Metanetwork Framework for Performance Analysis of Disaster Management System-of-Systems

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***Abstract*—The objective of this paper is to create and test an integrative framework for performance analysis of disaster management system-of-systems (DM-SoS). Effective disaster management systems and processes are critical for saving lives and protecting properties. However, the lack of integration between heterogeneous systems and entities involved in disaster management impacts coordination and operational efficiency. Greater integration and coordination among multiple heterogeneous entities is essential in improving performance and achieving network-centric disaster management. To address this gap, this paper, first examines the dimensions of analysis and a framework for a system-of-systems assessment of disaster management. In the proposed framework, the main entities include stakeholders, operations, resources, information, and infrastructure. Second, a metanetwork framework was employed to capture the network interactions among various types of entities. Then, measures of network efficiency (e.g., operational and coordination efficiency) were used to identify critical entities and evaluate the effectiveness of system integration strategies. The application of the proposed framework was shown in a case study of disaster management processes in the 2017 Hurricane Harvey. The findings highlight the importance of the SoS approach for evaluating the performance of disaster management processes under different disaster-induced perturbations (e.g., resources limitation, infrastructure disruptions, and lack of information). The findings also identify ways to improve system integration and coordination among various heterogeneous entities interacting in networks.**

***Index Terms*—Disaster management, metanetwork modeling, network-centricity, performance analysis, system-of-systems (SoS), system integration.**

I. Introduction

THE efficiency of disaster management systems and processes in response to natural disasters (e.g., hurricanes, wildfire, blizzards, and earthquakes) is critical to reduce the adverse impacts of disasters on communities [1]. Understanding and addressing inefficiencies, such as limited coordination and information flow [2], are essential to improve the performance of disaster management systems and processes. Inefficiencies in disaster management arise from complex relationships between multiple heterogeneous systems and entities [3]. Disaster management comprises early warning systems; critical infrastructure systems, such as electricity and gas supply systems; operational processes for evacuation; relief response; shelter distribution; and information systems for situation awareness and coordination among organizations and residents [4]. An artifact of the heterogeneity of these constituent systems and entities is fragmented coordination and communication, and their resultant performance inefficiencies.

Over the past decade, multiple studies have been conducted on the performance of individual systems, such as critical infrastructure [5], [6], information systems [7], [8], and human systems [9], [10] in disasters. For example, Alamdar *et al.* investigated access, exchange, and usage of multiagency sensor information amongst participants in disaster management [11]. Ouyang examined vulnerability and criticality in interdependent infrastructure systems under disaster-induced disruptions [12]. In addition, some studies [13], [14] have proposed conceptual frameworks to examine the control flow (e.g., architecture depicting the collaboration of information, human resources, and relief supply) for disaster management. The focus of these studies has been on examining potential operational barriers, such as communicating the risks resulting from lack of consistent protocols and technologies [15], [16].

While the existing studies provide insights regarding the characteristics of individual systems and processes, there is a lack of integrative frameworks that capture the heterogeneity of entities and complex interactions in disaster management [17], [18]. Recognizing this, a number of recent studies [19]–[21] have highlighted the significance and need for a system-of-systems approach to disaster management; however, documentation of such approaches is missing in the existing literature. To address this gap, this paper proposes a disaster management system-of-systems (DM-SoS) approach. The DM-SoS approach provides the conceptual lens to abstract and analyze various entities and interdependencies affecting the performance of disaster management systems and processes. This paper also shows the implementation of the DM-SoS approach using a metanetwork framework in a case study of disaster management of Hurricane Harvey in 2017 in south Texas. This paper mainly contributes to the methodological advances in dealing with disaster system problems. Nevertheless, the presented framework and methodology could help addressing scientific questions: What network structures and properties influence the efficiency of disaster management systems? What is the relative importance of different entities and relationships to the overall DM-SoS?

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II. Disaster Management as SoS

An effective evaluation of disaster management is contingent on proper characterization of the type of the system (e.g., monolithic systems or SoS) [17]. Systems have distinguishing traits requiring a specific approach to conceptualization and analysis [22]. According to the Department of Defense (DoD), "An SoS is a set or arrangement of systems that results when independent systems are integrated into a larger system that delivers unique capabilities" [23]. An SoS is an assemblage of individual systems possessing behaviors and capable of functions not performable by individual systems and greater than the sum of its individual systems [24]. Evaluation of disaster management through an SoS approach provides unique capabilities for better performance assessment and system integration.

A. Capabilities of the SoS Approach

An SoS approach provides an integrated perspective for understanding and analyzing the performance of disaster management systems and processes. As discussed earlier, existing studies lack an integrative approach to disaster management analysis. Most existing studies focus on individual systems or processes of disaster management, such as mitigation planning [25], critical infrastructure [26], [27], interorganizational coordination [16], [28], and emergency relief operations [29]. While analysis of these individual systems and processes is important, without an integrative perspective, potential integration risks (e.g., lack of coordination and inefficient information flow) would arise and could affect performance and outcomes through the entire life cycle of disaster management.

Second, an SoS approach enables the analysis of interdependencies between various systems (e.g., human, information, and physical systems). The analysis of interdependencies includes the evaluation of interorganizational coordination [30], critical infrastructure interdependencies [31], and self-organization and coevolution of network of systems and entities [32]. Of particular importance is the analysis of interdependencies among human, physical, and cyber systems. Designing effective architectures and developing robust mechanisms and procedures for disaster management would require integrative human-physical-cyber systems to be examined based on an SoS approach.

Third, an SoS approach can improve networked communication and information sharing. In large-scale heterogeneous SoS (such as disaster management), communication and information exchange among individual entities and systems is critical. In existing disaster management procedures, the required architecture and procedure for information exchange between different systems or entities is not fully specified for operational tasks [11], [33]. For example, flooding control agencies mainly focus on flood maps to reduce the exposure to flooding. But examination of flood-prone areas does not usually account for the failure of critical infrastructure that can extend the flood risks beyond the established flood plans. In addition, information regarding flood-prone areas is essential for establishing emergency response plans, determining shelter needs, and specifying evacuation protocols. Thus, it is essential that information about systems status, interdependencies, and performance requirements is communicated in a networked fashion. Such network-centric communication in disaster management can be studied more effectively using an SoS approach.

B. Distinguishing Attributes of the SoS Approach

In this section, the distinguishing attributes of SoS are examined in the context of disaster management. The distinguishing attributes of SoS (according to Maier [24]) are presented to examine whether the disaster management systems and processes can be characterized as such.

First, each individual system in the disaster management scenario can operate independently [34]. For example, emergency response service systems comprising disaster responders and agencies are operated and managed independent of other systems, such as critical infrastructure. The function of emergency response services is to provide capabilities for search and rescue, such as receiving urgent help requests, examining the affected areas, and determining the needs and priorities. While fulfilling this function depends on other systems, the management and operations of emergency response are independent of those of other systems.

Second, an SoS is composed of geographically distributed systems. Specifically, disaster management systems and processes extending across distributed geographic scales in disaster-affected areas. For example, critical infrastructure, such as electricity systems, transportation systems, sewage systems, and food supply systems, are distributed across extended geographic boundaries. The supply of disaster relief goods involves entities at regional, national, and global scales. The geographic distribution of entities and systems in DM-SoS requires abilities for spatial awareness, coordination, and information exchange to enhance the performance of disaster management processes.

Third, evolutionary development, as another attribute of SoS, implies that systems and constituent components can be added, modified, and removed over time by introducing structure, function, and purpose [35]. The evolutionary development is particularly important in evaluating disaster management. In the context of disaster response and humanitarian actions, the composition of a DM-SoS evolves as various entities and systems participate and leave the DM-SoS at different times. In the context of disaster mitigation and adaptation, the evolution of systems and processes in response to the evolving hazards leads to new policies and plans, adaptive behaviors, and objectives. For example, to improve the capability of the impacts of flooding, local agencies can consider multiple measures, such as increasing spending on flood defense structures, protecting wetlands, and building green infrastructure. Each measure can change the landscape of hazards and disaster management processes.

Fourth, the interaction among multiple heterogeneous systems and entities in an SoS initiate and develop emergent behaviors. Understanding emergent behaviors is essential to develop SoS architectures that promote positive emergent behaviors, such as community self-organization and resiliency, and eliminate negative emergent behaviors [34] In fact, resilience is a property that arises from the interaction of various human, physical, and cyber systems in response to disaster-induced perturbations. Hence, an SoS perspective is essential for understanding and achieving resilience in disaster management.

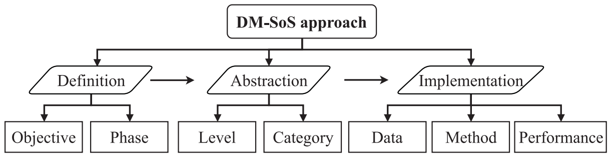

Fig. 1. DM-SoS approach.

Finally, disaster management systems and processes span four phases of disasters: Preparedness, response, recovery, and mitigation. Objectives and strategies in different phases are different in DM-SoS. For example, in the response phase of disasters, the primary goal of most entities is to provide relief response. In the mitigation phase, agencies and organizations in the focus on developing plan to reduce the negative impacts of future disasters. In disaster management, the systems and processes in each phase are studied and evaluated mainly in isolation. Considering temporal interdependencies among systems and processes across different phases is an essential element for improving integration and coordination in disaster management.

As discussed above, disaster management systems and processes can be investigated as an SoS rather than as individual systems due to the heterogeneity and complexity of entities, relationships, and functions. Thus, in this paper, we created a DM-SoS to measure the performance of disaster management.

III. DM-SoS Approach

The proposed DM-SoS comprises three dimensions of analysis: Definition, abstraction, and implementation (see Fig. 1).

The definition dimension specifies the boundaries of analysis by determining two elements: objective and phase. Objective defines the overall goal of using the DM-SoS approach for a particular analysis. For performance in disaster management, the analysis objective could be efficiency assessment in humanitarian logistics, strategic planning in command and control in management process, or architectural design in resource supply chains. An explicit analysis objective guides effective outcome by using the DM-SoS approach.

In the proposed DM-SoS approach, four disaster phases are considered: mitigation, preparedness, response, and recovery.

1) The mitigation phase encompasses the formulation of plans and policies for eliminating or reducing hazard exposure and impacts [25].
2) Preparedness is defined as a period when hazards are expected but have not yet impacted the systems.
3) Response is "the other side of preparedness, which is the activation of emergency response plans and preparedness activities in response to the threat or disaster event" [25]. In this phase, the primary tasks include reducing the loss of capital and lives, such as first aid, community-based response and sheltering, and individual and organizational coping strategies [36]. While implementation of plans is essential during the response phase, improvisation and emergent behaviors have important effects on the effectiveness and efficiency of response procedures.
4) Recovery occurs after disasters have passed, but the affected systems still need to be repaired and restored. An important aspect in the DM-SoS approach is the recognition and evaluation of relationships among various systems and processes involved in different disaster phases.

The second dimension of analysis in the DM-SoS approach is abstraction, which is to identify the categories of entities as well as their relationships at different levels. Levels refer to the geographic or jurisdictional scale, whether local, state, national, regional or global, determine the relevant entities and their interactions that can be abstracted for analysis. Analysis of a specific disaster management context may include single or multiple levels for local and regional entities. For example, an analysis may examine local mitigation of a particular city, where the level of analysis would be local level. Another analysis may examine the efficiency of response to a particular disaster involving national and state levels.

Five categories of entities can be abstracted at each level of analysis: stakeholders, information, resources, operations, and infrastructure. Stakeholders comprise human system entities such as local government, infrastructure managers and operators, first responders, and the public [37]. Information includes plans, policies, needs, and situations. Resources represent physical entities, such as fuel, gas, trucks, and equipment, that provide a service to enable stakeholders to implement a specific operation related to a specific disaster phenomenon. Operations include a series of tasks directing the activities of stakeholders. Infrastructure involves lifeline systems and service that enable the implementation of operations, such as roads and electricity networks.

The third dimension of analysis in the DM-SoS approach is implementation: Data gathering then modeling to examine attributes and relationships of entities at levels of analysis for performance assessment. The implementation dimension is composed of three elements: data, method, and performance measures. Data related to entity attributes and relationships enables performance assessment of disaster management by modeling of appropriate scenarios. The type of data and selection of appropriate modeling method depend upon the analysis objective, such as social network analysis [38], system dynamics [39], and agent-based modeling [3]. These analysis methods are capable of modeling SoS with heterogeneous entities and complex relationships. In this paper, a metanetwork framework is created and tested for performance assessment in DM-SoS. The details of this framework are explained in the following section.

The third element in the implementation dimension is performance measures. The selection of measures or indicators depends on analysis objectives defined in the definition dimension. In this paper, two measures of operational and coordination efficiency are proposed to assess performance in DM-SoS.

IV. Metanetwork Framework for Implementation of DM-SoS

Several existing studies have highlighted the merits of network approaches in dealing with heterogeneous and interdependent systems in multiple aspects, including cascading failure and system restoration. For example, Nguyen *et al.* proposed a greedy algorithm with centrality functions to detect critical nodes that, on removal, will lead to a large-scale cascading

TABLE I
METAMATRIX CONCEPTUALIZATION OF DM-SOS

Networks	Stakeholder (S)	Information (I)	Resource (R)	Operation (O)	Infrastructure (U)
Stakeholder (S)	Social network (SS) (who works with who)	Information access network (SI) (who knows what information)	Resource access network (SR) (who can get access to what resource)	Operation execution network (SO) (who conducts what operation)	Infrastructure governance network (SU) (who manages or operates what infrastructure)
Information (I)		Information network (II) (what information is dependent on what information)	Expertise network (IR) (what information is needed to use what resource)	Operation knowledge network (IO) (what information is needed for what operation)	Infrastructure condition network (IU) (what plan/information pertains to what infrastructure)
Resource (R)			Resource network (RR) (what resource consumes what resource)	Operation resource network (RO) (what resource is needed for what operation)	Infrastructure resource network (RU) (what resource support what infrastructure)
Operation (O)				Operation dependency network (OO) (what operation is dependent on what operation)	Operation Infrastructure Network (OU) (what infrastructure is needed to perform operation)
Infrastructure (U)					Infrastructure dependencies network (UU) (which infrastructure depends on another)

failure in the coupled power-information systems [40]. Buldyrev *et al.* studied the percolation properties of interacting networks to examine the effects of the degree distribution on network vulnerability to random failure [41], [42]. In addition, the restoration interdependencies that exist among infrastructure systems are analyzed to characterize the precedence of tasks and motivate the needs for enhanced coordination in the restoration efforts [43]. Besides, there are some studies discussing the measurement of criticality of a node in a network. For example, Dangalchev proposed residual closeness, which is a modified measurement of graph closeness to assess the graph vulnerability in the case that the removal of nodes or links does not disconnect the graph [44]. Some researchers also formalized a group centrality measure such as group closeness [45] and an extension in clique centrality [46] that led to betweenness-central cliques [47], [48], which indicates the extent to which a group's centrality is principally due to a small subset of its members. These approaches consider a given group of nodes as a new entity in the network and focus on the interaction between the nongroup nodes and the group members.

The generalized frameworks and solutions in these studies have advanced the theories and computational methods in dealing with a network of interdependent networks (i.e., network of networks) and network centrality. However, due to the limitation of domain knowledge in disaster management, the adaptation of these frameworks in analyzing the interactions among multiple disaster-involved entities is insufficient. Specifically, the general frameworks in the literature denote the dependency among the nodes in different networks only by their functioning capability (i.e., single-type relation). A typical example is that the functioning of a node in one network depends on the functioning of a node in another network. In DM-SoS, the stakeholder nodes not only operate the relief efforts, but also coordinate with other stakeholder nodes for information sharing and collaborations (i.e., multitype relation). Thus, removal of a resource node only affects the operation capability of a stakeholder node, and its coordination capability still works. Recognizing this, identifying a fraction of critical nodes (i.e., group consideration) that, on removal, maximizes the fragmentation, is important to evaluate the vulnerability of the network with single-type links. However, in the network with different types of nodes and links, it is important to consider both the criticality of each node as well as the effect of node removal on the network efficiency. Additionally, the vertex residual closeness centrality is limited to distinguish the functioning failure of the nodes with multiple types of relations and the corresponding impacts on network efficiency under the condition of removal of a node. Therefore, an integrative methodological framework that can cope with these existing limitations is essentially needed to examine the performance of DM-SoS.

The proposed metanetwork framework can capture data on multiple entities (e.g., stakeholder, resource, operation, information, and infrastructure [49], [50]) and their interactions consistent with the DM-SoS approach. The metanetwork analysis approach has previously been adopted in other complex systems for assessing performance, such as information systems [51] and construction projects [22]. In this paper, a disaster management metanetwork (DMMN) framework is proposed for performance analysis within the DM-SoS. The DMMN includes three steps: Specification of meta-network, formulation of performance indicators, and evaluation of performance.

A. Metanetwork Modeling of DM-SoS

The first step in the proposed DMMN framework is to specify and model entities and their relationships. In the DMMN framework, the five nodes represent five entity categories. Relationships between the entities are modeled as 15 types of links, presented in a metamatrix in Table I and network model in Fig. 2. In the metanetwork model, each set of nodes and their

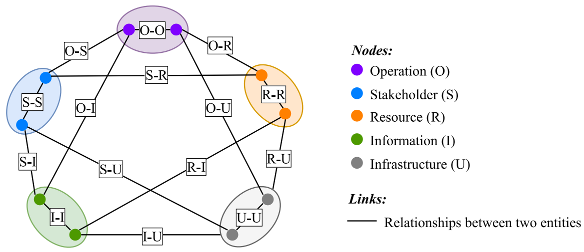

Fig. 2. Metanetwork modeling of DM-SoS.

relationships form a distinct network [49], [52]. For example, stakeholder nodes and their relationships form the social network of disaster management. A social network (SS) in disaster management represents communication or collaborations among the stakeholders. The operation and resource nodes and the links connecting these types of nodes form the operation resource network (RO), representing the interactions between operations and resources (i.e., what resource is needed for what operation). Examples of operation resource network include employing trucks for transporting bottled water and batteries. Infrastructure and resource nodes and links connecting those two types of nodes form the infrastructure resource network (RU), showing the supporting resources (i.e., what resource supports what infrastructure) such as having backup equipment for flooded power substations. The information and operation nodes and links connecting these two types of nodes form the operation knowledge network (IO), exhibiting the need for information for operations (i.e., what information is needed for what operations), such as implementing disaster relief policies to help victims. Meanwhile, information and infrastructure nodes and their connecting links form the infrastructure condition network (IU), displaying which plans or information pertains to what infrastructure. For example, the flooding control plans are associated with reservoirs and bayous. The operation and stakeholder nodes and their connecting links form the operation execution network (SO), representing the operation implementation (i.e., who conducts what operation). For example, the personnel in department of transportation take responsibility for removal of debris on the roads. Similarly, other types of networks shown in Table I can be specified and modeled using the metanetwork framework. These 15 individual networks are interconnected via shared nodes. As such, the metanetwork model can be established.

To extract the metanetwork model in DM-SoS, the first step is to identify the nodes which pertain to one of the categories in the metamatrix. Multiple entities can be identified from a vast number of sources, such as government reports, social media, news articles, and plans. Once the nodes are identified, the next step is to abstract the links among these nodes. As shown in the examples above, the links should be identified based on the relationships defined in the metamatrix. For example, by discerning "who manages what infrastructure," the connections between infrastructure nodes and stakeholder nodes can be established in the metanetwork.

B. Formulation of Performance Indicators

In this paper, the DMMN framework is used to determine critical nodes and links and their influence on the efficiency and performance in disaster management. Of particular importance is the analysis of operational efficiency. In the proposed framework, operation is defined as the application of intent to direct the activity of physical and nonphysical entities [37], such as funding and resources allocation, locating shelters, and conducting search and rescue. In the metanetwork model, operation nodes and their relationship to other node entities (e.g., stakeholders, information, resources, and infrastructure) can determine the performance of disaster management processes. For example, conducting debris removal in flooding-affected areas requires access to different resources (i.e., high-water rescue support trucks), coordination among stakeholders [i.e., the Department of Transportation and Texas Military Department (TMD)], and information related to damages and infrastructure conditions such as damaged roads. Each link between operation nodes and other node entities is important for the efficiency of disaster response (the absence of a link implies that an operation may not be implemented efficiently).

Another important node entity is stakeholders (e.g., emergency managers, infrastructure agencies, and NGOs), which are critical nonphysical entities to conduct operations, collaborate with each other, and share situational information in DM-SoS. For example, the Department of Transportation delivers the information of impassable flooded roads to the public utility commission to allow them to identify a feasible path to access a damaged transmission line. Meanwhile, a military National Guard deploys guardsmen with vehicles, boats, shelters, and communication packages to support a state health services to allocate shelters and conduct evacuation. Hence, the coordination between stakeholders is another important component of efficient disaster management.

Two quantitative indicators (i.e., operational efficiency and coordination efficiency) are proposed to examine the performance of efficient and network-centric operations in DMMN. First, operational efficiency is based on the fraction of operations that can be completed based on the availability of resources, information, and infrastructure. The completion of an operation depends on the following four conditions.

1) Each operation should be managed and executed by one or more stakeholders.
2) Resource-based operations (e.g., shelters and food allocation) should have access to the resources.
3) Information-based operations (e.g., damage assessment) should have access to the overall compilation of information.
4) Infrastructure-based operations (e.g., evacuation) should have access to the roads.

An operation cannot be completed if the required resources, information, or infrastructure are not available. Thus, the operational efficiency can be examined based on the following equation:

$$E_O = \frac{N_O^C}{N_O^T} \tag{1}$$

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where E_O is the operational efficiency in DMMN, N_O^C is the number of operations that can be completed, and N_O^T is the total number of operations in DMMN. The value of operational efficiency ranges from 0 to 1, which is independent of the number of operation nodes. Thus, the formula is applicable to any case of disaster management context and analysis. The closer the value of E_O to 1, the more efficient the entire DM-SoS.

Another important component in the DMMN framework is the links between stakeholders, which indicate the coordination in disaster management. Thus, coordination efficiency is defined to capture the level of coordination among stakeholders based on the degree of each stakeholder compared to the total number of connections. The degree of a stakeholder node is the number of connections it has to other stakeholders. The total number of connections between stakeholders is the number of pairs of stakeholders. The equation for coordination efficiency can be represented as follows:

$$E_S = \frac{\sum_{i=1}^{N_S} \deg_i}{2 \times \binom{N_S}{2}} \tag{2}$$

where E_S is the coordination efficiency in DMMN, N_S is the number of stakeholder nodes in DMMN, and $\deg_i$ is the degree of each node of stakeholders. In this equation, only the connections to other stakeholders are counted in this calculation. Also, the sum of degree of stakeholder nodes should be divided by 2 because the connections are counted twice in the summation of degrees. The value of the coordination efficiency ranges from 0 to 1, which is independent of the number of stakeholder nodes. A greater value of coordination efficiency indicates a greater level of coordination among stakeholders.

To integrate the operational efficiency and coordination efficiency as an indicator of network-centricity of the metanetwork structure, a global efficiency measure is proposed as follows:

$$E_g = \alpha \cdot E_O + \beta \cdot E_S \tag{3}$$

$$\alpha + \beta = 1 \text{ and } \alpha, \beta \geq 0 \tag{4}$$

where E_g is global efficiency of a metanetwork model, and α and β are the weighting coefficients that can be used to adjust the weight of each indicators contributing to the global efficiency. The global efficiency is a convex combination of the operational and coordination efficiencies for measuring the performance of DM-SoS: i.e., E_g is the linear combination of E_O and E_S with nonnegative coefficients (i.e., α and β) with unit sum. The values of these weighting coefficients are determined by users' preference and objectives. Because operational efficiency and coordination efficiency are equally important, in most cases, the weighting coefficients can be 0.5.

C. Evaluation of DM-SoS Performance

Evaluation of DM-SoS performance is essential to identify critical entities and understand what if the critical entities are removed. In this paper, critical entities are the nodes that would significantly influence the efficiency (i.e., operational efficiency and coordination efficiency) of the DM-SoS when these nodes are removed. For example, some stakeholders [e.g., Federal Emergency Management Agency (FEMA), National Guard, and a state's emergency operations center] connect to or coordinate with multiple stakeholders. In that case, these stakeholders have frequent communication and collaboration with each other to conduct the disaster response operations. In addition, some stakeholders, resources, information, and infrastructure are involved in multiple operations. To identify such critical entities, the criticality of a node as regards operational efficiency was defined based on the impact of removing the node and its links on E_O. Similarly, the criticality of a node with respect to coordination efficiency is determined based on the impact of removing the node and its links on E_S. The impact of the node removal on the network-centricity can be measured by the reduction of global efficiency (i.e., E_g). Accordingly, the following equations can be used to quantify the criticality of nodes:

$$\Delta_g = E_g - E'_g \tag{5}$$

$$\Delta_O = E_O - E'_O \tag{6}$$

$$\Delta_S = E_S - E'_S \tag{7}$$

where Δ_g, Δ_O, and Δ_S are the differences in global efficiency, operational efficiency, and coordination efficiency when removing a node, and its links, E_g, E_O, and E_S are the global efficiency, operational efficiency, and coordination efficiency of the DMMN before removing a node and its links, and E'_g, E'_O, and E'_S are the global efficiency, operational efficiency, and coordination efficiency of the DMMN after removing the node and its links. Using these equations, the critical stakeholder, resource, information, and infrastructure can be identified through ranking the differences of the global efficiency of the DMMN before and after the removal of the nodes. The greater the difference in efficiency measures, the more critical the node.

Since the values of efficiencies range from 0 to 1, the value of difference in efficiencies due to node removal will be very small and, hence, less intuitive. Thus, the efficiency reduction factors are developed to measure the percentages of efficiency reduction (compared to preremoval value) due to node removal. The equations are shown as follows:

$$P_{\Delta g} = \frac{\Delta_g}{E_g} \tag{8}$$

$$P_{\Delta O} = \frac{\Delta_O}{E_O} \tag{9}$$

$$P_{\Delta S} = \frac{\Delta_S}{E_S} \tag{10}$$

where $P_{\Delta g}$, $P_{\Delta O}$, and $P_{\Delta S}$ are the global, operational, and coordination efficiency reduction factors to show the efficiency reduction due to the removal of nodes. The efficiency reductions can be effective measures to show the importance of nodes. Also, the results can be utilized to identify improvement strategies to achieve network-centric operation in disasters. For example, establishment of information systems among some critical stakeholder entities can significantly improve network-centric coordination and sharing resources and information, thus improving

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TABLE II
DURATION OF DISASTER PHASES THAT ARE INVESTIGATED IN THIS PAPER

Disaster phase	Phase duration
Response phase	August 26–August 29
Short-term recovery phase	August 30– September 4

TABLE III
DURATION OF DISASTER PHASES THAT ARE INVESTIGATED IN THIS PAPER

Types of nodes	Examples of nodes	Types of connected nodes	Examples of connected nodes
Stakeholder (S)	Dept of Housing and Urban Development	Operation (O)	Assess damage and identify unoccupied units
Resource (R)	Personnel and ground support teams	Stakeholder (S)	Texas Military Department (TMD)
Operation (O)	Report dirt/debris or water over the roadways	Stakeholder (S)	Texas Department of Transportation (TxDOT)
Information (I)	Roadways are becoming impassable	Operation (O)	Inbound personnel are advised to find a place to stop for the night due to impassable roadways
Infra-structure (U)	SH 146 near Dickinson	Operation (O)	Check lower bayou area

the operational efficiency for better allocating limited resources and for better relief actions. The application of this metanetwork framework is demonstrated in a case study of disaster response to Hurricane Harvey in August 2017 in South Texas.

V. CASE STUDY OF DISASTER MANAGEMENT IN HURRICANE HARVEY

To demonstrate the application of the proposed DM-SoS approach and metanetwork framework, a case study of disaster management in Hurricane Harvey landfall was conducted. Hurricane Harvey caused $125 billion in damage, primarily in the Houston metropolitan area and Galveston [53]. Harvey became a Category IV hurricane in August 24, 2017 and made landfall at peak intensity on the Texas coast in August 26, 2017. Harris County was active at the emergency condition level to deploy personnel and vehicles performing search and rescue. After August 30, Harvey moved north-northeast at 7 mi/h and quickly waned until dissipating [53]. Stakeholders and emergency responders effected recovery efforts, such as removal of debris, restoration of power, provision of medical care, and allowing residents to return to their homes. After September 5, most short-term recovery efforts for affected citizens and urban facilities had been completed. The objective of the case study analysis was to examine critical entities using the proposed metanetwork framework. The two disaster phases considered were the response phase and the short-term recovery phase (see Table II) at the federal and state levels. Understanding the critical entities in these two important phases is essential in informing future disaster management processes [54].

A. Data Collection and Metanetwork Mapping

This study used the official daily situation reports (from August 26 to September 4) about Tropical System Harvey released by the Texas Department of Public Safety (TxDPS) and two official reports in response and short-term recovery phases released by FEMA to map metanetwork entities and relationships. The TxDPS is a state and law enforcement agency which is responsible for rescue service, emergency communications, and services. Besides, the TxDPS serves as a hub of operation and information about response and recovery efforts during and after Hurricane Harvey. The TxDPS situation reports summarized weather information, affected areas, damages in physical and technological systems, stakeholder status, operations conducted by stakeholders, and applicable resources in each day. This information includes details related to different entities and their relationships to conduct the metanetwork analysis. For example, the report stated "The Texas General Land Office deployed field personnel, two boat crews, and one support trailer to work between Interstate Highway (IH) 45 and State Highway (SH) 3 in Dickinson for evacuation on August 29." TxDPS state situation reports documenting statewide weather conditions, operational tasks and priorities, and available resources in a total of 206 pages, supplemented by FEMA reports, were analyzed to extract entities and their relationships for mapping the metanetwork. The mission of FEMA is disaster management: preparing for, protecting against, responding to, effecting short-term recovery from, and mitigating effects of disasters. FEMA also posted summary reports about the coordination and operation efforts conducted by organizations and institutions at the federal level, including economic loss, relief actions, and resources provided for victims during and after Hurricane Harvey. For example, the FEMA reports states "The Department of Health and Human Services deployed more than 1110 personnel with medical equipment and supplies for providing medical care to 5359 patients and conducted 60 shelter assessments."

This study abstracts the information from the TxDPS and FEMA reports to build the metanetwork models for each of the response and short-term recovery phases. Some examples of the node entities and links in the metanetwork models are shown in Table III. For example, the TxDPS report states, "TxDPS Texas Highway Patrol (THP) inbound personnel are advised that roadways are becoming impassable, and to find a place to stop for the night." [55] The stakeholder node, THP, the information node, impassable roadways, as well as the stakeholder-information relationship are abstracted for the metanetwork. In another example, from this statement, "Texas Department of State Health Services (DSHS) evacuation of over 700 medical patients has been completed."[55] We can extract the stakeholder node, DSHS, the operation task, evacuation of patients, and the stakeholder-operation relationship. An example from FEMA reports states that "Defense Logistics Agency (DLA) is providing more than 645 000 gal of fuel in

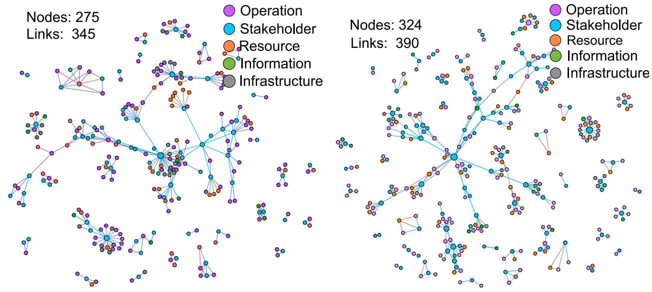

Fig. 3. DMMN in two disaster phases (the sizes of the nodes in the figure indicate the degree of the nodes). (a) Response phase. (b) Short-term recovery phase.

TABLE IV
General Measures of DMMN in Two Disaster Phases

Categories	Response phase (numbers)	Short-term recovery phase (numbers)
Operation	120	133
Stakeholder	78	97
Resource	49	53
Information	9	23
Infrastructure	19	18

several locations" [56]. The federal stakeholder node, DLA, the resource node, fuel, and the relationships between stakeholder and resources can be abstracted.

As shown in Fig. 3, the numbers of entities and connections in the metanetwork models are different in two disaster phases. In the response phase, a total of 275 entities and 345 connections between these entities existed, whereas there were 324 entities and 390 connections in recovery phase. The numbers of each node-type entity are summarized in Table IV. The reason for the differences in numbers of entities in two disaster phases is that after hurricane passes, more organizations and institutions, such as the Federal Communication Commission, Federal Trade Commission,and Texas Alcoholic Beverage Commission joined the short-term recovery efforts, subsequently the resources (e.g., personnel and specialists), operations (e.g., monitoring the status of communications networks), information (e.g., Regional Declaration of Emergency), and related infrastructure (e.g., railroads) entities increase as well.

B. Evaluation of DM-SoS Performance

The metanetworks are vulnerable to the removal of critical nodes. That is, the networks would disintegrate when the critical nodes are removed according to impacts on the efficiency [57]. In the context of this analysis, large critical nodes with high impacts on the network efficiency [e.g., FEMA, USGS, and Texas Department of Transportation (TxDOT)] not only play critical roles in network integration, but they also make the network sensitive to node failures (e.g., limitation of resources, department closures, and infrastructure damages). To examine the criticality of the nodes, the measures of efficiency reduction were calculated and the maximum reductions for each type of efficiency are shown in Table V. It was assumed that.

1) Both weighting coefficients α and β are 0.5 in the calculation of global efficiency and its reduction factor.
2) The operational efficiency without any node removal is 1 in both disaster phases because the operations were identified from the governmental reports.
3) The coordination efficiency was obtained based on the numbers of stakeholder nodes and their connections by using (2).

As shown in Table V, the critical stakeholder node with the greatest global efficiency reduction in the response phase was TxDOT. The removal of the TxDOT node led to 9.17% reduction in the operational efficiency, 4.87% reduction in coordination efficiency, and 9.11% reduction in global efficiency. Also, the operational efficiency reduction reached the maximum value when the TxDOT node is removed. This is because that TxDOT dispatched a large number of personnel and equipment to repair the damaged roads and shorelines during the response phase. In addition, FEMA played a more important role in coordination with other stakeholders in the response phase. The maximum reduction of coordination efficiency was observed when FEMA node was removed. That is because FEMA, as a government agency, undertakes the responsibilities of commanding the coordination among different agencies and allocating resources. For example, some stakeholders, such as Small Business Administration, Railroad Commission of Texas, and Civil Air Patrol needed to work with FEMA to conduct response actions for restoration of affected areas. The U.S. Department of the Interior also works with FEMA to provide funding and active relief programs.

While these critical stakeholders in both response and short-term recovery phase play an important role in the integration of entities in disaster management, the social networks in the metanetworks could not achieve network-centric coordination. The reductions (26.83% and 13.95%, respectively) of coordination efficiency due to the removal of the critical stakeholders were too large that caused fragmentations in the metanetwork structures. Hence, a potential improvement strategy would be establishing some information systems or collaboration mechanisms among stakeholders to achieve network-centric coordination. For example, the U.S. Department of Health and Human Services, the U.S. Department of Education, the U.S. Department of Housing and Urban Development, and the U.S. Department of Labor can coordinate with each other to develop communication protocols (such as a centralized information system) or hold regular meetings to exchange relief progress information as well as to share human and physical resources.

The critical resource which made the greatest impact on both operational and coordination efficiency reductions were volunteers from voluntary organizations in the response phase of Harvey. Volunteers as a human resource were deployed by the Salvation Army and AmeriCorps Disaster Response Teams to provide emotional and spiritual care for affected residents and to help residents to repair and rebuild housing. In the short-term recovery phase, personnel from DoD were identified as a critical human resource in the metanetwork. The personnel were deployed to conduct temporary housing technical monitoring, debris removal, and technical assistance and support for temporary power activation. The disaster information about relief actions

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TABLE V
CRITICAL NODES WITH HIGH IMPACTS ON GLOBAL EFFICIENCY OF DMMNS WHEN THEY ARE REMOVED

Response phase ($\alpha = 0.5$, $\beta = 0.5$)				**Short-term recovery phase ($\alpha = 0.5$, $\beta = 0.5$)**			
Critical nodes (node types)	Operational efficiency reduction (%)	Coordination efficiency reduction (%)	Global efficiency reduction (%)	Critical nodes (node types)	Operational efficiency reduction (%)	Coordination efficiency reduction (%)	Global efficiency reduction (%)
TxDOT (S)	9.17 (max)	4.87	9.11	FEMA (S)	6.77 (max)	11.63	6.81
FEMA (S)	5.83	26.83 (max)	6.12	The U.S. Department of the Interior (S)	0.00	13.95 (max)	0.13
TxDOT (S)	9.17	4.87	9.11(max)	FEMA (S)	6.77	11.63	6.81 (max)
Voluntary organizations (R)	3.33 (max)	7.32	3.39	Personnel from DoD (R)	2.26 (max)	4.65	2.28
Voluntary organizations (R)	3.33	7.32 (max)	3.39	Personnel from DOD (R)	2.26	4.65 (max)	2.28
Voluntary organizations (R)	3.33	7.32	3.39 (Max)	Personnel from DoD (R)	2.26	4.65	2.28 (max)
Relief information from FEMA (I)	0.83 (max)	4.88	0.89	Resources information from FEMA (I)	2.26 (max)	4.65	2.28
Relief information from FEMA (I)	0.83	4.88 (max)	0.89	Resources information from FEMA (I)	2.26	4.65 (max)	2.28
Relief information from FEMA (I)	0.83	4.88	0.89 (max)	Resources information from FEMA (I)	2.26	4.65	2.28 (max)
Roadways (U)	1.67 (max)	2.44	1.68	Closed roads due to flooding (U)	0.75 (max)	2.33	0.77
Charging stations (U)	0.83	4.87 (max)	0.88	39 PWS and 29 wastewater treatment plants that are inoperable (U)	0.00	4.65 (max)	0.04
Roadways (U)	1.67	2.44	1.68 (max)	Closed roads due to flooding (U)	0.75	2.33	0.77 (max)

and resources from FEMA was critical to the performance of the DM-SoS in both the response and short-term recovery phases of Hurricane Harvey. By making a comparison between global efficiency reductions in both phases, the disaster information from FEMA in the short-term recovery phase caused a greater reduction in efficiency than the reduction in the response phase. That is due to the fact that after Harvey passed, the relief operations and resources increased distinctively from multiple organizations [e.g., Disaster Survivor Assistance Teams (DSATs) and the American Red Cross], agencies (e.g., the U.S. Social Security Administration and the Department of Energy), and the public. Those stakeholders needed situational information to allocate their resources and implement relief action plans. Recognizing the importance of the information from FEMA, a potential improvement strategy would be establishing an information clearinghouse platform to improve the information sharing between stakeholders.

Infrastructure is an essential component in disaster management systems and processes, although it does not affect the network efficiency significantly. In the response phase, the removal of roadways (as a node in the metanetwork) reduced the operational efficiency by 1.67%, flooded and impassable roadways delayed or hindered disaster response actions. Thus, infrastructure systems (e.g., charge stations, roadways, and boiled water systems) are important to the performance in DM-SoS. A potential improvement strategy would be to formulate mitigation plans to harden and improve the capacity of critical infrastructure needed for relief actions during response and short-term recovery phases.

The example findings above show that the proposed framework enables the identification of critical node entities for evaluating and improving the performance of disaster management. The operational, coordination, and global efficiency reductions with each type of node removal are shown in Figs. 4 and 5. As shown in these figures, stakeholders are the most critical nodes that significantly affect the efficiency of DM-SoS. Of stakeholders, 10% play an important role in operation and coordination efficiency. Those stakeholders can be considered as coordination and operation hubs which are connected to multiple other stakeholders. As discussed earlier, however, metanetwork structures with these coordination and operation hubs become sensitive to the failures or removal of such hubs. For example, if relief organizations cannot get access to disaster information about relief actions and resources provided by FEMA, they fail

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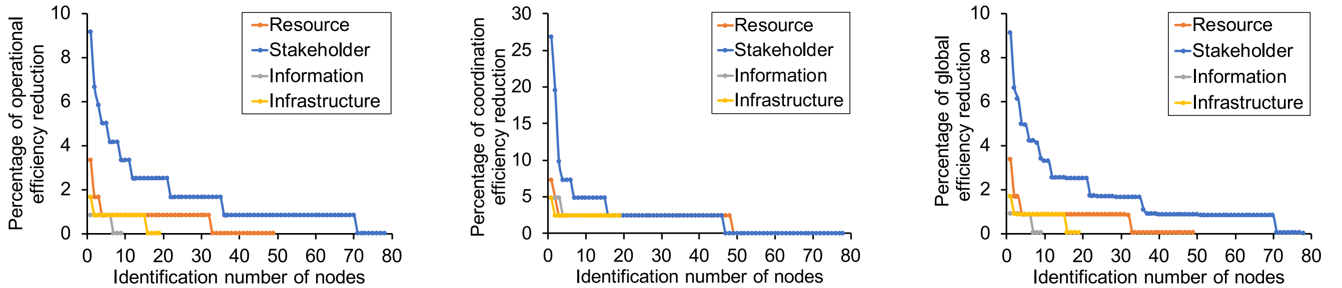
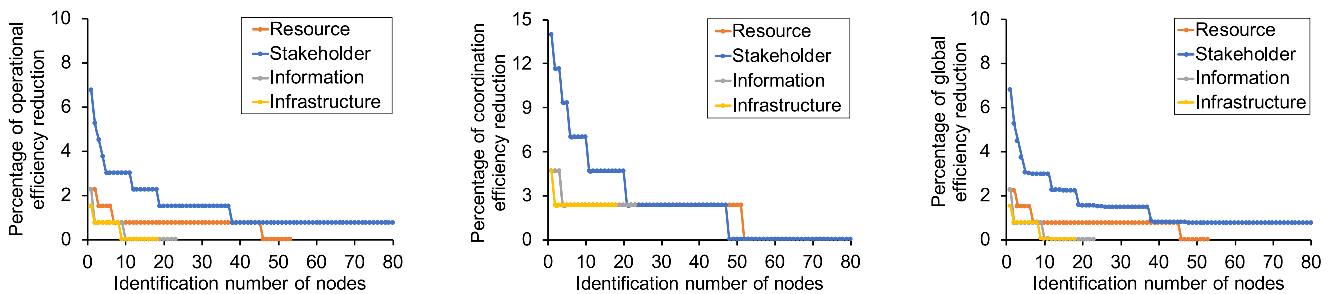


(a) (b) (c)

Fig. 4. Efficiency reduction of node removal in response phases. (a) Operation efficiency reduction. (b) Coordination efficiency reduction. (c) Global efficiency reduction.



(a) (b) (c)

Fig. 5. Efficiency reduction of node removal in short-term recovery phase. (a) Operation efficiency reduction. (b) Coordination efficiency reduction. (c) Global efficiency reduction.

to distribute their personnel and equipment effectively. Hence, to reduce such inefficiency (caused by centralized structures), establishing communication channels among stakeholders is essential for sharing situational information, networked coordination, and improving operational efficiency.

The metanetwork analysis demonstrates the implementation of the DM-SoS framework using the selected measures: operational efficiency, coordination efficiency, and global efficiency. These measures were selected to evaluate important characteristics of DM-SoS. For example, efficiency of search and rescue in disasters depends on the availability of boats, vehicles, as well as relief personnel. Measuring the dependency among these components can uncover the important resources and relationships in DM-SoS. In this paper, the adopted metanetwork approach has captured the dependency among the relief tasks, stakeholders, and resources, and show its capability for quantifying the efficiency of the relief tasks in disaster management. However, there are additional metanetwork measures [58], such as the relationship between information and actions [59], the effectiveness of information communication technology [60], and the consequences of relief actions in crisis environment [61], [62], which could also be examined by using the proposed metanetwork analysis. Future studies can adopt the proposed framework and metanetwork modeling approach and evaluate the usefulness of different metanetwork analysis measure for examining the structure and attributes of disaster management SoS.

VI. Concluding Remarks

This paper proposes a DM-SoS approach to identify and analyze heterogeneous entities and their complex relationships. In addition, a metanetwork framework was proposed for modeling and assessing performance in DM-SoS. The application of our DM-SoS approach was demonstrated in a case study of disaster management in Hurricane Harvey which made landfall on the South Texas coast in 2017. The results identify critical entities that are important to the efficiency of disaster management. The findings uncovered the potential and significance of the presented approach in abstracting heterogeneous entities and their complex relationships and understanding the contributions of various entities to the performance of DM-SoS.

From a methodological perspective, the DM-SoS approach and metanetwork framework provide an integrative perspective for understanding the performance of disaster management. The proposed SoS approach enables an integrative analysis of interdependencies among entities as well as networked communication and information sharing. For example, the coordination among stakeholders, efficiency of operations, importance of resources, dependencies of infrastructure, and effects of fragmentation were investigated in this approach. Also, the metanetwork approach advances the network-based approach to quantify the efficiency to compute the criticality of entities in disaster management. The quantitative indicators can be furthered extended to analyze specific interactions among entities.

From a practical perspective, the identified critical entities and their relationships can provide insights for developing improvement strategies. For example, this paper highlighted the sensitivity of large hubs to disruptions. Thus, identifying and strengthening these hubs to resist perturbations in disasters is important to the performance of DM-SoS. The findings in the case study showed that sharing situational information among stakeholders is essential to improve the connectivity of other nodes. As such, the degree of network distribution and network-centricity in disaster management could be improved. A situational information clearinghouse would increase the capacity to achieve networked coordination. Second, the established metanetwork framework can help disaster responders and managers in related organizations to better understand the impacts of their response actions and relief plans on the performance of disaster management. Accordingly, lack of certain nodes and links (e.g., lack of funding, no damage assessment, and limitation on personnel mobilization) can be proactively identified and mitigated.

The proposed DM-SoS approach and metanetwork framework in this paper also have limitations. First, abstracting the relationships between different entities for mapping the metanetwork models is potentially difficult because some collaborations and coordination between entities cannot be identified from the written documents, including from government reports and news articles. Thus, one possible approach would be developing link-prediction techniques to perceive the relationships between the entities based on their shared resources, similar operations, empirical experiences, and knowledge. Another possible approach is to conduct comprehensive interviews and surveys with involved stakeholders in the disaster aftermath to identify the missed connections in the DM-SoS. Second, abstracting and mapping node entities and links could be time-consuming if it is conducted manually. Recognizing this, automatic approaches (such as natural language processing techniques) can be developed to abstract the entities involved in DM-SoS and establish their relationships. Such automated approach would be helpful for researchers to investigate and integrate other sources, such as news articles, social media data, and private institution reports in building and analyzing metanetworks.

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