A Socio-Physical Governance Framework for Emergency Response and Preparedness

William Ross, *Student Member, IEEE,* Alex Gorod, *Member, IEEE,* and Mihaela Ulieru, *Senior Member, IEEE*

***Abstract*—A holistic approach to emergency response and preparedness, in which the physical and social layers are explicitly and integratively represented within a governance framework, is proposed, and its application on a case study is presented. The governance framework offers a systemic perspective on the response and preparedness process, including the System of Systems (SoS) of interest, feedback mechanisms, external factors and constraints, and the influencing actions of the governing body. It is unique in that it allows the SoS to be considered from a socio-physical perspective, explicitly capturing the critical relationships that exist within and across components of both social and physical dimensions. A case study example illustrates how this framework makes it possible for emergency response governance to be conducted simultaneously in a proactive and reactive manner. Network analysis demonstrates the effectiveness and value of the proposed approach in revealing crucial criticalities that remain hidden to the unidimensional views. It further shows that such a systemic approach is instrumental in improving emergency response and preparedness in today's complex world.**

***Index Terms*—governance framework, socio-physical view, emergency response and preparedness, system of systems, proactive governance, reactive governance.**

I. Introduction

In the world of emergency-response operations, responders are facing situations of increasing complexity (e.g., 9/11, Katrina, Haiti earthquake, and most recently the Japanese earthquake and tsunami). The unique nature of each of these situations/rare events, the clash of the interacting organizational policies burdening the necessary rapid reaction, and the unforeseen consequences and cascading effects make it impossible to adequately plan for an appropriate response, due to the difficulty in evaluating a priori the effectiveness of response practices and preparedness measures.

The loss of life and disruption to business continuity in an emergency are typically the result of a combination of failures on two fronts: physical (e.g., affected critical infrastructure, such as bridges, buildings, and resource providers) and social (e.g., an individual, organization, or policy hindering appropriate action). Traditionally, these factors have been considered separately, yet frameworks that incorporate both and the interface between them are expected to improve situational awareness during critical events [1].

In an emergency, the affected area of interest can be viewed as a System of Systems (SoS), consisting of a number of integrated complex systems working together to achieve a common goal. To the best of our knowledge, no existing framework ([2], [3], [4], [5], [6], [7], [8], [9]) provides an explicit socio-physical view of the SoS of interest while considering external factors, feedback, the emergency-response governing body, constraints affecting its decision-making, and the governing process. Furthermore, none of the earlier work explicitly identifies nodes and the interrelationships between and across the physical and social layers of an SoS.

W. Ross and M. Ulieru are with the Adaptive Risk Management Lab, University of New Brunswick, Fredericton, NB, Canada e-mail: (william.ross@unb.ca, ulieru@unb.ca).

Alex Gorod is with SystemicNet, LLC in New York, NY, USA e-mail: (agorodis@yahoo.com).

Manuscript received December 6, 2011; revised.

II. General governance framework for emergency response and preparedness

Governance allows for the "coordination of wholly or partially autonomous individuals or organization units on behalf of interests to which they jointly contribute" [10]. From a proactive standpoint, it is possible that governance in a complex context can be designed using micro and macro-level perspectives to examine patterns and to better understand the emergent behaviours of the SoS before an incident occurs. On the other hand, from a reactive governance perspective, that is, following an incident, it is important to influence the SoS environment in order to achieve recovery in a time-efficient manner, which would reflect the extent of resiliency of the SoS [8]. Since the SoS impacted is far too complex to be controlled using a top-down approach [11], what is required instead is a mechanism to influence the SoS to maintain its normal (or non-emergency) state or restore it as quickly as possible during an emergency. Due to the dynamic nature of an SoS, the governing body becomes an adaptive entity, consisting of various individuals who can emerge from within and outside the SoS of interest, thereby contributing to its resiliency. Still, there is always a degree of centrality, and, consequently, authority, under which the governing body influences the SoS.

As a new platform for analysis and decision-making, we propose a framework that offers a more comprehensive understanding of the SoS's network architecture, which is central to determining the degree of connectivity of nodes and their criticality in an emergency.

As illustrated in Fig. 1, the framework consists of the SoS of interest, external factors that could influence the SoS, the feedback mechanism from the SoS's emergency response governing body, constraints that could affect the governing body's decision-making process, and the governing process itself. These components, adopted from [12], and integrated with the socio-physical view of the SoS, focus on four key questions based on an enterprise approach [8], [12], [9], [13]:

- What needs to be influenced?
- Why is there a need for change within the environment?

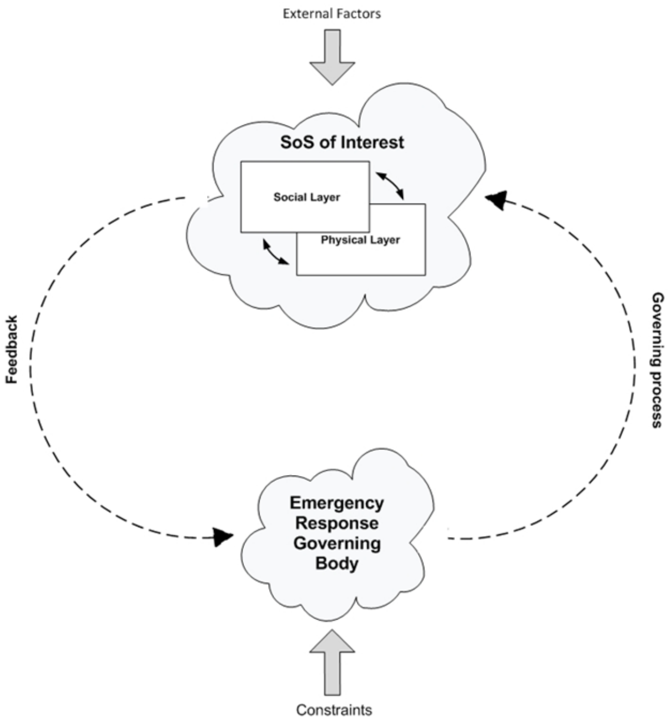

Fig. 1. General Governance Framework

- How should the environment be influenced?
- When should the process of influencing be stopped?

These questions are revisited in Section V, when the application of this general framework to the following case study is discussed.

III. Case study: a steam incident on a university campus

The incident we refer to below is real, but, for reasons of confidentiality, we do not disclose the location where the events took place.

At approximately 10:20 a.m., routine repairs at the university steam plant resulted in a water-hammer—an explosion caused when steam comes in contact with water in the pipes. A simultaneous combination of factors including a drop in water supplied by the city, a leak in the pipes, and a failure of a flow-back valve in the boiler led to the explosion that ruptured the boiler releasing steam into the plant and requiring a hasty evacuation of the immediate area. Plant operations were immediately halted, and following a safety inspection by the local fire department, repairs to the system began shortly after 11:00 a.m.

The steam produced by the plant is used to heat the various buildings on the university campus. In addition, the university hospital, not managed directly by the university, uses the steam to sterilize equipment and bedding. As a result of the explosion and due to the cooler December weather, temperatures in buildings on campus and at the hospital decreased, forcing the hospital to consider evacuating patients to the network of nearby city hospitals.

From the university's perspective, several actions were taken to conserve heat and ensure the protection of critical labs and research. These activities were overseen by the university's emergency operations centre (EOC), the governing body in charge of handling the incident. The potential evacuation of the hospital was by far the major concern of the day; however, the university also had to consider the impact the steam plant shutdown would have on their normal operations, specifically, whether or not they would be forced to cancel planned course examinations the following day.

Through a concerted effort of all parties involved, including the EOCs from the hospital and city, the steam plant was successfully repaired (at approximately 2:00 p.m.) and normal steam levels restored (at approximately 5:30 p.m.) so that the evacuation of the hospital was not necessary and the university was able to continue its activities. Even still, the planned evacuation caused consequences persisting days after the incident had been resolved, as the normal operations of the university and neighbouring hospitals were disrupted by the implemented preparations for transporting and receiving evacuated patients.

In the end, no casualties were reported, and the consequences of the incident were confined to the delayed business operations of the various organizations involved. However, the interdependency between the university steam plant and the hospital network was identified as a critical factor. While the incident was taking place, it was staff members from the hospital who notified the university that the steam incident was interfering with their hospital operations and might result in an evacuation if the steam was not restored later that day. This example of the university not being aware of the broader systemic picture reflects the deficiency of a unidimensional view and in this concrete case reveals that the socio-physical view was not considered as part of the emergency-response governance process pointing to the critical need for a governance framework in which such interdependencies are properly identified and addressed.

A. *SoS views*

Historically, emergency response governance has taken into consideration either a physical ([6], [14], [15], [16]) or a social perspective ([17], [18], [19], [20]]), not a combination of the two; or if both have been taken into account, there has not been explicit emphasis on the interaction between the views ([1], [21], [22], [23]). Research in the area of socio-technical systems, in contrast, is replete with work related to the crucial interface boundary [24], and emphasizes that it is exactly at these interfaces that the majority of problems occur [25]. Addressing this crucial issue, the proposed framework incorporates a holistic socio-physical view of the SoS of interest. For an emergency response governance framework, such an integration of physical and social views can help to better govern the SoS in the wake of an unfolding event. Below, the physical (see Fig. 2), social (see Fig. 3), and socio-physical (see Fig. 4) views of the SoS under discussion are presented using notation derived from systemigrams [26]. A network analysis follows in Section IV.

1) Physical view: As seen in Fig. 2, there are 13 physical constituents of the SoS, numbered P1 to P13. The constituents

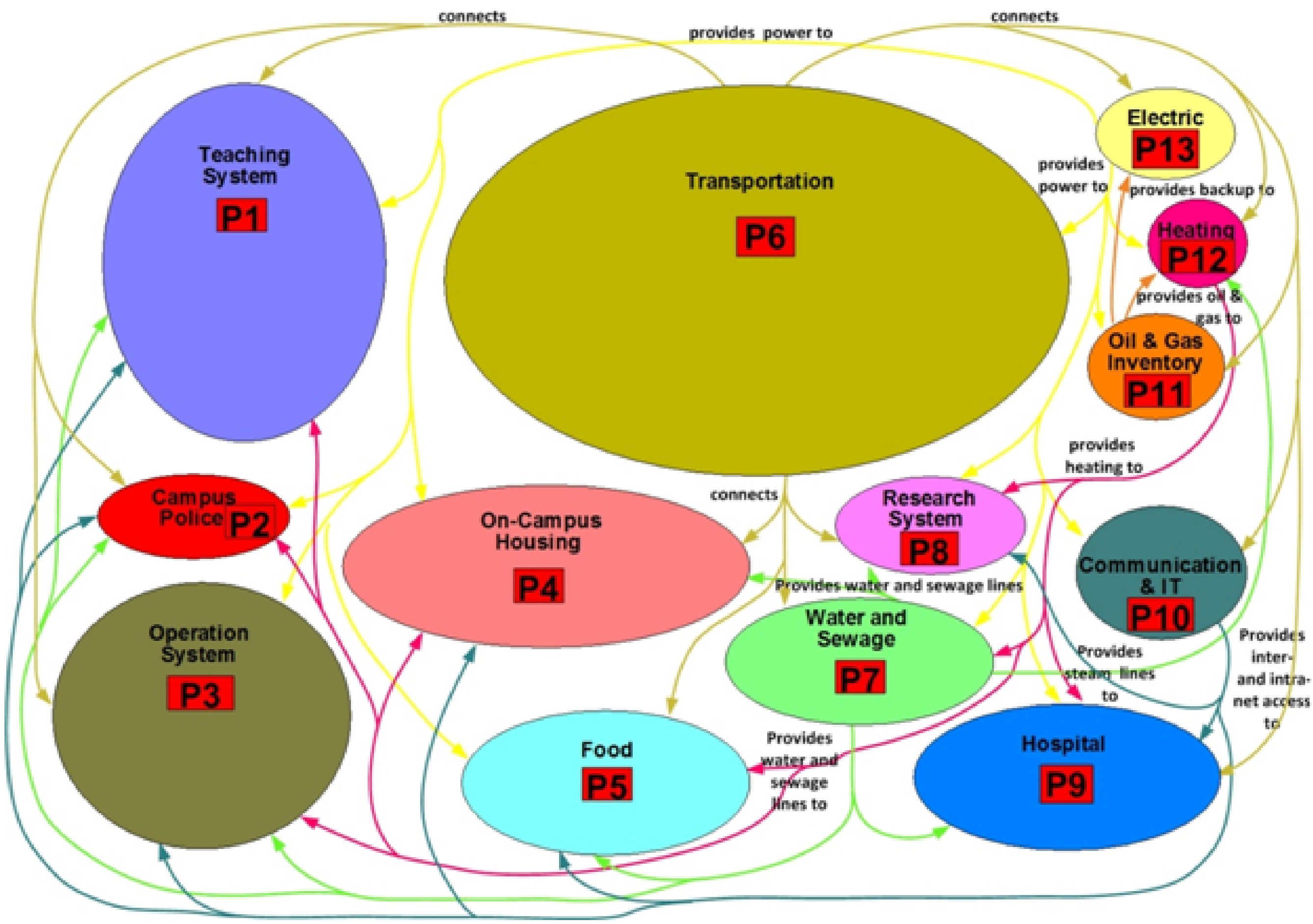

Fig. 2. University SoS Physical Network Diagram

have been identified from multiple data sources, including government reports [27], official press releases, the university's disaster plan, website, bio-safety plan guidelines, hazardous materials handbook, and campus map, and also a peer-reviewed conference proceeding related to the case [1].

In addition to considering the constituents separately, the interrelationships between them have also been depicted as links and labelled according to their function. Each constituent node is itself a system, consisting of various subsystems. For example, the Transportation node (P6) consists of the road network, parking lot, traffic light, bus stop, crosswalk, and traffic sign subsystems. However, for clarity, these subsystems have been omitted from the figure.

2) Social view: The 15 social components of the SoS and their interrelationships, shown in Fig. 3, have also been identified from multiple public data sources, including the university's website and various reports and presentations [1]. This figure represents the social capital network of the SoS, i.e., the "social connections that exist between people which enable and encourage mutually advantageous social cooperation" [28].

3) Socio-Physical view: Fig. 4 shows the interrelationships existing across the two views. This socio-physical view represents an integrated perspective of the university SoS, consisting of 28 nodes (13 physical and 15 social). It also includes implicitly the links within each dimension, though for clarity these have been omitted from the figure. By examining the physical and social views separately, interrelationships within views can be analyzed, but it is not possible to see interrelationships across views. As such, it is critical that the boundaries between these layers be explicitly captured. Only then can a node's effect on the entire SoS be understood.

IV. SoS NETWORK ANALYSIS

An SoS is a network, consisting of nodes and directed edges [3], [29], [30], [31], [32]. Since centrality is a figure of merit that is commonly used in network analysis, especially in relation to social networks [33], four different measures of centrality are used to analyse the university SoS's physical, social, and socio-physical views. During an emergency, it is important to focus efforts on protecting the most critical nodes in the SoS, as not doing so may result in cascading effects. However, the criticality of nodes is subject to the view (or network) being considered. The measures applied include in-degree centrality, out-degree centrality, closeness centrality, and eigenvector centrality. Each measure is described in turn, followed by the results of the analysis.

In-degree and out-degree centrality relate, respectively, to the number of relations (or edges) coming into a node and going out from a node [34]. Conceptually, the first case

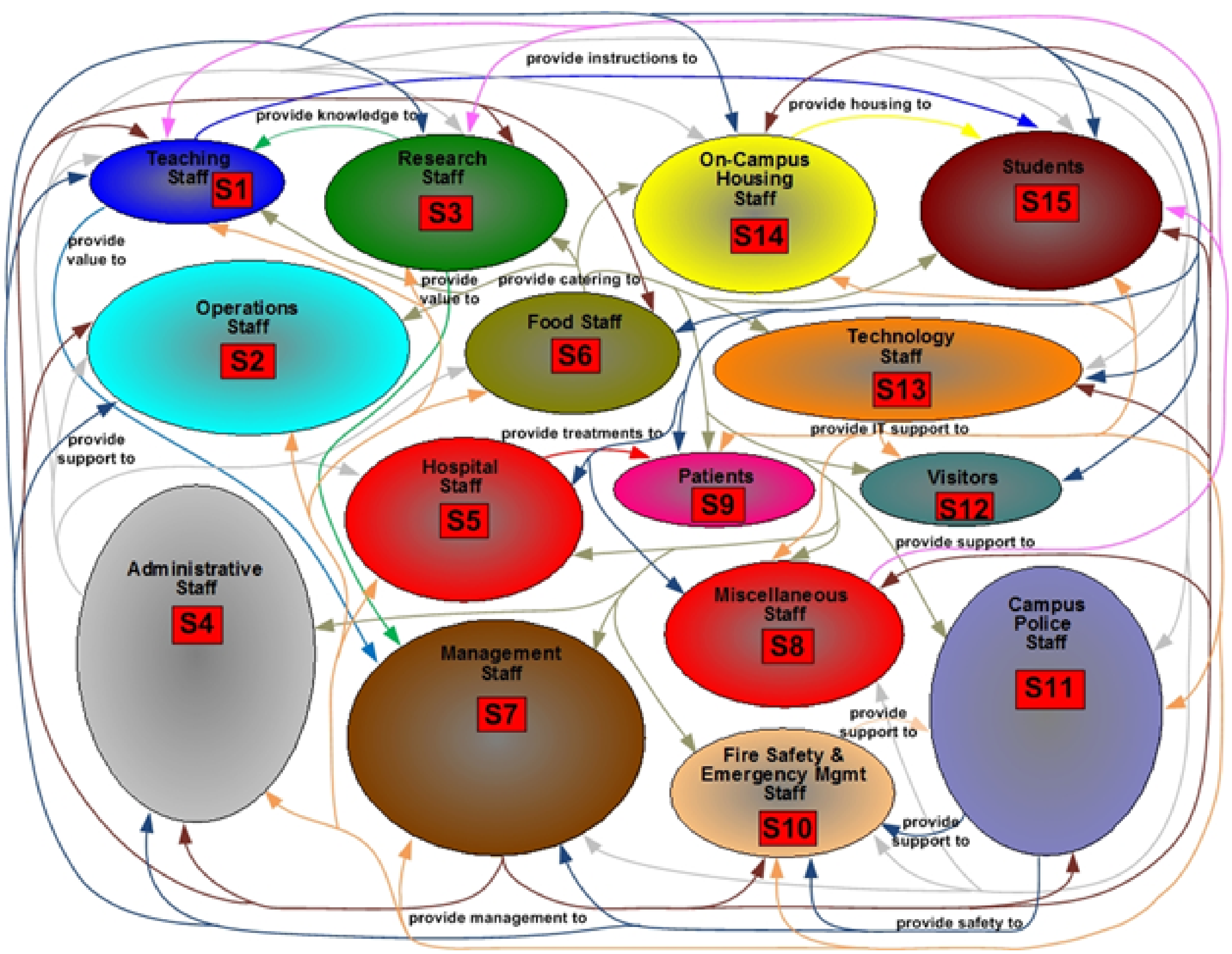

Fig. 3. University SoS Social Network Diagram

refers to how many other nodes are required for the current node to operate (dependency), while the second case indicates how many nodes the current node is providing a service for (criticality). These measures are calculated using Equation 1 [33]

$$C_D = \frac{deg(v_i)}{n-1} \tag{1}$$

where C_D refers to the degree centrality of node v_i, $deg(v_i)$ refers to either the in-degree or out-degree of node v_i (i.e., how many in-links or out-links node v_i has), n refers to the total number of nodes in the network, and $n-1$ is the normalizing factor.

Closeness centrality refers to how quickly a node can access all other nodes in the network (i.e., how "close" it is to other nodes) [35]. In emergency response, this could represent a measure of the criticality of a node, as nodes that are able to connect more readily with other nodes can also have a greater impact on the SoS (e.g., cascading effects). Closeness is calculated using Equation 2 [35]

$$C_C = \frac{\sum_{t \in V \setminus v} d_G(v,t)}{n-1} \tag{2}$$

where C_C refers to the closeness centrality of node v, t refers to some node other than v, $d_G(v,t)$ refers to the distance between nodes v and t (i.e., how many edges separate the nodes), n refers to the number of nodes in the network, and $n-1$ is the normalizing factor.

Lastly, the eigenvector centrality measure refers to the criticality of a node as well. It posits that nodes that are attached to highly connected nodes are more critical than nodes that are not, and this measure can be thought of as the influence the current node is able to exert on the entire network [35]. It is computed using Equation 3 [35]

$$\lambda \mathbf{v} = \mathbf{A}\mathbf{v} \tag{3}$$

where $\boldsymbol{A}$ is the adjacency matrix of the graph, λ is a constant (the eigenvalue), and $\boldsymbol{v}$ is the eigenvector.

Table I contains the computed centrality measures for the three views related to the university case study. The "physical or social" columns relate to the measures where only one

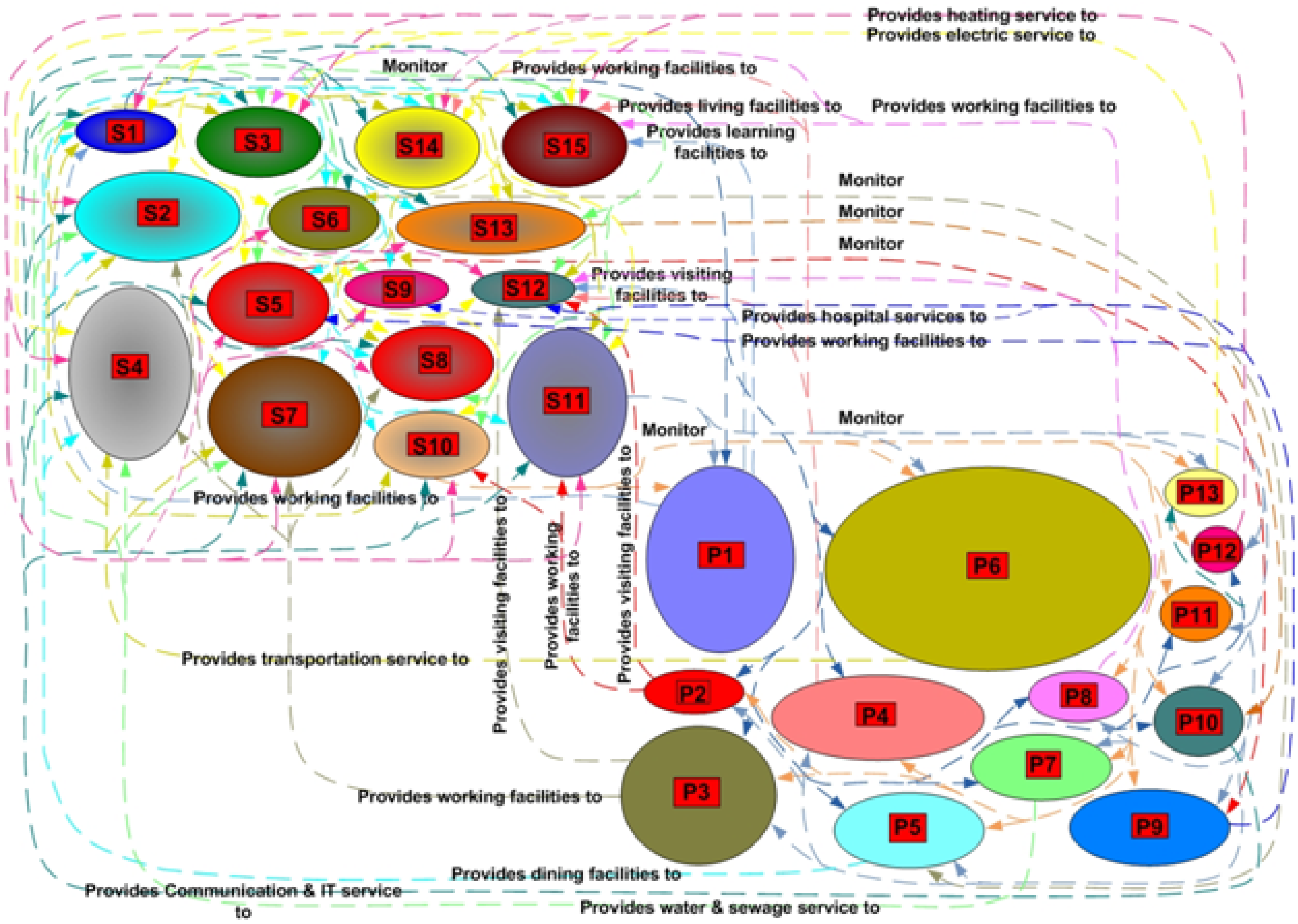

Fig. 4. University SoS Socio-Physical Network Diagram

of the views is considered: physical for the physical nodes, P1-P13 (see Fig. 2); and social for the social nodes, S1-S15 (see Fig. 3). The "socio-physical" columns, on the other hand, represent the measures of centrality where both physical and social nodes are considered in one network, along with their associated interrelationships (see Fig. 4).

These four centralities are important measures in emergency response, as they indicate both the interdependencies and criticality among the nodes in the network. Many papers highlight the usefulness of centrality measures in emergency response [36], [37], [38], [39]. However, most relate only to the social network, not the physical network, and none relates to the combined socio-physical network.

Fig. 5 shows the in-degree centrality measures for the physical and social nodes. As seen, there is a shift in terms of which nodes have the highest value when the combined view is considered versus considering separately the physical and social views. For example, the five biggest consumers (and ties) are the Teaching (P1), Campus Police (P2), Operations (P3), On-Campus Housing (P4), Food (P5), Research (P8), Hospital (P9), Teaching Staff (S1), Research Staff (S3), Management Staff (S7), and Students (S15) nodes, when considering the physical and social views separately. However, Teaching Staff (S1), Research Staff (S3), Management Staff (S7), Visitors

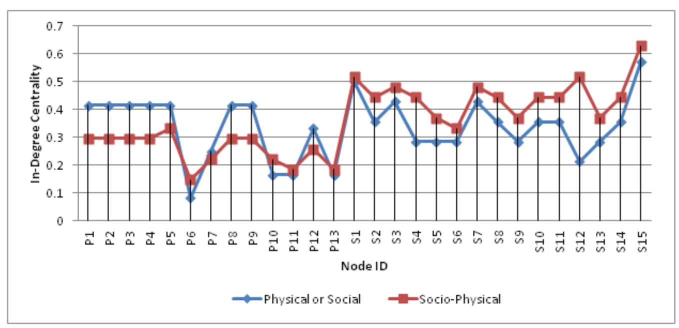

Fig. 5. In-Degree Centrality Measure

(S12), and Students (S15) are the highest valued nodes when the combined socio-physical view is taken into account.

The in-degree relates to the demand or need of a node. On the other hand, as illustrated in Fig. 6, the out-degree relates to how many other nodes the current node is supplying a service to. As the relative importance of nodes changes when considering the combined view, these differences are important as the holistic view uncovers interdependencies within and across the various networks that are not otherwise explicitly apparent. For example, the five biggest suppliers are the Transportation (P6), Electricity (P13), Food Staff (S6),

TABLE I
CENTRALITY MEASURES

ID	In-Degree (Physical or Social)	In-Degree (Socio-Physical)	Out-Degree (Physical or Social)	Out-Degree (Socio-Physical)	Closeness (Physical or Social)	Closeness (Socio-Physical)	Eigenvector (Physical or Social)	Eigenvector (Socio-Physical)
P1	0.41666667	0.29629629	0	0.11111111	0	0.30681818	0	0.00245891
P2	0.41666667	0.29629629	0	0.11111111	0	0.52941176	0	0.07822923
P3	0.41666667	0.29629629	0	0.18518518	0	0.52941176	0	0.06972893
P4	0.41666667	0.29629629	0	0.11111111	0	0.11111111	0	0
P5	0.41666667	0.33333333	0	0.51851851	0	0.675	0	0.20061883
P6	0.08333333	0.14814814	1	1	1	1	0.64793651	0.38907509
P7	0.25	0.22222222	0.66666667	0.85185185	0.66666667	0.87096774	9.20E-06	0.27408376
P8	0.41666667	0.29629629	0	0.11111111	0	0.31034482	0	0.00274665
P9	0.41666667	0.29629629	0	0.11111111	0	0.11111111	0	1.47E-09
P10	0.16666667	0.22222222	0.58333333	0.74074074	0.58333333	0.79411764	0	0.24201387
P11	0.16666667	0.18518518	0.16666667	0.07407407	0.54545454	0.51923076	0.400445444	0.0775947
P12	0.33333333	0.25925925	0.66666667	0.85185185	0.66666667	0.87096774	9.20E-06	0.27408376
P13	0.16666667	0.18518518	1	1	1	1	0.64793651	0.38907509
S1	0.5	0.51851851	0.14285714	0.07407407	0.48275862	0.39705882	0.09227595	0.02101492
S2	0.35714285	0.44444444	0	0.44444444	0	0.64285714	0	0.23398105
S3	0.42857142	0.48148148	0.14285714	0.07407407	0.48275862	0.39705882	0.11162084	0.02347383
S4	0.28571428	0.44444444	0.85714285	0.44444444	0.875	0.62790697	0.44015526	0.17714500
S5	0.28571428	0.37037037	0.07142857	0.07407407	0.07142857	0.08333333	0	9.78E-10
S6	0.28571428	0.33333333	1	0.55555555	1	0.69230769	0.44015552	0.20061883
S7	0.42857142	0.48148148	0.78571428	0.40740740	0.82352941	0.62790697	0.44015552	0.17960391
S8	0.35714285	0.44444444	0.21428571	0.11111111	0.36842105	0.3	0.04274550	0.00520556
S9	0.28571428	0.37037037	0	0	0	0	0	0
S10	0.35714285	0.44444444	0.07142857	0.51851851	0.51851851	0.675	0.09227569	0.27950586
S11	0.35714285	0.44444444	1	1	1	1	0.44015552	0.38907509
S12	0.21428571	0.51851851	0	0	0	0	0	0
S13	0.28571428	0.37037037	1	0.55555555	1	0.69230769	0.44015552	0.20495500
S14	0.35714285	0.44444444	0.07142857	0.03703703	0.07142857	0.03703703	0	0
S15	0.57142857	0.62962963	0	0	0	0	0	0

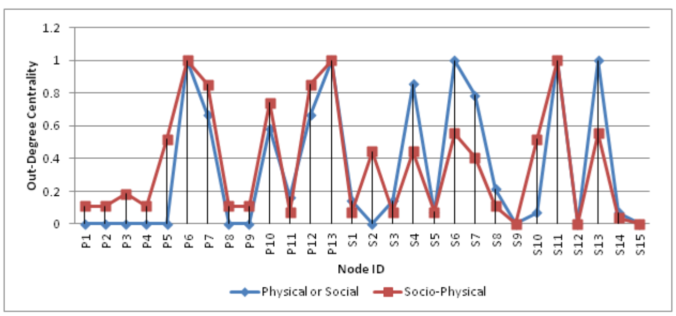

Fig. 6. Out-Degree Centrality Measure

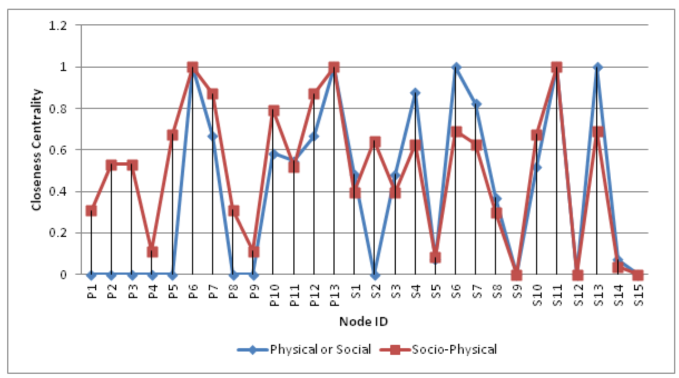

Fig. 7. Closeness Centrality Measure

Campus Police Staff (S11), and Technology Staff (S13) nodes, when considering the physical and social views separately; and Transportation (P6), Water and Sewage (P7), Heating (P12), Electricity (P13), and Campus Police Staff (S11) nodes, when adopting the socio-physical view.

Fig. 7 shows the closeness centrality results. While this measure equates criticality with the speed with which the current node is able to access all other nodes in the network, the five most critical nodes are also Transportation (P6), Electricity (P13), Food Staff (S6), Campus Police Staff (S11), and Technology Staff (S13), when considering the physical and social views separately; and Transportation (P6), Water and Sewage (P7), Heating (P12), Electricity (P13), and Campus Police (S11), when viewing the network from the socio-physical perspective.

Similarly, Fig. 8 indicates the eigenvector centrality results, which relate criticality to how well-positioned the current node is. According to this measure, the five most critical nodes (and ties) are Transportation (P6), Electricity (P13), Administrative Staff (S4), Food Staff (S6), Management Staff (S7), Campus Police Staff (S11), and Technology Staff (S13), when considering the physical and social views separately; and Transportation (P6), Water and Sewage (P7), Heating (P12), Electricity (P13), Fire Safety and Emergency Management Staff (S10), and Campus Police Staff (S11) in the socio-physical view.

Based on the results revealed by these centrality measures, it is evident that the holistic view offers a completely different perspective, shedding light on criticalities which would otherwise remain hidden allowing less relevant nodes to be considered critical instead. This is fundamental for the success and effectiveness of Emergency Management Organizations

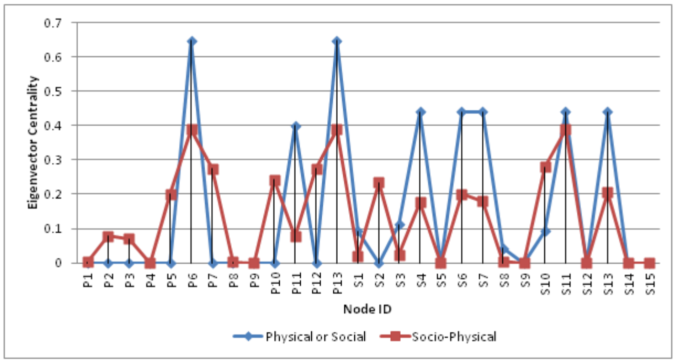

Fig. 8. Eigenvector Centrality Measure

(EMOs) especially in identifying hidden criticalities timely to avoid cascading effects of the kind that pervade the classic incidents (e.g., Katrina, Japan, and Thailand). It is worth noting that the three measures of node criticality—out-degree, closeness, and eigenvector—agree on the most critical nodes for the socio-physical view.

V. Application of the Holistic Governance Framework

This section describes the application of the proposed framework in the context of the considered SoS case study. It presents the case-specific framework (see Fig. 9) by answering the questions outlined in Section II, and also highlights the benefits of the proposed framework using the university case study for comparison (see Table II).

What needs to be influenced?
In this case, the university needs to be influenced as an SoS viewed through a socio-physical lens because it provides an integrated, systemic perspective of the university's operations in emergency response and preparedness. The proposed governance framework offers such a socio-physical view of the SoS of interest.

Why is there a need for change within the environment?
The university SoS's operations can be disrupted internally and/or externally, and it is imperative to bring the system back to its non-emergency state of operation. This can be done reactively after the incident occurs or proactively through stress-testing of the possible "what if" scenarios (i.e., internal and/or external factors) in relation to the non-emergency state of the SoS. Some of the potential external factors have been identified and depicted in Fig. 9, including external food supply, economic, environmental, and external water supply factors. In addition, how these factors impact the SoS is also significant. For example, the shutdown of the external water supply will disrupt the state of operation of the SoS, impacting both social and physical dimensions as well as the socio-physical interface. The proposed framework allows one to capture this dynamics and understand the nature of the change to a greater degree than the current practice.

How should the environment be influenced?
The SoS's governing body, called the Emergency Operations Control Group (EOCG), which is coordinated through the Emergency Operations Center (EOC), is responsible for proper

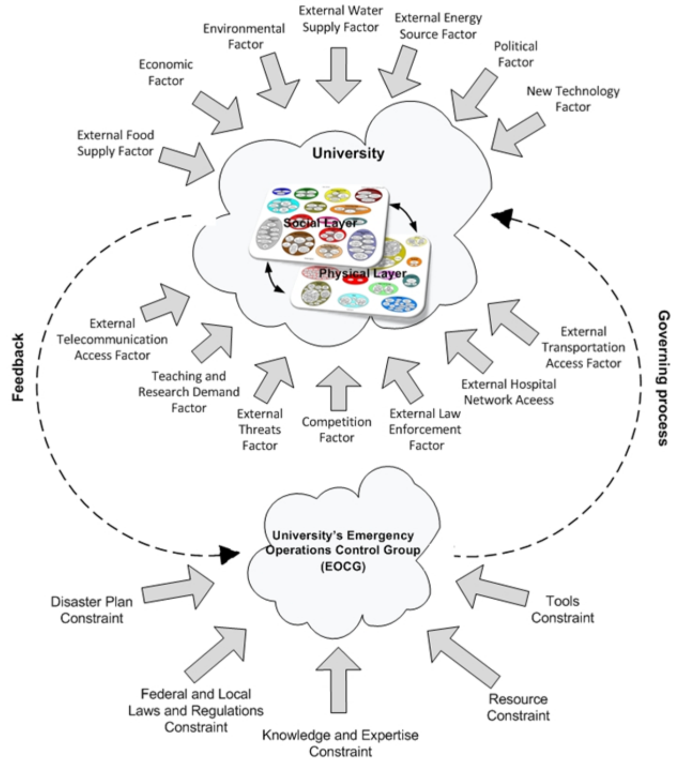

Fig. 9. University SoS Governance Framework

and timely information dissemination and emergency decision-making. The EOCG receives updates on the current state of the SoS's operations through a feedback process, which consists of a set of various sensors that are social, physical, and socio-physical. Subsequently, the EOCG makes governing decisions to address changes in the environment that are classified as emergency situations. The proposed framework captures this feedback process explicitly and identifies possible constraints that can affect the EOCG's decision-making. Some of these constraints include the limitations imposed by a defined disaster plan, federal and local laws and regulations, knowledge about best practices, and the available resource tools at their disposal to prepare for and respond to a particular emergency situation.

When should the process of influencing be stopped?
The EOCG receives feedback through the strategically positioned sensors from the SoS. Once there is an indication that the emergency situation has been resolved and the SoS returned to its non-emergency state of operations, the EOCG should stop the reactive process of influencing in response to the emergency. However, it should continue the proactive modelling and monitoring of the SoS to increase the SoS's resiliency in the face of future incidents.

VI. Conclusion

This paper proposes a novel socio-physical governance framework for emergency response and preparedness. To show the merits of this framework, a real-world case study involving the failure of a university steam plant and the subsequent potential evacuation of the university hospital was examined.

TABLE II
BENEFITS OF FRAMEWORK USING CASE STUDY FOR COMPARISON

Criterion	Example from case study	Benefit of using framework
Capture the SoS of interest	Some of the interdependencies were known a priori. However, the socio-physical interconnections were not explicitly considered. For example, the notification about the impact of steam on the hospital was not immediately understood.	The framework provides a more expanded view of the interdependencies, which is possible due to explicitly capturing them within and across different layers (i.e., physical, social, and socio-physical).
Identify critical nodes	During the incident, the criticality of nodes was assessed based solely on the nodes' impact on the SoS. It was not based on any formal network analysis, where all of the links associated with the node are considered in the assessment of criticality. This could result in the improper allocation of resources to the most obvious node, in a "squeaky wheel gets the grease" type of fashion, rather than based on an objective and comprehensive evaluation.	The framework asserts that the criticality of nodes is view-specific. The combined socio-physical view reveals criticalities otherwise hidden to the unidimensional views and offers a much broader perspective taking into account the true interdependencies within the SoS, as both social and physical layers and their interface are considered.
Model for proactive preparedness	The governing body had no model of the SoS. Instead, during the incident, it was limited by the feedback information it received from the actual SoS in response to its actions.	The framework provides a blueprint for proactive preparedness modelling. It allows for greater understanding of the dynamics present within the SoS of interest, including the effects of external factors, which can help in the assessment of the SoS's resiliency. It can also help in determining where sensors ought to be made explicit to reveal "blindspot criticalities." It can further serve as a platform for modelling what-if scenarios, stress-testing, and extracting best practices. During an emergency, it can also be used to test various responses in real-time through simulations, thus, allowing the governing body to choose from a broader range of possible actions.
Respond more efficiently	The feedback mechanism, including sensors, was not explicitly identified. Moreover, critical feedback was delayed, as the governing body was not immediately aware of the full extent of the emergency.	The framework allows for a more rapid assessment of the situation through an explicit feedback mechanism that captures the socio-physical dynamics. It also facilitates effective and efficient resource allocation by identifying the most critical nodes in an emergency and distributing the resources accordingly.
Understand constraints impacting governing body	No constraints were explicitly considered during the emergency, though some may have been identified in after-action reports.	The framework allows for explicit identification and inclusion of possible constraints affecting the governing body's decision-making process. This is critical for understanding the various ways in which the problem situation can be addressed.

Assessing the SoS of interest from multiple views—physical, social, and socio-physical—provides the governing body with essential information during an emergency, including the identification of the most critical nodes using network centrality measures. In addition to response-time activity, this framework can also be used offline to model the effect of various factors on the SoS of interest which can help in the development of best practices through the investigation of what-if scenarios.

The proposed socio-physical governance framework helps:

- Reveal criticalities which are hidden to the unidimensional views—a major cause of the classic cascading effects pervasive in the EMO history
- Assess more accurately the problem situation; capture SoS dynamics (including nonlinear effects) during emergency
- Assess more accurately a node's degree of connectivity; identify critical nodes (hubs) and ensure their protection; isolate affected hubs during an emergency such as in prevention of a spread of an infectious disease
- Stress-test or model the effects of external factors on an SoS of interest to explore how complex emergency situations can arise; assess the level of the SoS's resiliency and readiness to respond
- Point to where to strategically position appropriate sensors as part of the feedback mechanism for a more efficient and effective response
- Point to where to strategically allocate resources for response and preparedness
- Understand in more depth the governing body's constraints in coping with an emergency situation

In order to substantiate the application of the proposed framework, the authors plan to survey subject matter experts in the field of emergency response, and in particular related to the case study presented, on the effectiveness of the governing model in practice. Furthermore, the case study presented in this paper will be modelled using all three views, and evaluated by subject matter experts. With key nodes and interrelationships captured, the SoS of interest can then be "stress tested" to determine how well it behaves under specific configurations of initial conditions and external factors. Lastly, because this framework is general and can be applied to any incident, a general simulation API is also being developed.

REFERENCES

[1] W. Ross, A. Morris, A. Cunha, and M. Ulieru, "Discovering best practices in emergency response with combined physical and organizational

simulation," in *Electrical and Computer Engineering (CCECE), 2011 24th Canadian Conference on*, may 2011, pp. 001 499 –001 502.

[2] A. Gorod, B. Sauser, and J. Boardman, "System-of-systems engineering management: A review of modern history and a path forward," *Systems Journal, IEEE*, vol. 2, no. 4, pp. 484 –499, dec. 2008.

[3] A. Shenhar, "A new systems engineering taxonomy," *4th International Symposium National Council Systems Engineering*, pp. 261 –276, 1994.

[4] Irish Department of Health, "A framework for major emergency management: a guide to preparing a major emergency plan," 2006.

[5] University of North Dakota, "Emergency management framework," 2011.

[6] U. S. DHS, "National response framework," 2008.

[7] D. McLoughlin, "A framework for integrated emergency management," *Public Administration Review*, vol. 45, pp. 165 –172, 1985.

[8] A. Gorod, M. DiMario, B. Sauser, and J. Boardman, "'Satisficing' system of systems (SoS) using dynamic and static doctrines," *International Journal of System of Systems Engineering*, vol. 1, pp. 347 –366, 2009.

[9] M. Mansouri, A. Gorod, T. H. Wakeman, and B. Sauser, "Maritime transportation system of systems management framework: a system of systems engineering approach," *International Journal of Ocean Systems Management*, vol. 1, pp. 200 –226, 2009.

[10] H. C. J. Lynn, L. E. and C. J. Hill, *Improving Governance: A New Logic for Empirical Research*. Washington, D.C.: Georgetown University Press, 1997.

[11] M. B. Takeda and M. M. Helms, ""Bureaucracy, meet catastrophe": Analysis of the tsunami disaster relief efforts and their implications for global emergency governance," *International Journal of Public Sector Management*, vol. 19, pp. 204 –217, 2006.

[12] A. Gorod, "System of systems engineering management framework: a 'satisficing' network approach," Ph.D. dissertation, Stevens Institute of Technology, Hoboken, NJ, 2009.

[13] J. A. Zachman, *The Zachman Framework for Enterprise Architecture: A Primer for Enterprise Engineering and Manufacturing*. www.zachmaninternational.com, 2003.

[14] Government of Canada, "An emergency management framework for canada: second edition," 2001.

[15] G. Barbarosoglu and Y. Arda, "A two-stage stochastic programming framework for transportation planning in disaster response," *The Journal of the Operational Research Society*, vol. 55, no. 1, pp. 43 –53, 2004. [Online]. Available: http://www.jstor.org/stable/4101826

[16] D. Dudenhoeffer, M. Permann, and M. Manic, "Cims: A framework for infrastructure interdependency modeling and analysis," in *Simulation Conference, 2006. WSC 06. Proceedings of the Winter*, dec. 2006, pp. 478 –485.

[17] A. Abruzzi, "Problems of inference in the socio-physical sciences," *The Journal of Philosophy*, vol. 51, no. 19, pp. pp. 537–549, 1954. [Online]. Available: http://www.jstor.org/stable/2021457

[18] N. R. Britton, "A new emergency management for the new millennium?" in *Second International Conference on Cities on Volcanoes*, feb. 2001.

[19] D. Mendoca, G. E. G. Beroggi, and W. A. Wallace, "Decision support for improvisation during emergency response operations," *International Journal on Emergency Management*, vol. 1, pp. 30 –38, 2001.

[20] L. K. Comfort, K. Ko, and A. Zagorecki, "Coordination in rapidly evolving disaster response systems," *American Behavioral Scientist*, vol. 48, no. 3, pp. 295 –313, 2004.

[21] M. Abrahamsson, H. Hassel, and H. Tehler, "Towards a system-oriented framework for analysing and evaluating emergency response," *Journal of Contingencies and Crisis Management*, vol. 18, no. 1, pp. 14 –25, 2010.

[22] X. Pan, "Computational modeling of human and social behaviors for emergency egress analysis," Ph.D. dissertation, Stanford University, 2006.

[23] S. Dwarkanath and M. Daconta, "Emergency services enterprise framework: A service-oriented approach," in *Proceedings of the 3 International ISCRAM Conference (B. Van de Walle and M. Turoff, eds.), Newark, NJ (USA)*, 2006.

[24] E. Lawler, A. Hedge, and S. Pavlovic-Veselinovic, "Cognitive ergonomics, socio-technical systems, and the impact of healthcare information technologies," *International Journal of Industrial Ergonomics*, vol. 41, pp. 336 –344, 2011.

[25] J. Rasmussen, P. Nixon, and F. Warner, "Human error and the problem of causality in analysis of accidents [and discussion]," *Philosophical Transactions of the Royal Society of London. B, Biological Sciences*, vol. 327, no. 1241, pp. 449 –462, 1990.

[26] J. Boardman and B. Sauser, *Systems thinking: Coping with 21st century problems*. CRC, 2008, vol. 4.

[27] J. Moteff and P. Parfomak, "Critical infrastructure and key assets: definition and identification. washington: Congressional research service," in *Library of Congress*, 2004.

[28] Dictionary, "Social capital," 2011.

[29] M. Maier, "Architecting principles for systems-of-systems," *Systems Engineering*, vol. 1, no. 4, pp. 267 –284, 1998.

[30] J. Lane and R. Valerdi, "Synthesizing sos concepts for use in cost estimation," *Systems, Man and Cybernetics*, vol. 1, pp. 993 –998, 2005.

[31] D. DeLaurentis, "Understanding transportation as system-of-systems design problem," in *43rd AIAA Aerospace Sciences Meeting and Exhibit*, 2005, p. 2005.

[32] A. Gorod and B. Sauser, "An application of prims algorithm in defining a sos operational boundary," in *5th Conference on Systems Engineering Research*, 2007.

[33] L. Freeman, "Centrality in social networks conceptual clarification," *Social networks*, vol. 1, no. 3, pp. 215 –239, 1979.

[34] R. Hanneman and M. Riddle, "Introduction to social network methods," 2005.

[35] S. Borgatti, "Centrality and network flow," *Social Networks*, vol. 27, no. 1, pp. 55 –71, 2005.

[36] J. Harris and B. Clements, "Using social network analysis to understand missouri's system of public health emergency planners," *Public Health Reports*, vol. 122, no. 4, pp. 488 –498, 2007.

[37] Board on Earth Sciences and Resources, "Social network analysis to improved disaster preparedness and intervention planning," in *Application of Social Network Analysis for Building Community Disaster Resilience: Workshop Summary*, 2009.

[38] S. Choi and R. Brower, "When practice matters more than government plans," *Administration & Society*, vol. 37, no. 6, pp. 651 –678, 2006.

[39] N. Kapucu, F. Yuldashev, and M. Feldheim, "Nonprofit organizations in disaster response and management: A network analysis," *European Journal of Economic and Political Studies*, vol. 4, pp. 83 –112, 2011.

William Ross received his BCS (2005) and MCS (2007) from the University of New Brunswick. Prior to returning to graduate studies, he worked in the e-learning industry as a software developer and instructor. Currently, he is a Ph.D. student under the supervision of Dr. Mihaela Ulieru. His research focuses on investigating and modelling interdependencies and emergence for the development of agile organizational practices.

Alex Gorod received his BS in Information Systems, MS in Telecommunications from Pace University and PhD in Engineering Management from Stevens Institute of Technology. Prior to his graduate studies, he held a research analyst position at Salomon Smith Barney. He is a former Robert Crooks Stanley doctoral fellow in Engineering Management at Stevens Institute of Technology, with research interests in the area of management of complex systems. He is a member of SystemicNet, LLC in New York and a visiting fellow at the University of Adelaide in Australia.

Mihaela Ulieru (S93M95SM02) received the Ph.D. degree in diagnostics and controls of dynamical systems from the Darmstadt University of Technology, Darmstadt, Germany, in 1995. She was a Postdoctoral Fellow in the Intelligent Robotics and Manufacturing Group led by Prof. William Gruver at Simon Fraser University, Burnaby, BC, Canada, from 1996 to 1998. She was a Member of the faculty with Brunel University, Uxbridge, U.K., and with the University of Calgary, Calgary, AB, Canada, where she held the Junior Nortel Chair in Intelligent Manufacturing and founded the Emergent Information Systems Laboratory. She has been holding the Canada Research Chair in Adaptive Information Infrastructures for the e-Society since 2005 when she also established (with the Canada Foundation for Innovation funding) and leads the Adaptive RiskManagement Laboratory (ARM Lab), researching complex networks as control paradigm for complex systems to develop evolvable architectures for resilient e-networked applications and holistic security ecosystems. In 2007, she was appointed to the Science, Technology and Innovation Council of Canada by the Minister of Industry to advise the government and provide foresight on innovation issues related to the information communication technology (ICT) impact on Canadas economic development and social well-being against international standards of excellence. She has held and holds appointments on several international science and technology advisory boards and review panels, among which are the Science and Engineering Research Council of Singapore, the Scientific Council of the EU Proactive Initiative on Pervasive Adaptation (PERADA), the EU Network of Excellence in Intelligent Manufacturing (IPROMS), and the Natural Science and Engineering Research Council of Canadas Advisory Panel on International Strategy, and as an expert on its ICT and security review panels, as well as the U.S. National Science Foundation Cyber-Systems and several EU FP7 expert panels. To capitalize on her achievements and expertise in distributed intelligent systems by making ICTs an integrated component of policy making targeting a safe, sustainable, and innovation-driven world, she recently founded the Innovation Management and Policy Accelerated by Communication Technologies (IMPACT) Institute for the Digital Economy, for which she currently acts as President. Dr. Ulieru, as a member of the Administrative Committee of the IEEE Industrial Electronics Society (IES), founded the international industrial informatics research community and its two major forums: the IEEE Industrial Informatics Conferences and the IEEE-IES Industrial Agents Technical Committee. She also founded the IT Revolutions Forum and was the General Chair of its first conference held in Venice, Italy, in December 2008.