Risk Analysis in Disaster Planning by Superposition of Infrastructure and Societal Networks

James H. Lambert[1] and Priya Sarda[2]

Abstract

This paper addresses disaster planning for infrastructures and their related societal entities through innovative modeling that coordinates multiple networks against the contingency scenarios that disrupt plans for mitigation, preparedness, response, and recovery. Across disciplines, interdependent infrastructures and related societal entities are increasingly amenable to characterization as mathematical networks. Effective disaster planning for complex systems is known to rely on the identification and management of a multitude of diverse contingency scenarios. Modeling of such contingencies in disaster planning for interdependent infrastructures and societal entities can proceed with a superposition of multiple network models. We study the interactions among contingency scenarios and diverse superposed networks. The developed theory and methodology will guide the multidisciplinary selection and management of relevant worst-case scenarios, an essential activity for disaster planning in large-scale, complex systems.

Introduction

Planning for large-scale disasters such as hurricanes, floods, earthquakes, and terrorism involves phenomena across interdependent transportation, telecommunications, water, power, and related societal entities such as religious and ethnic groups, health care, human services, and tourism. Amin [2002] identifies critical infrastructure systems as cable and wireless telecommunications; banking and finance; land, water, and air transportation; gas, water, and oil pipelines; electric

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[1]Research Assistant Professor and Associate Director, Center for Risk Management of Engineering Systems (CRMES) and Department of Systems and Information Engineering (SIE), University of Virginia, Charlottesville, VA 22903; 434-982-2072; lambert@virginia.edu

[2]Graduate student, CRMES-SIE, University of Virginia, Charlottesville, VA 22903; 434-982-2072; ps2y@virginia.edu.

power grids; and the internet, which can be international, national, state, and local in scope. Haimes and Jiang [2001] describe a need to assess the vulnerabilities of complex interdependent infrastructures. Hecker et al. [2000], Ezell and Farr [2000], and Heaney et al. [2000] further address the risk of disasters to infrastructures. Juhl [1993] describes efforts of FEMA to increase the efficiency of pre- and post-disaster plans by GIS database applications. Ardekani [1992] evaluates the response following the 1989 Loma Prieta earthquake and provides recommendations for the preparedness of transportation agencies in the future. Kovel [2000] addresses modeling of disaster response. Mondul [1997] describes information-sharing among agencies relying on the transportation system in the preparation and recovery processes. Parentela et al. [2000] describe a variety of disaster-planning factors, including the environment, the capabilities of emergency response providers, and the economy. Disaster planning is further addressed by practitioners including ASIS International [2003], ASIS [2003], Myers [1999], Erickson [1999], and Gigliotti and Jason [1991]. Haimes et al. [2002], Lambert et al. [2001], and Haimes [1998] perform risk identification for system hierarchies, using hierarchical holographic modeling [Haimes 1981; Hall 1989] to effect a superposition of hierarchical systems. Sharit [2000] uses hierarchies of factors for risk identification. Lambert and Patterson [2002] develop risk identification for delay scenarios in the hurricane recovery of a transportation agency. Kaplan and Garrick [1981] provide a framework for risk analysis. Wei [1991] describes failure mode, effects, and criticality analysis in risk analysis. Watts [2003], Barabási [2002], and Arquilla and Ronfeldt [2001] address the impetus to model various infrastructure and societal systems as networks and, for an example, Marburger and Westfechtel [2002] study telecommunications networks. Buckley and Lewinter [2002] and Xu [2001] describe advances in the foundations of graph theory.

We recognize an opportunity to better understand disaster planning that surrounds infrastructures and societal entities. Toward such ends, mathematical networks are suited to the study of advanced relationships among contingency scenarios in these areas. Specifically, we develop an approach to improve multidisciplinary disaster planning through the integration of risk identification with multiple network analyses. Interdependent networks of both critical infrastructures and the related societal entities are addressed.

The organization of this paper is as follows. The methodology section describes the relationship of contingency scenarios to interdependent networks. The example section describes an application of the methodology to contingencies involving three networks. Finally, the conclusions describe the context for application of the methodology in the refinement of disaster planning, including preparedness and mitigation, response, and recovery.

Methodology

Following Lambert and Sarda [2003] and Sarda [2003], the following describes infrastructure systems and related societal organizations as networks for correspondence to a set of contingency scenarios that can be disruptive to disaster plans.

Let $G = \{ G_i \}_i$

denote the set of infrastructure and related societal networks. The networks are indexed by the set i = A to Z, AA to ZZ, etc. The i^{th} network is described by

$G_i = (N_i, A_i)$, where

i ε {A,B,.....,Z, AA....ZZ....etc.}

For example, Network "A" can represent an oil pipeline system, Network "C" can represent a cultural, political, or religious network, Network "M" can represent a telecommunication network, etc. Furthermore, let N denote the set of all nodes in the superposition of the multiple networks as follows:

$N = \{ N_i \}_i$

where N_i is the set of nodes of the i^{th} network.

$N_i = \{ N_i^k \}_k$

where k ε positive integers indexing the nodes of a Network "i." Similarly, let A denote the set of all arcs. Each individual arc, $A_i^{l,m} = (N_i^l , N_i^m)$, is an ordered pair of two nodes as shown. The order indicates the direction of the arc in the network diagram.

$A = \{ A_i \}_i$ where $A_i = \{ (N_i^l , N_i^m) \}_{l,m}$

where l,m ε positive integers indexing the nodes of Network "i."

Let U denote the set of contingency scenarios that are developed for disaster-planning trouble-shooting:.

$U = \{S_1 \ldots\ldots\ldots\ldots S_j\}$, where

j ε positive integers and j ε {1,.........,J}.

Let S_0 denote the as-planned scenario involving disaster mitigation, preparedness, response, and/or recovery activities. A sample of contingency scenarios can be compiled by using historical data, brainstorming with cultural and religion experts, and conducting interviews with experts on the infrastructure and societal networks. A database of such activity is comprised minimally of the following data fields: description of the scenario, direct interactions (arcs and nodes) identified for each scenario, and indirect interactions (arcs and nodes). In turn, these are described as follows: an interaction arises when either singular or a combination (higher order) of network components is related to a contingency scenario.

Define a family of operators Θ_d to obtain network interactions that are directly involved in a contingency scenario. The operation that returns the arcs and nodes that are in direct interaction with contingency scenario "j" is

$\Theta_d(S_j)$.

The output will be in the form of nodes and arcs from across the superposition of networks G. To obtain only arc interactions directly involved in contingency scenario "j", the operation is modified to

$\Theta_{dA}(S_j)$.

For example, arc interactions that are directly involved with the scenario S_{0006}, disruption of information systems, are given by the operation

$\Theta_{dA}(S_{0006})$

which returns the arcs (C02,C05),(F05,F17) corresponding to a telecommunications link between two servers and the corridors of an office building. Similarly, to obtain only node interactions directly involved in contingency scenario "j", the operation is modified to

$\Theta_{dN}(S_j)$.

For example, node interactions that are directly involved with the scenario S_{0630}, contamination of a drinking water supply, are given by the operation

$\Theta_{dN}(S_{0630})$

which returns the nodes K02,K03,W08 corresponding to an elevated water tank, a water-pipe junction, and an e-business entity used for the purchase/logistics of chemicals.

Direct interactions are *prima facie* relationships of network components and contingency scenarios. Advanced relationships can be identified to describe rippling influences among network components. The study of advanced relationships can lead to understanding the subtle interconnectivity and interdependency across superpositioned networks. Thus, let q index the several definitions of rippling effects that propagate across nodes and arcs of the networks (to be explored in the research tasks).

Let Θ_q be an operator used to obtain the network components indirectly associated with a contingency scenario, and a particular relationship "q" is given by the operation

$$\Theta_q(\Theta_d(S_j)).$$

The operation has the set of direct node and arc interactions of a particular contingency scenario as its input, resulting in an output of nodes and arcs indirectly associated with the contingency scenario. For example, the node interactions that are indirectly associated with contingency scenario S_{0202}, an event that occurs on a cultural or religious holiday, is given by the operation

$$\Theta_q(\Theta_{dN}(S_{0202}))$$

which returns nodes for a particular rippling effect "q." This includes H01, J06 components which are objects of the rippling effects of the contingency scenario S_{0202}, and not direct interactions that are members of the set $\Theta_{dN}(S_{0202})$.

An interaction of a contingency scenario with networks can be singular or in pairs, triples, etc. A singular interaction is just a node or an arc. A paired interaction is a combination of components such as arc-arc, node-node, and arc-node. The higher-order interactions are studied to investigate interdependencies among the networks associated with a contingency scenario or collection of scenarios. The pairs of arcs interacting with a contingency scenario "j" is given by

$$\{(A_i^{l,m}, A_k^{l',m'}) : A_i^{l,m}, A_k^{l',m'} \ \varepsilon[\Theta_q(\Theta_d(S_j)) \cup \Theta_d(S_j)]$$

where l, m, l', m' are integers and when i = k, where (l,m) is not equal to (l',m').

That is, individual arcs $A_i^{l,m}$ and $A_k^{l',m'}$ are a subset of the direct and indirect components related to the j^{th} scenario. For example, node pairs that are interacting with a contingency scenario TS_{0685}, shutdown of a nuclear reactor, is given by the operation

$$\{(N_i^l, N_k^s) : N_i^l, N_k^s \ \varepsilon \ [\Theta_q(\Theta_d(S_{0685})) \cup \Theta_d(S_{0685})] \}.$$

The node pair interactions are (V04,V12),(L56,L15), corresponding to a section of highway abutting the nuclear facility and a source of cooling water for the reactor.

Now define a family of operations to count the various nature of interactions. The cardinality, defined as η ( ), is a measure of number of interactions. For example η (N_B) is the number of node interactions in Network "B", a railway system. Similarly η (A_G) will count the number of arcs in Network "G", a distribution network of cereal grains. The cardinality of paired arc indirect interactions of contingency scenario S_{0890}, the release of panic-inducing information to the public, is given by the operation

$$\eta \{(A_i^{l,m}, A_k^{l',m'}) : A_i^{l,m}, A_k^{l',m'} \ \varepsilon \ [\Theta_q(\Theta_d(S_{0890})) \cup \Theta_d(S_{0890})] \}.$$

The cardinality of a particular interaction set being high indicates a need for further examination of the highlighted relationship between the superpositioned networks G and the contingency scenarios U.

Example

Consider a contingency scenario TS_{0005}, the unavailability of an oil pipeline section. The scenario can be related to the network representations of the following interdependent network systems: oil pipeline system, railway system, and societal organization. The modeled networks describe the physical characteristics of the infrastructure system by nodes and arcs. The nodes in Network "A" are pipeline junctions and the arcs connecting the nodes represent the pipeline sections. Similarly, in Network "B" the nodes are the railway intersections or station and the arcs are the connecting tracks. Similarly, in Network "C" the nodes represent the entities of the societal organization and the arcs are the information and physical distribution channels. The node label consists of the indexing alphabet of the particular network followed by the numeral representing the node position in the network. The notations as applied to the node labels are of the form "A3", depicting the junction at Santa Clara in the network representation of oil pipeline network "A". The arc labels are of the form (A4,A5), describing the oil pipeline section between junctions: San Jose (A4) and Evergreen (A5). The node interactions directly involved in the scenario S_{0005} are A4, A3, B6, B5, and C6. The node representations are the junctions of the affected pipeline sections: A4, San Jose; A3, Santa Clara; B6, the railway station at San Francisco; B5, the railway station at San Jose; and C6, an entity of the societal organization. The indirect interactions are defined by their relationships with the direct components and can span across multiple networks. The interactions that are indirectly associated with the contingency scenario S_{0005} are the nodes A1 and C5 and arc (B6,B7). A1 is the junction at Alviso, C5 is the organizational entity at Berlin, and the arc (B6,B7) is a track connecting the nodes B6, San Francisco, and B7, Matlock.

The cardinality of direct interactions involved with individual contingency scenarios is as follows: The contingency scenario S_{0390}, contamination in the food supply, has 48 direct node interactions and 60 direct arc interactions. The contingency scenario S_{0571}, loss of capability for water treatment, has only two direct node interactions and four direct arc interactions, indicating a close-knit societal organization operation in comparison with the magnitude of the scenario S_{0390}. The ripples of the contingency scenarios can span multiple infrastructure systems, supporting the claim that disjoint infrastructure systems are interdependent with respect to the execution of a disaster plan.

The infrastructure systems can be related to multiple scenarios to identify the system interfaces most in need of attention in disaster planning. Such relevant information, extracted from contingency scenario lists, consists of the infrastructure system and the different scenarios with which it has been involved. For example, the Network "E" electric power system has appeared in two scenarios, S_{0005} and S_{0010}.

The infrastructure network appearing most frequently on the scenario list should be of greater interest in disaster planning. For example, Network "O", the internet, is the most prominent infrastructure system across different contingency scenarios, suggesting a well-developed knowledge base of internet technology in the societal organization. Such analysis will alert agencies and officials to take further steps which might well involve reconfiguration of a disaster plan.

Frequency diagrams, which depict the cardinality of interactions of a contingency scenario, can be developed in the next step of the analysis by identifying the most prevalent interactions. These will be used in reconfiguring disaster planning against any threat. For example, we can consider the direct interactions across all contingency scenarios. The dominating component is the arc (C2,C5) which has approximately 340 interactions. The arc (C2,C5) represents the flow of information between the organizational cells C2, Boston, and C5, Berlin, indicating the most active component of the societal organization "C". The information compilation about principal interactions involved in a scenario is a useful precursor to risk modeling. Pair interactions are a result of interactions between the components of networks related to a contingency scenario. The different interactions are arc-node, node-node, and arc-arc interactions. An arc-node interaction, a variant in the pair interactions, is the node C6 related to the arc (B4,B5). This can be interpreted as the use of a section of the railway system "B" by a member of the organizational cell C6 in the scenario S_{0390}.

We can consider as well the greatest number of direct pair interactions. The paired components typically have fewer interactions than the dominant singular components. Few interactions in a paired interaction diagram mean that there is very little interdependency between the infrastructure networks in the context of a set of contingency scenarios. In an iteration of the analysis, the cardinality of the indirect interactions are calculated across the set of contingency scenarios.

Next, consider the cardinality of the indirect interactions across different contingency scenarios. Indirect relationships broaden and enhance the scope of investigation by studying the less-apparent interactions between network components. For example, node Z6 was not of particular significance in the direct interaction study. But the node Z6, a fundraising center in Network "Z", has approximately 150 interactions and is the most prominent indirect interaction. Arcs and nodes indirectly associated with involved arcs and nodes can help to identify the significant paths of warning or rescue operations. By securing the involved and indirectly associated arcs and nodes, risk of an attack could be mitigated.

Now consider the most prevalent paired interactions of indirect (rippling effects) components across all scenarios. A plot of interaction frequency can indicate a relationship between the pair of interactions and must be further investigated to explain that relationship. For example, the paired arc (C1,C4),(Z5,Z6) has approximately 30 interactions. The arc (C1,C4) represents the flow of information between the Atlanta and Denver cells of the societal organization. The arc (Z5,Z6) represents a financial network transaction between the United States and Africa. Such analysis proceeds iteratively in refining the disaster-planning scenario S_0, network models G, and the contingency scenarios U.

Conclusion

The implementation and context of our approach for characterizing contingency scenarios in multidisciplinary disaster planning are as follows: an initial set of contingency scenarios affecting disaster planning for infrastructure and societal networks is identified by planners and risk managers. Direct interactions of the scenarios and network components are identified across the superposition of networks. Indirect interactions of scenarios and network components are generated through study of the rippling of scenarios across network components. Rippling is characterized by proximity, reliability-cut-set methods, and shortest-path algorithms. Higher-order interactions are identified when multiple network components are associated, directly or indirectly, with the same contingency scenario. The relationships of the scenarios to the networks are thus studied by the combination of the several modes: (i) direct and indirect interactions, and (ii) singular and higher-order interactions. Frequency analyses of the interactions among scenarios and the networks will be useful to characterize the rippling effects of the scenarios across the superposition of networks. The approach supports iterative refinement of disaster-response plans based on the relevant contingency scenarios. The paper addresses a fundamental research direction at the multidisciplinary intersection of risk analysis and network systems analysis to provide understanding of and ultimately improve disaster planning for complex systems. Future work should address the implications of the analysis approach effort for operational-support databases in disaster planning.

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