Establishing a Framework for Disaster Management System-of-Systems

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***Abstract*—The objective of this paper is to propose a System-of-Systems (SoS) framework for disaster management systems and processes to better analyze, design and operate the heterogeneous, interconnected, and distributed systems involved in disasters. With increasing frequency and severity of disasters, improvement of efficiency and effectiveness of disaster management systems and processes is critical. However, the current approaches for conceptualization and analysis of disaster management processes do not provide a holistic perspective for analysis of multiple heterogeneous systems and processes that are interconnected and embedded in networks across various spatial and temporal scales. In this paper, a disaster management system-of-systems (DM-SoS) framework was proposed to identify the dimensions of analysis and characteristics towards a more integrative approach to disaster management. Three dimensions of analysis (definition, abstraction, and implementation) and their corresponding components for examining disaster management SoS are explored. The DM-SoS framework would enable specification and characterization of system attributes and interdependencies, as well as capturing emergent properties and cross-scale interactions.**

Keywords—disaster management and processes; system-of-systems; ; disaster phases; holistic framework

I. INTRODUCTION

Over seven hundred thousand people lost their lives, over 1.4 million were injured and approximately 23 million were made homeless as a result of disasters in the past ten years [1,2]. Disaster management involves multiple actors and their heterogeneous and distributed systems of human, physical, and technological entities. Examples of systems in disaster management include early warning systems, critical infrastructure 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. While the current approaches [3,4] for analyzing disaster management have focused on individual systems and processes, an integrative framework to capture multiple systems and their interdependencies is missing. From a systemic perspective, disaster management involves multiple interdependent systems and processes for preparedness, response, recovery, and mitigation, aiming to reduce the negative impacts and consequences of disasters on communities. In the existing literature, different studies have focused on individual systems and phenomena related to disaster management [5,6]. Some studies (such as [4]) have studied the role of information in disaster management processes. Other studies have examined the role of critical infrastructure in disaster situations. For example, Ouyang [7] studied operational issues in power and water system. Another stream of research has investigated command and control in disaster management. For example, some studies [8,9] have proposed hierarchical conceptual frameworks to examine the control flow (e.g., architecture depicting the collaboration of information, human resources, and relief supply). The focus of these studies has been on examining the potential operational barriers, such as communicating risks resulting from lack of consistent protocols and technologies [10,11]. The focus of the majority of the existing studies have been on individual systems and processes such as critical infrastructure systems [10,12], relief operational processes [8], and inter-organizational coordination processes [13,14]. While the existing studies provide insights regarding the characteristics of individual systems and processes, an integrative framework for analyzing the interdependencies and complex relationships among individual systems and processes across multiple temporal and spatial scales is missing. Recognizing this, a few studies [13,15,16] have emphasize the need for a system-of-systems perspective for integrative analyses of disaster management phenomena. A SoS approach to disaster management provides opportunities to explore interdependencies among various systems and processes and examine emergent properties that could reinforce or exacerbate the performance of systems and processes. However, the existing literature does not include a framework specifying the dimensions of analysis for SoS analysis of disaster management phenomena. To address this gap, this study proposed a Disaster Management SoS (DM-SoS). The following sections explain the capacities and dimensions of analysis for the proposed DM-SoS.

II. DISASTER MANAGEMENT AS SYSTEM-OF-SYSTEMS

The first step is to examine the distinguishing attributes of SoS in order to verify disaster management processes and systems as a SoS. According to Department of Defense (DoD) definition, "*a SoS as a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities*" [17]. In this perspective, the DM-SoS takes an integrative approach for the analysis of multiple independent human systems, physical systems, and built environment for achieving capabilities to minimize harm to communities due to disasters. The interdependencies among these systems are due to inter-organizational relationships, development of technologies, and operational, physical, and functional interactions.

The distinguishing attributes (according to Maier [18]) of SoS exist in disaster management systems and processes.

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First, each individual system in disaster management can operate independently. For example, emergency response service system comprised of disaster responders and agencies (e.g., commanders, rescuers, fire fighters, and back supporters) is an important system whose operation and management is independent of other systems (e.g., critical infrastructure). The function of emergency response services is to provide abilities for search and rescue such as receiving urgent messages, examining the affected areas, and determining the needs and priorities. "*The component systems in the disaster management processes and systems not only can operate independently, they do operate independently* [19]". The managerial independence of individual systems in disaster management is another SoS attribute. For instance, organization and institution maintain a continuing managerial independence in the context of the disaster management systems and processes [20]. Each organization can have specific work procedures and protocols for operation and resources allocation. The third distinguishing characteristic of SoS is geographic distribution. Disaster management systems and processes extend across extended geographic scales. For example, critical infrastructure such as electricity systems, transportation systems, sewage systems, and food supply systems are distributed across extended geographic boundaries. With the expansion of urban boundaries and population growth, the geographic distribution of disaster management systems and processes will grow extensively. The geographic distribution in DM-SoS requires abilities for failure detection and information exchanging in order to enhance situation awareness using advanced technologies [21]. The forth attribute of SoS is evolutionary development. Evolutionary development means that the systems and corresponding components can be added, modified, and removed over time through introducing structure, function, and purpose [14]. In the context of disasters, the evolution of systems would mainly depend on the response of human systems to severity of hazards, requirements for new functions, adaptive behaviors and objectives, and available resources. For example, in order to improve resilience to the impacts of flooding, local agencies can consider multiple measures such as increasing spending on flood defense structures, protecting wetlands and building green infrastructure [2]. Each measure (e.g., new infrastructure development) can change the landscape of hazards, and subsequently lead to the evolution of disaster management systems and processes. The fifth distinguishing attribute of SoS is emergent behaviors. In disaster management and processes, for example, evacuation and community self-organization are emergent behaviors across the disasters-affected areas. A SoS perspective provides insights to study emergent properties from interaction of human and physical systems. An example of such emergent properties is resilience. In fact, resilience is a system property that arises from interaction of human and physical systems in response to hazards. The last distinguishing attribute of SoS is temporal distribution. As discussed earlier, disaster management systems and processes span across four phases of disasters: preparedness, response, recovery, and mitigation. Objectives and strategies in different phases are different in DM-SoS. Considering temporal interdependencies among systems and their attributes is an essential consideration in the analysis of disaster management systems and processes. According to the above discussion, disaster management systems and processes have all the distinguishing attributes of SoS, and hence, a SoS framework is essential for more integrative planning and operations to enhance the effectiveness and efficiency of disaster management.

III. Capabilities Of A SoS Perspective

To illustrate the capabilities of the proposed DM-SoS, this section highlights a number of dimensions that would lead to a new understanding regarding disaster management.

A. Integrative perspective of disaster management systems and processes

As discussed earlier, the existing studies only focus on limited aspects of disaster management, such as mitigation planning, critical infrastructure, inter-organizational coordination, and emergency relief operations. While the analysis of these individual systems and phenomena are important, understanding the complex interaction among various systems and processes and multiple phenomena is essential in achieving the desired outcomes. Without an integrative perspective, potential integration risks and coordination issues will arise and could affect performance through the entire life cycle of disaster management. In fact, a least studies area in disaster research is robust integration of individual systems and processes. In complex disaster management systems and processes, lack of an integrative perspective inhibits the ability to analyze and develop robust strategic and operational strategies to deal with the impacts of disasters. The proposed DM-SoS enables an integrative analysis by taking into account three dimensions of analysis (e.g., definition, abstraction, and implementation). These dimensions of analysis are explained in the following section.

B. Considering emergent behaviors

Emergent behaviors are ones that arise as a result of interactions among various systems and processes and cannot be attributed to individual systems or processes. The current disaster management frameworks do not provide the capability to capture and analyze the emergent behaviors. Further, the emergent behaviors are unintended, and even cannot be restricted to what can be deliberately achieved through design [22]. In fact, in the context of disaster management, it is essential to establish architectures and systems to be rich in emergence and broad capability to absorb the unforeseen emergence. For example, the effectiveness of a large-scale evacuation in affected communities during disasters is an emergent behavior that arise based on the interaction of early warning systems, human system protocols, and critical infrastructure. Through the lens of the proposed DM-SoS framework, emergent properties can be better specified and characterized. The understanding of emergent behaviors and properties in DM-SoS is essential in order to achieve the desired outcomes such as resilience to disasters.

C. Analysis on interdependencies

Specification and characterization of interdependencies in DM-SoS is critical for achieving integrative processes that yield the desired outcomes. The analysis of interdependencies includes the evaluation of inter-organizational coordination, critical infrastructure dependence, co-location and co-evolution of individual systems and processes, and systems integration requirements. Of particular importance is the analysis of interdependencies among human, physical, and cyber systems. In fact, designing effective architectures and developing robust protocols for disaster management requires integrative cyber-physical-human systems. In DM-SoS, the interdependencies among component systems exist in different levels (i.e., global, national, regional, state, and local). An important aspect of interdependencies analysis in DM-SoS is the determination of the attributes (i.e., autonomy, belonging, connectivity, diversity, and emergence) of the whole SoS based on integration of various systems and processes.

D. Networked communication and information sharing

In large-scale heterogeneous systems (such as disaster management), communication and information exchange among individual systems is critical. In existing disaster management architectures, the required information exchange between different systems or entities are not fully specified for operations. The component systems should be able to fulfill their own duties on different information sources and formats [11]. For example, the flooding control agencies mainly focus on the flood maps to reduce the exposure to flooding. But, the examination of flood-prone areas does not account for the failure of critical infrastructure that can extend the areas exposed to flooding. The information regarding flood-prone areas is essential for determining shelter needs and determination of evacuation protocols. So, it is essential that the information about systems status, interdependencies and performance requirements is communicated in a networked fashion. An advantage of the proposed DM-SoS is its ability to determine robust network environments to maximize data sharing [23], such as standardizing the data, incorporating the network-centricity into strategic disaster management processes. Effective integration and rapid synchronization of information would lead to increased speed of decision making. However, network-centric information exchange involves challenges such as information inundation and redundancy that need to be considered in DM-SoS.

IV. SoS Framework For Disaster Management

The dimensions of the proposed DM-SoS framework are presented in this section. The proposed DM-SoS framework enables conducting more integrative analysis and study of architecture design, technology integration, and coordination in disaster management processes. The framework comprises three dimensions of analysis: definition, abstraction, and implementation (see Figure 1.).

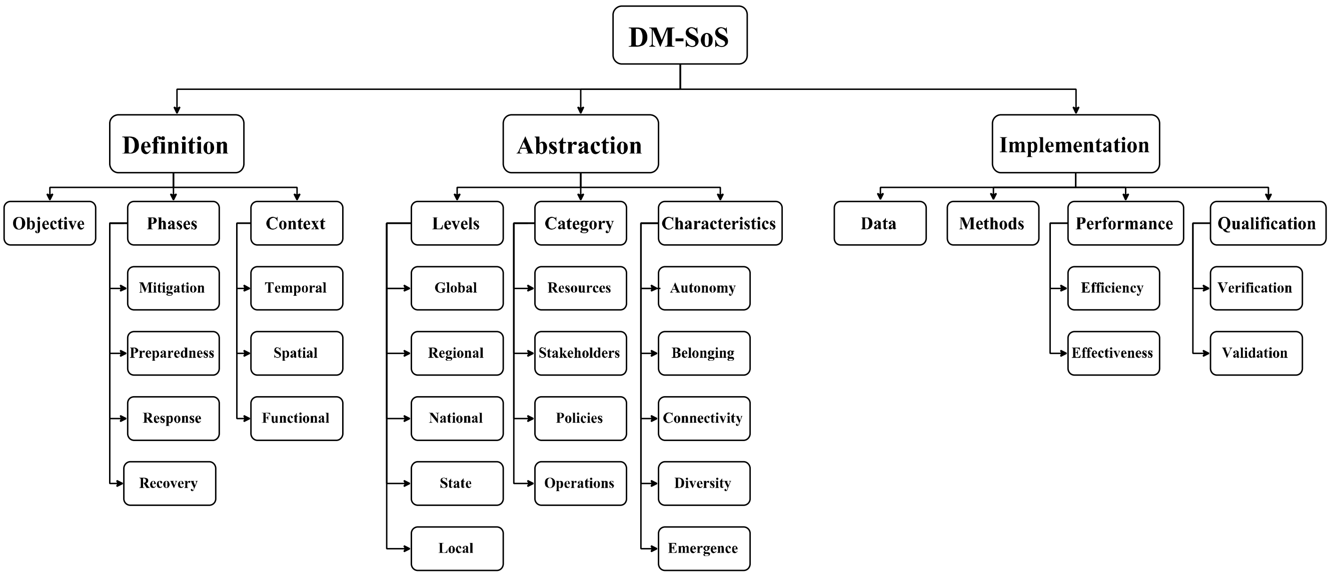

Fig. 1. Dimensions, elements and components of DM-SoS

A. Definition

The definition dimension consists of three elements: objective, phases and context. First, the objective specifies the overall goal of conducting a DM-SoS analysis. For disaster management analysis, the objectives vary from performance assessment to operational improvement to strategic planning. Examples of analysis objective include: resilience performance analysis of communities, improving humanitarian logistics [24], enhancing system integration and coordination, and community and infrastructure recovery.

As human and natural stressors are parts of the equation, disaster phases are important indicators to perceive the changes, divide management processes into several stages, and study their systematic properties in each phase. In this framework, the sequential phases are defined as: mitigation, preparedness, response, and recovery. Mitigation refers to the plans and policies that are conducted for eliminating or reducing the unexpected impacts from disasters. Those are the long-term efforts, like building design, land use practices, regulation acts, and disaster risk reduction plans. Preparedness is defined as a period of time when disasters have not yet impacted the systems. In this stage, vulnerabilities and potential risks in the systems should be detected based on historical data and model-based information. Early warning for the public and timely coordination among relevant organizations and agencies should be established. The stakeholders (e.g., local government, residents, infrastructure operators, and insurance companies) affected and resources (e.g., shelters, food, drinking water, and electricity) needed during disasters should be recognized and their performance should be tracked in each disaster phase. Response is "*the other side of preparedness, which is the activation of the plan and preparedness activities in response to the threat or disaster event*" [9,25]. The critical points in this phase mainly focus on reducing the loss of capital and lives, such as first aid, community-based response and sheltering, individual and organizational coping strategies [26]. 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. Through the lens of a SoS approach, the attributes and interactions that enhance positive emergent behaviors can be better understood. Recovery is the phase when the disasters have past but the affected systems still need to be restored and repaired. An important aspect in the DM-SoS framework is the recognition of temporal relationships among various systems and processes and considering how different instances of DM-SoS contribute to a specific performance measure at a specific disaster stage. In the DM-SoS framework, disaster stages are not examined in isolation, but rather the temporal relationships among processes in different disaster stages should be considered.

Context defines the boundaries of the DM-SoS analysis, including temporal distribution, spatial distribution, and functional distribution. For disaster management analysis, the temporal and spatial distributions specify the boundary of analysis for situations and events. For example, in disaster response phase, the events (e.g., flooding, house damage, grid failure, and communication interruption) are in the sequence of time, appear in certain areas, and are correlated with each other. In order to capture the evolvement of events and make timely decisions, SoS entities should be tagged with temporal and spatial notions, such as specific time, intervals, and geolocations for mapping and visualization of evolutionary development. Functional context provides insights to specify the functional distribution (e.g., emergency services, rescue operation, and critical infrastructure repair) for better allocation of resources and coordination of agencies.

B. Abstraction

The second dimension in the proposed DM-SoS is abstraction, which is to specify the key components of the current systems for analyzing and characterizing a specific disaster phenomenon. The elements in this dimension includes: levels, category and characteristics. Levels (e.g., global level, regional level, national level, state level, and local level) are hierarchical notions of systems that determine the level of abstraction for the constituent systems and interactions in disaster management. Different levels contain different stakeholders, resources, policies and operations, which are different categories of entities. For example, international cooperation between countries is essential in coping with disasters. At the global level, the coordination, policies, and operations such as Paris Agreement and international humanitarian technologies are examined. At the national level, measurements and actions are more detailed based on the specific situation and the capacities of risk reduction. Following this pattern, the management processes (e.g., traffic control, renew drainage systems, building reinforcement, and public training) are fulfilled on the local level.

Category defines the entities in a DM-SoS and their relationships. Entities include resources, stakeholders, policies, and operations [27]. Resources represent the physical entities (e.g., fuel, roads, trucks, equipment, and pipelines) that provide a specific service and enable stakeholders to implement a specific task or operation related to a specific disaster management phenomenon. Stakeholders are the non-physical entities such as local government, infrastructure managers and operators, first responders, and the public. Policies (e.g., contracts, disaster risk reduction plans, and regulation acts) are protocols that govern the operation and decision-making processes of stakeholders [27]. Operation includes series of tasks and application of intent from stakeholders to direct the activities of stakeholders. In the context of flooding, the Stakeholders include, but are not limited to, households, emergency response department, volunteers, transportation departments, and non-government organizations provide sheltering and conduct search and rescue for the injured. Resources (e.g., rescue equipment, IT platforms, and critical infrastructure services) are allocated and distributed based on operation and strategic policies (e.g., mitigation and emergency response plans).

Characteristics of a DM-SoS determine autonomy, belonging, connectivity, diversity and emergence and also affect the types of SoS as well as the implementation approach. Diversity in a SoS is the indicator of heterogeneity and may contribute to certain degrees of freedom in a SoS [15]. DM-SoS is characterized by significant diversity. For example, FEMA coordinates with a number of agencies and organizations (e.g., Department of Agriculture, DoD, Department of Energy, The Centers for Disease Control, and Social Security Administration) for immediate response. Physical systems (e.g., electricity grid, flood reservoirs, and roads) interact with each other for maintaining their functionality in times of disasters. So, in Figure 2, the diversity of DM-SoS is represented by “D” and located very close to heterogeneity. Another SoS characteristic is connectivity, which is the ability to achieve interoperability and net-centricity among components in order to enhance agility, responsiveness, and resilience in DM-SoS [17]. For example, with the advancement of social media, disaster situations can be mapped and reported by citizens in a networked fashion. The user-generated information can be accessed by public and relevant agencies in a timely manner [28,29]. Improving connectivity in DM-SoS is essential in achieving integration among various human, physical, and cyber systems. So, the degree of connectivity in DM-SoS is represented by “C” and placed close to net-centric in Figure 2, as it still needs to be improved. The autonomy is a characteristic in DM-SoS determines the extent to which a system wants to be a part of the DM-SoS or operate as a monolithic system. As discussed earlier, the component systems are capable of being congruent and independent. So, the degree of autonomy in DM-SoS is represented by “A” and placed in the middle of autonomy axis in Figure 2. Emergence, as an important characteristic of DM-SoS, is the least understood property in disaster context. For example, when the human systems are integrated and network-centric communication is enabled via IT systems, self-organization may arise as an emergent behavior in a DM-SoS. Emergence is not always a favorable property in DM-SoS. Due to its inherent unpredictability, emergent behaviors may make the decision-making processes in disaster setting more complex and uncertain. So, the degree of emergence in DM-SoS is represented by “E” and located close to indeterminate in Figure 2. Belonging in DM-SoS is the authority and choice of component systems to get access to the SoS. The level of belonging restricts or allows systems to receive information and resources allocation. The degree of belonging in DM-SoS is various in different disaster stages, so it is represented by “B” and located close to the middle of belonging axis in Figure 2.

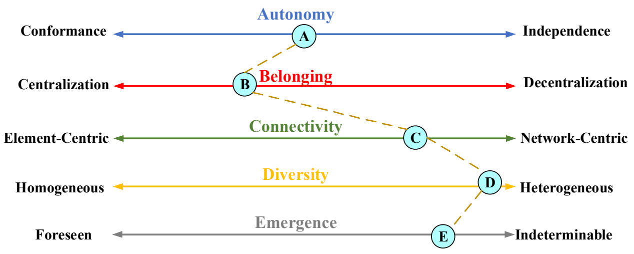

Fig. 2. Characterizatics of DM-SoS

C. *Implementation*

The implementation dimension of the proposed DM-SoS framework includes three elements: data, methods and performance. The implementation dimension enables the use of data and models to evaluate a specific phenomenon in DM-SoS based on the abstracted entities and interactions. Data related to entity attributes and relationships can be gathered from real-world situations and the processes of management. For example, in assessment of community resilience to flooding, data requirements include, but are not limited to: flood maps, critical infrastructure conditions, socio-economic attributes of households, and housing conditions. Various methods could be used to model and implement DM-SoS dynamics. Methods include mathematical modeling, network analysis, agent-based modeling, and dynamic simulation. The selection of appropriate method would depend on the analysis objective and disaster phenomena of interest. For instance, network analysis can be used to studying interdependencies among critical infrastructure systems as well as inter-organizational coordination among agencies. The third element of implementation dimension is performance in which measures to examine DM-SoS effectiveness and efficiency are determined. Selection of appropriate measures depends on the objective of a study. For example, cost-benefit ratio is a ubiquitous measure of effectiveness in disaster management, and request-response latency is another quantitative measure of efficiency in system-of-systems [30]. In addition, resilience is also considered as an important measure for DM-SoS, but, specific indicators and metrics for assessment of resilience in DM-SoS are missing. The last element in the implementation dimension is qualification where verification and validation are conducted to ensure the credibility of the DM-SoS analysis. Verification is an objective process including testing, inspection and specification analysis to examine if the DM-SoS is well-developed and error-free. Validation is the process of checking if the designed DM-SoS satisfies the requirements and needs (e.g., high interoperability, and adaptive capacity to the evolving environment) of real-word disaster operation and coordination. For instance, as the demand of disaster responders and victims, the DM-SoS should provide the capability of sharing real-time information and rapidly developing response strategies when extreme events burst (e.g., building damage, road closure, and pipe burst). Furthermore, because the DM-SoS is the result of integration of multiple heterogeneous systems, verification and validation at the interfaces of various systems are also important to the success of DM-SoS [31].

V. Discussion On Type Of DM-SoS

In the SoS literature, different types of SoS have been specified (Table I). In order to determine the type of DM-SoS, the proposed framework utilizes a three-dimensional taxonomy [27] (see Fig. 3). A SoS can be categorized as one of four SoS types (i.e., directed SoS, acknowledged SoS, collaborative SoS, and virtual SoS) based on the authority, relationships, and operation among the corresponding constituent systems [17,32]. First, authority represents the degree of central command and control in DM-SoS. A directed SoS is controlled by the central managing entities, while a virtual SoS does not have central management. The directed SoS is strong in consistency of resources because of its centralized management and directed information flow. In contrast, virtual SoS is comparatively decentralized and good at triggering voluntary behaviors (e.g., emergence of new entities). Second, relationship (e.g., contractual and free relationship) defines the connection between component systems in a DM-SoS. Contractual relationship (e.g., Service Level Agreement) is a constraint among pairs of systems and their owners to conduct operation depending on recognized protocols [32,33]. Third, the mode of operation can vary from interoperation to directed operation.

TABLE I. Definitions Of SoS Types

Type	*Authority*	*Relationship*	*Operation*
Directed SoS	Centrally managed	Contractual	Directed operation
Acknowledged SoS	Semi-centrality	Contractual	Directed operation
Collaborative SoS	Voluntarily managed	Semi-contractual	Interoperation
Virtual SoS	Voluntarily managed	Free	Directed operation

In DM-SoS, the type of SoS may change based on the disaster stage. For example, during the mitigation phase, a DM-SoS may be collaborative and during the response stage it may be directed. Also, hybrid SoS types may exist concurrently. For example, in disaster response, some instances of DM-SoS (e.g., government-led relief operations) may work as a directed SoS and other instances (e.g., community-based relief operations [34]) may work as collaborative SoS. The dynamic changes and combinations of SoS types in DM-SoS are essential to integrate the strengths of different types of SoS in accordance to the objectives of disaster operation. For example, a hybrid directed-collaborative SoS type can achieve better performance than a directed SoS (since self-organization and network-centricity is limited in directed SoS).

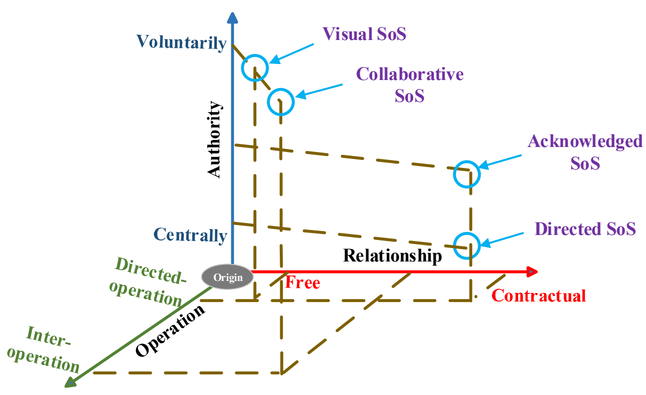

Fig. 3. Different types of SoSs

VI. Conclusion Remarks

This paper proposed a framework, disaster management system-of-systems (DM-SoS), for integrated analysis of disaster management and processes. The dimensions of analysis (e.g., definition, abstraction, and implementation) and corresponding key elements in each dimension were discussed. In practical aspects, the presented DM-SoS framework highlighted the significance of interdependencies of constituent systems and emergent properties from an integrative perspective. In theoretical aspect, the DM-SoS showed some implications of understanding and assessing the system exposure and adaptive capacities to disasters.

The disaster management system-of-systems framework provides a holistic approach in assessment of complex relationships among human, physical, and cyber systems in the context of disasters. Future research studies can apply the proposed framework to better understand and design more resilience disaster management systems and processes. In particular, the proposed framework can be adopted in analysis of: (1) inter-organizational coordination, (2) network-centric communication and information exchange, (3) human-in-the loop cyber-physical systems, (4) system integration, and (5) emergent behaviors in the context of disasters.

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