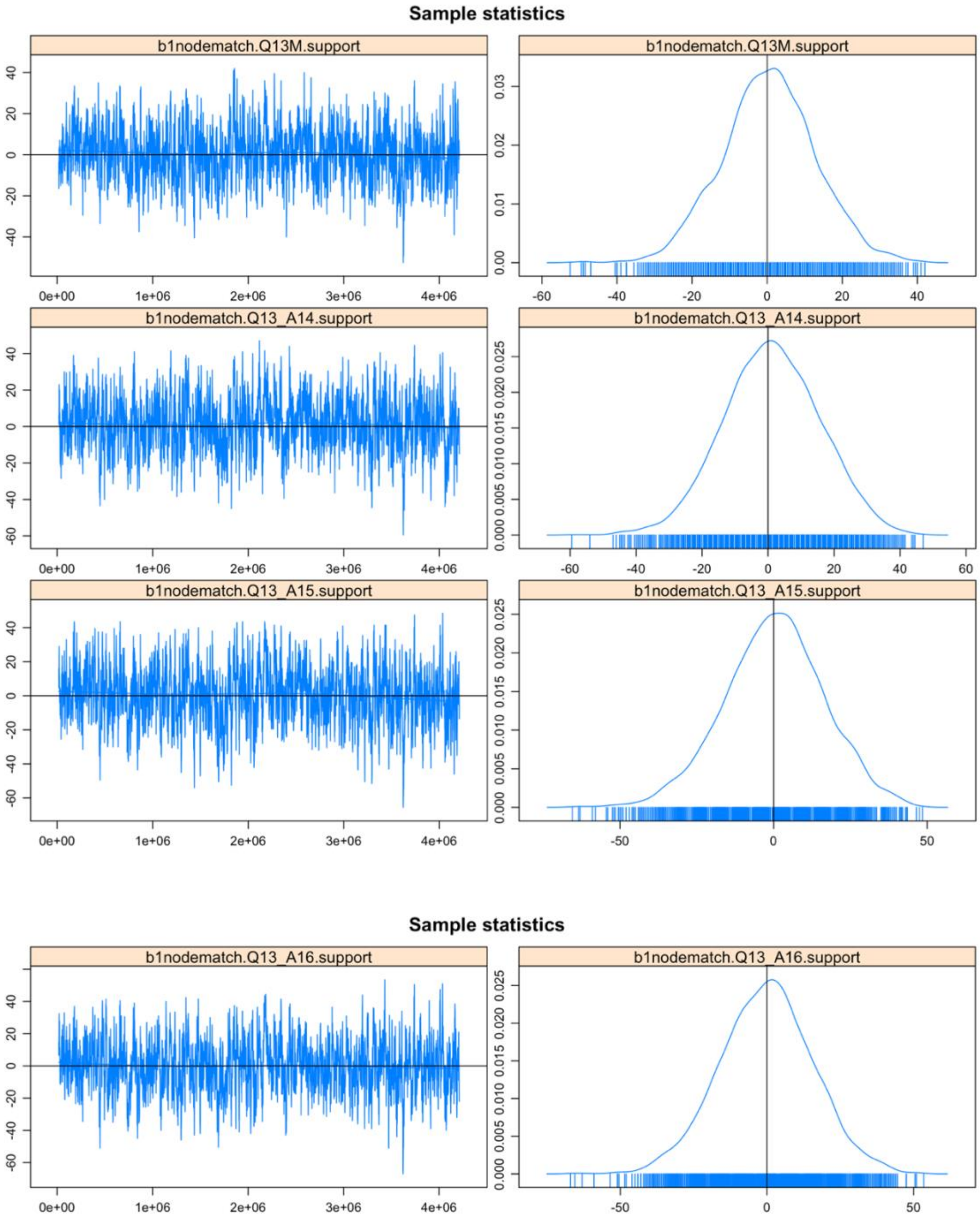


Figure 42 The MCMC diagnostic plots of ERGMs: P13, P14, P15 and P16.