Meta-Network Framework for Analyzing Disaster Management System-of-Systems

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***Abstract*— The objective of this paper is to establish a meta-network framework to identify constituents in Disaster Management System-of-Systems (DM-SoS), conceptualize relationships and interactions among the constituents, and formulate quantitative measurements of DM-SoS performance for achieving network-centric operation and coordination in the context of disasters. With increasingly serious impacts of disasters on interdependent and heterogeneous systems, the improvement of effective and integrative disaster response and coordination is needed. However, some existing literature only proposed some frameworks for modeling disaster management systems, while another stream of studies only examined the social network analysis (SNA) for understanding the interactions between stakeholders. Thus, quantitative and integrative measurements in DM-SoS are missing. To address this knowledge gap, the authors created and discussed a meta-network framework integrating various types of entities and relationships for quantitatively analyzing the performance of DM-SoS. First, this framework defined nodes and links in meta-metrics for abstracting constituents in disaster management. Second, some performance indicators (e.g., effectiveness, the extent of information sharing, and the extent of self-organization) were created to show the capacities of disaster systems, and the potential perturbations in disaster environment were translated by network theory. Finally, we examined the impacts of perturbations on the indicators and assessed the performance by integrating overall indicators. This study highlighted the significance of quantitative measurements and an integrative perspective on analyzing efficiency and effectiveness of disaster response and coordination. The study also provides implications for making comparisons of different response strategies for decision makers to achieve resilient disaster management systems.**

Keywords—Meta-Network framework; Disaster System-of-Systems; Network-centric operation; perturbations

I. INTRODUCTION

The increasing frequency and severity of natural disasters such as hurricanes (e.g., Harvey 2017, Sandy 2012), wildfires (e.g., Los Angeles wildfires 2017, Napa wildfires 2017), blizzards (e.g., bomb cyclone 2017) and earthquakes (e.g., California earthquake 2018) are making destructive impacts on human and physical systems (e.g., large-scale power outage, shortage of boiled water, and building collapse). For example, in Hurricane Harvey, more than 100,000 residential properties were affected, and more than 70 fatalities were reported in communities of Houston area [1]. To reduce the negative impacts of disasters, improving community resilience is an urgent priority. Community resilience is defined as the ability of a community to maintain its status and perform its intrinsic functions in the context of disasters. Disaster management systems are recognized as a critical element in improving community resilience during the occurrences of disasters. Thus, improving the effectiveness and efficiency of disaster response and coordination in disaster management systems is significant.

While frameworks for modeling disaster management systems have been presented in existing literature [2]–[4], an integrative and quantitative approach for analyzing the disaster management systems based on system-of-systems perspective is still missing. Such need is highlighted by the interdependencies of multiple systems and their dynamic interactions during disasters. Failures in a system can spread to other interdependent systems through their interactions. For example, when hurricane Harvey approached Texas, more than 300,000 people were left in power outage, more than 200 highway locations were closed or flooded, and all flights were suspended in the Houston Airport System due to the failure of drainage systems [5]. Furthermore, these failures caused traffic congestion, delayed evacuation, and increased the cost of rescue [6]. However, the studies [7] on individual systems only focus on the internal structure and performance of individual systems and processes. Thus, they cannot identify the connections and cascading effects of the disaster events on overall relevant systems, such as the failures from drainage systems to transportation systems. An integrative approach to analyze the interdependencies and dynamic perturbations in interconnected systems is essential for effective disaster response. Meanwhile, quantitative indicators are also needed for decision-makers to develop, analyze, and prioritize disaster response strategies and the consequences of applying the strategies. For example, locating shelters is a task that should be connected to available resources, stakeholders, and information in disasters. The task cannot be completed if one of the related entities cannot be reached at the same time. The uncompleted task will also slow down other tasks such as distributing food and drinking water. In order to compare the locations of shelters, the extent of the effects of each strategy should be estimated precisely, such as how many people will be involved, what information and resources will be consumed, and whether the resources can be accessed. Thus, quantitatively identifying and assessing the potential effects of decisions in disaster management processes are essential for achieving the effective response.

However, in existing literature, there are two important gaps in the body of knowledge in disaster management. First, a quantitative approach for measuring the extent of network-centric operations and the impacts of external perturbations on the disaster management systems is missing. The majority of existing studies only proposed frameworks for modeling disaster management systems and operations for improving the efficiency and effectiveness of disaster response [8]–[10]. For example, Kirov developed a conceptual network-centric model and a software architecture for enhancing information-sharing and coordinated decision-making in crisis management [11], while Gu established a conceptual framework with a built-in information-sharing system including command and collaboration processes [12]. These studies provided insights into analyzing information flows and emphasized the importance of synergistic cooperation among interconnected systems [13]. However, quantitative and comparable indicators for estimating the impacts of disaster response actions and physical events are missing.

Second, an approach integrating various types of objects in conceptual network analysis has yet to be developed. Social network analysis (SNA) is employed in existing disaster management systems for analyzing the coordination among stakeholders and detecting potential communication risks in times of disasters [14]–[16]. For example, Enos quantified interoperability in the complex system of systems using SNA metrics [17]. The application of SNA metrics contributes to quantify the network-wide impacts of changes to the defense systems through examining the properties such as degree, closeness, and eigenvector. In addition, the evolvement of social networks of communities in disasters was investigated in some studies [16]. For example, Misra illustrated the interactions of cyclone-affected communities and optimize resources allocation through SNA on community members [16], while Kapucu found the performance of intergovernmental and intra-organizational response through SNA on stakeholders [18], and identified the major organizations that participated in the response operations and their interactions through SNA on organizations [19]. As these examples show, SNA only facilitates human-related entities and their interactions. SNA cannot integrate the entities from different systems such as physical, technical, and human systems [20], [21]. Thus, an approach integrating multiple actors and their complex relationships as well as measuring the extent of collaboration operations is missing.

To address these critical knowledge gaps, we established a meta-network framework, incorporating multiple actors within various heterogeneous systems [22], for analyzing Disaster Management System-of-Systems (DM-SoS) to measure the extent of the network-centric operation. The study is organized as follows. First, we defined the nodes and links in meta-networks to abstract constituents in DM-SoS and show the relationships among various nodes. Second, we formulated the indicators of meta-network properties such as the extent of self-organization, information accessibility, and effectiveness of DM-SoS. Third, the authors discussed some perturbations such as appearance and disappearance of entities and relationships, and corresponding real-world scenarios and translated them to the components of meta-networks. Fourth, the study examined the impacts of translated perturbations on the quantitative indicators in a meta-network. Fifth, the presented framework assessed the performance of DM-SoS by integrating the indicators. Finally, the paper concluded with a discussion of the importance and implications for disaster responders and decision makers based on the proposed meta-network framework.

II. COMPONENTS OF META-NETWORK FRAMEWORK

This study adopts some novel concepts from network theory and complex system engineering to investigate the structural properties of multiple interconnected constituents within a system, such as centrality, diversity, structural risks and congruence [22], [23]. As discussed earlier, DM-SoS is an integrative system that includes various systems and their connection to each other [24]–[26]. The meta-network framework is capable of classifying concepts into ontological categories (e.g., human, technical, and physical [27]) to analyze the reciprocal actions (e.g., information diffusion [28], and catastrophic consequences). Meanwhile, meta-network has been applied to many complex systems for assessing vulnerabilities, such as information system [29] and construction projects [30]. In this study, we established a meta-network framework including five components (i.e., abstraction, formulation, translation, examination, assessment) for performance analysis of DM-SoS.

A. Abstraction of disaster management meta-network

Identifying entities as nodes and relations as links in meta-network is the first step for abstraction. The DM-SoS is composed of five types of entities (e.g., stakeholder, information, resource, operation, and policy) and fifteen types of relationships among different entities (see Table I). Each set of relationships and their certain types of nodes form their own networks [31], such as social network (SS) which is composed by stakeholders and their subordination, information network (II) which is composed by information nodes and their dependencies, and operation execution network (SO) which is composed by operation and stakeholder nodes as well as their relations. We abbreviated the name of the nodes involved in each network as the name of the network. Those networks connect to each other via the connections among the nodes, forming a meta-network. Figure 1 shows an illustration of the meta-network comprising multiple networks and their interdependencies. As such, the changes (e.g., failure, emerging, and disappearance) can lead to large-scale effects on the entire network through their interactions.

We highlighted some critical nodes and links in our studies to analyze the performance of disaster management system-of-systems (see Figure 1). First, the operation is defined as the application of intent to direct the activity of physical and non-physical entities [32], such as budget and resources allocation, locating shelters, conducting search and rescue, maintenance activities, and rehabilitation planning. The definition also highlights the potential relationships between operations and other entities (e.g., stakeholder, information, policy, and resource). For example, conducting an operation should get access to some essential resources (e.g., power, food, and boiled water) and information (e.g., floodwaters level, the scale of a power outage, and building damages) as signals. operations are the key component of disaster preparedness, response, and recovery. Thus, we developed an indicator, effectiveness of a meta-network, to examine the performance of disaster management processes. For example, a large set of operations in a meta-network cannot be completed because they cannot get enough information. Operators in the management system need to figure our improvement actions to overcome the lack of knowledge. Second, stakeholders (e.g., public infrastructure and disaster management agencies, asset owners and operators, non-profit organizations [26], and victims) is the non-physical entities to develop and conduct the operations in DM-SoS. They play a critical role in disaster management systems and processes, including conducting operations, consuming resources, delivering information, and formulating policies. Thus, we expressed two indicators, information accessibility and capability of self-organization, to assess the performance of a meta-network. Policy (e.g., Homeland Security Act, Disaster Mitigation Act, and National Flood Insurance Reform Act) is another category of entities as external forcing functions that impose restrictions on operations.

TABLE I. MATE-MATRIX CONCEPTUALIZATION OF DISASTER MANAGEMENT SYSTEM-OF-SYSTEMS

Networks	Stakeholder	Information	Resource	Operation	Policy
Stakeholder	Social network (SS) (*who works with whom*)	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*)	Policy formulation network (SP) (*who develops what policy*)
Information		Information network (II) (*what information is dependent on what information*)	Necessary expertise network (IR) (*what information is needed to use what resource*)	Operation need network (IO) (*what information is needed for what operation*)	Policy need network (IP) (*what information is needed for what policy*)
Resource			Resource network (RR) (*what resource consumes what resource*)	Operation need network (RO) (*what resource is needed for what operation*)	Policy need network (RP) (*what resource is needed for what policy*)
Operation				Operation network (OO) (*what operation is dependent on what operation*)	Policy support network (OP) (*what operation is supported by what policy*)
Policy					Policy network (PP) (*what policy is subject to what policy*)

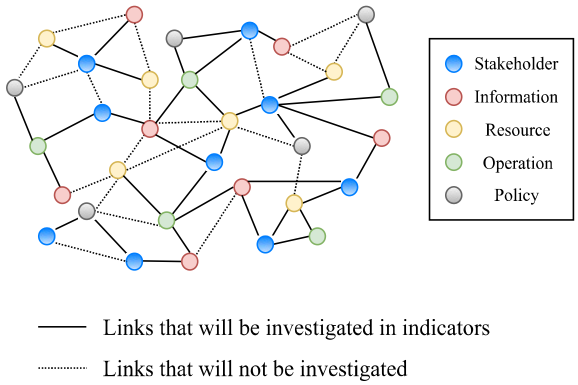

Fig. 1. An illustration of meta-network for DM-SoS.

B. Formulation of performance indicators

In this component, we aim to formulate some quantitative indicators (e.g., information accessibility, the capacity of self-organization, and effectiveness) for evaluating the properties of the meta-networks and providing evidence to an assessment of DM-SoS performance. First, we defined that information accessibility is the capability of delivering information to stakeholders. The necessity of obtaining information is that the stakeholders can be aware of the situation they are currently in and make proper decisions of disaster response (e.g., providing helps to others, evacuation, transporting resources, and locating shelters) based on the information they gathered. Thus, to assess the information accessibility of a stakeholder, an equation is developed as a function of the number of stakeholder-information links (*SI*) within the information access networks:

$$Acc_i = \frac{(SI)_i}{N_I} \tag{1}$$

where Acc_i is the percentage of stakeholder i can get the information from the information pool in disasters, $(SI)_i$ is the number of stakeholder-information links the connect to stakeholder i, and N_I is the number of information nodes in the entire meta-network. The value of Acc_i ranges from 0 to 1. When Acc_i equals 0, the stakeholder i cannot get any information. This stakeholder is very sensitive to the external attacks since it does not know anything about the changes. Therefore, the indicator, Acc_i, can potentially identify the stakeholders at risk. Also, a stakeholder who has the highest information accessibility can be the information hub and is critical for information transmission. Corresponding strategies such as establishing information channels between the information hub and other stakeholders can be developed to improve the information dissemination and situational awareness in disasters. Furthermore, the information accessibility of the entire meta-network can be defined as follow:

$$Acc = \frac{\sum_{i=1}^{N_S} Acc_i}{N_S} \tag{2}$$

where Acc is the average information accessibility of entire meta-network, and N_S is the number of stakeholders. To some extent, the indicator, Acc, focuses on the overall performance of information accessibility. Thus, it increases the tolerance of individual stakeholders with low information accessibility (e.g., close to 0). In reality, low information accessibility in some cases is allowed because some stakeholders do not need all information. For example, it is not necessary for the public in affected areas to get the information about an international donation to the country. As such, those two indicators, Acc_i and Acc, have their contributions to the assessment and improvement of information dissemination in meta-networks.

Second, self-organization is a spontaneous emergence of order in DM-SoS and exhibits the behaviors of entities involved in the stricken communities responding voluntarily with their time, resources, skills, and knowledge to restore the statues [33]. It manifests in two forms: adding nodes and links as well as adding links (see Figure 2). As the figure shows, self-organization behaviors of these two stakeholders are triggered by the capability of accessing the same resources and information. The stakeholders can establish connections (e.g., communication channels, physical interactions, and collaborations) with other stakeholders as well as figure out new operations (e.g., donating money to victims) because they have the same information and accessibility of resources. However, the context is a necessary condition but not sufficient. It means the context only shows the capability of self-organization rather than the inevitability. For example, the residents in flooding areas have boats and information about the water level, but they do not need to connect to each other since everyone has the ability of evacuation and does not need any help from others. Therefore, in this paper, we defined an equation showing the capability of self-organization:

$$Cap = \frac{N_{Pairs}}{\binom{2}{N_S}} \tag{3}$$

Where Cap is the capability of self-organization in a meta-network, $\binom{2}{N_S}$ is the number of N_S-combinations in a meta-network, and N_{Pairs} is the number of stakeholder-stakeholder pairs that link to the same information and resource nodes. This quantitative indicator, Cap, ranges from 0 to 1, which is represented by the percentage of pairs of stakeholders among all combinations.

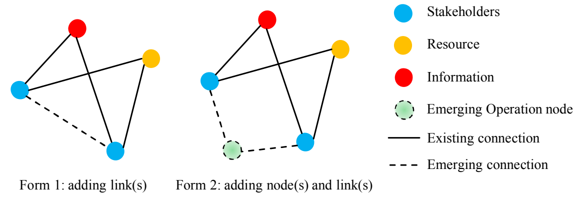

Fig. 2. An illustration of the context for self-organization.

Third, the effectiveness of a meta-network is defined as the percentage of operations that can get access to the information and resources, be in line with policy, and be conducted by stakeholders. This definition is also consistent with the meta-network theory in existing literature [34]. We assume that an operation can be executed when it is connected to a stakeholder, and the executed operation when it is connected to information, resources or policy as basic needs. Thus, we define the conditional probability of an operation that can be completed as:

$$p(O_S|O_R) = \frac{p(O_S \cap O_R)}{p(O_S)} = \frac{N_O^{SR}}{N_O^{S}} \tag{4}$$

$$p(O_S|O_I) = \frac{p(O_S \cap O_I)}{p(O_S)} = \frac{N_O^{SI}}{N_O^{S}} \tag{5}$$

$$p(O_S|O_P) = \frac{p(O_S \cap O_P)}{p(O_S)} = \frac{N_O^{SP}}{N_O^{S}} \tag{6}$$

Where $p(O_S|O_R)$ is the probability of an operation that can be executed and completed, given that the resources for this operation can be accessed; $p(O_S|O_I)$ is the probability of an operation that can be executed and completed, given that the information for this operation can be accessed; and $p(O_S|O_P)$ is the probability of an operation that can be executed and completed, given that the policy support this operation. In addition, O_S, O_R, O_I, and O_P are the collections of operations that can get access to stakeholders, resources, information, or policies; N_O^S is the number of operations that can be executed; and N_O^{SR}, N_O^{SI}, and N_O^{SP} are the number of executed operations that can get access to resources, information, or policy. As the equations shown above, the equation (4), (5), and (6) represents the performance of operations in each category (e.g., information-based operations, resource-based operations, and policy-based operations). Therefore, the effectiveness of a meta-network gives:

$$Eff = \frac{1}{3}\sum_{j \in T} p(O_S|O_j) \cdot F \tag{7}$$

$$T = \{I, R, P\} \tag{8}$$

$$F = \frac{N_O^S}{N_O} \tag{9}$$

where Eff is the effectiveness of a meta-network, F is a reduction factor, N_O is the number of operations. Equation (7) has two parts: (1) average probability of completed operations given that the needs (e.g., information, resource, and policy) are satisfied in the set of executed operations; (2) reduction factor. The reduction factor is used to transform the local probability to overall probability which considers both sets of unexecuted and executed operations.

C. Translation of perturbations in disasters

Perturbations in DM-SoS are caused by external physical or man-made events such as heavy rainfall, power outage, and road damages. From system of systems perspective, the perturbations during disasters are the changes of inputs (e.g., resources and losses), controls (e.g., budget, funding, and law enforcement), mechanism (e.g., personnel), activities (e.g., search victims and transport resources), or interactions (e.g., miscommunication). Those phenomena will lead to the changes in meta-networks including the link(s) or node(s) disappearances. Some examples in DM-SoS and translation rules are illustrated in Table II.

Because of interactions among component systems in DM-SoS, some perturbations can cause cascading effects and even catastrophic consequences for the entire DM-SoS. For example, infrastructure damages such as power outage tend to result in loss of communication and response delay.

Thus, the effects will be applied to the nodes of operations and information, as well as the links among stakeholders, information, and operations.

TABLE II. TRANSLATION OF PERTURBATIONS IN DM-SOS

Perturbations in DM-SoS	**Effects on the meta-network**
Staff turnover [31];	Disappearance of node(s) and link(s)
Federal/local policy adjustment;	
Infrastructure damages;	
Deficiency in some resources;	
Information loss;	
Communication interruption;	Disappearance of link(s)
Command delay;	
Traffic congestion or accident;	

D. Examination of perturbation impacts on performance indicators

In order to detect and examine the effects of perturbations on a meta-network, the first step is to compute the changes of the formulated indicators (e.g., Acc, Cap, and Eff) by applying the perturbations on the meta-network. Because the structure of the meta-network has been changed by perturbations, all indicators are changed as well. The differences of the indicators before and after the perturbations are a quantitative indicator showing the effects on the meta-network and can be used to evaluate the importance of the disappeared links and nodes. The equations give:

$$DA_i = Acc - Acc' \tag{10}$$

$$DC_i = Cap - Cap' \tag{11}$$

$$DE_i = Eff - Eff' \tag{12}$$

$$Imp_i = \alpha \cdot DA_i + \beta \cdot DC_i + \gamma \cdot DE_i \tag{13}$$

$$\alpha + \beta + \gamma = 1 \tag{14}$$

where DA_i is the difference of information accessibility when node i and corresponding links disappear; DC_i is the difference of capability of self-organization when node i and corresponding links disappear; DE_i is the difference of effectiveness of meta-network when node i and corresponding links disappear; Imp_i is the importance of node i; α, β, and γ are weighting coefficients that can be used to adjust the weight of each indicators in evaluating node importance in meta-networks. The values of these weighting coefficients are determined by the users and their experience. As the equations (10) – (14) shows, the importance of a node is proportional to the difference of the index before and after perturbations. It means the nodes that do not make significant changes on the indicators are less important than the nodes that make a substantial impact on the indicators.

E. Assessment of disaster management system-of-systems performance

The performance of DM-SoS includes the extent of network-centric operations, which is represented by the efficiency of a meta-network, and risk tolerance, which is evaluated through the impacts of perturbations. These two aspects are detailed by the formulated indicators in this paper. In this component, the indicators need to be integrated to assess the response strategies in DM-SoS and compare the effects of operations on DM-SoS. Figure 3 shows the implementation process of this meta-network framework to measure the extent of network-centric response and risk tolerance in the context of disasters. First, we need to identify the disaster perturbations in DM-SoS and translate them into node and link behaviors. Second, integrating all behaviors at a network level is essential to determine the structural changes (e.g., centrality, degrees, network types, and core structure) of a meta-network. Third, based on the definitions of formulated indicators and the conceptual meta-network, we can compute the values of these indicators. With the results of Acc, Cap, and Eff, the importance of a node in meta-network can be evaluated. It will be a significant signal for decision makers to determine if they need to take actions to response the perturbation and what strategies they need to make. If the node is less important, decision makers and disaster responders can ignore this perturbation and focus on other essential tasks. This process can also assess the risk tolerance of a meta-network. Based on the indicator Imp, adding redundancy through adding nodes and links into the meta-network is critical to reducing negative consequences of the perturbation. It raises the demands of accessing external entities outside the network in a dynamic environment. For example, governors can raise funds from industrial companies when the funding from federal and state agents is limited. After assessment of the network-centric operation and risk tolerance, decision makers (e.g., public works manager, emergency managers, and urban planners) can put forward corresponding strategies (e.g., increase connections between different entities, and involve more entities to the network) in response to the perturbations.

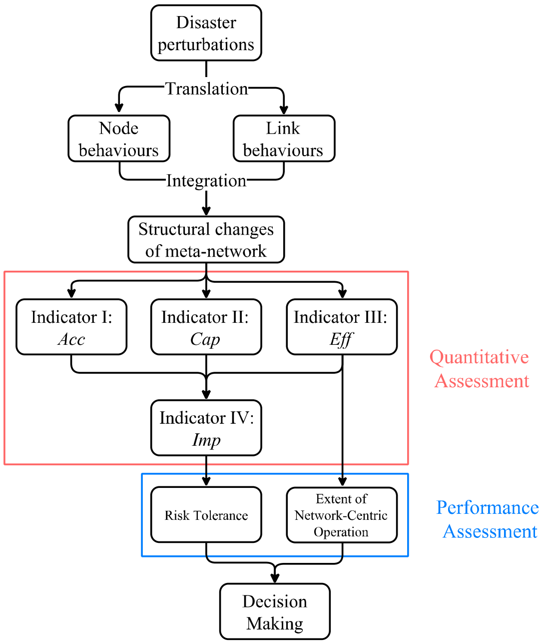

Fig. 3. Implementation of the proposed meta-network framework.

III. CONCLUSION REMARKS

This paper created and examined a meta-network framework for a quantitative and integrative analysis of disaster management system-of-systems. The proposed framework comprises five components: abstraction of meta-metrics, formulation of performance indicators, translation of perturbations, examination of perturbation effects, and assessment of operating performance.

The proposed meta-network framework in this paper has multiple theoretical and practical contributions. For example, the meta-network framework enables the application of network theories and methods for fundamentally analyzing structural properties and raising feasible improvement of the DM-SoS. The developed indicators show the features of a meta-network from node and link levels (e.g., information accessibility) as well as a network-structure level (e.g., the importance of disappeared components). Second, the meta-network framework enables dynamic network analysis (DNA) in DM-SoS. The framework integrates all disaster-related constituents and can be implemented in different time periods. The changes of network structure and performance are critical to understanding the time-dependent performance of a meta-network.

The meta-network also shows many implications for decision makers in developing and evaluating response strategies and planning from a practical perspective. The proposed framework enables to identify critical nodes through formulated equations. Thus, decision makers can use the empirical meta-networks to design mitigation plans such as landscape planning and transit systems and use the real-time meta-network to set tasks, distribute resources, and establish communication channels.

Meanwhile, this meta-network framework can be further developed in several aspects: (1) consider the time-dependent factors and indicators in the meta-network, and formulate the efficiency of disaster response; (2) explore the methods to collect and detect the constituents in each category efficiently, as well as identify their relationships in a timely manner, which will contribute to the improvement of efficient decision-making processes; (3) the translation process is subjective in this study. However, automatically detecting and translating the perturbations to meta-network behaviors is essential to trace the dynamics of meta-network and develop strategies in response to the perturbations.

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