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VULNERABILITY ASSESSMENT OF CIVIL INFRASTRUCTURE SYSTEMS: A NETWORK APPROACH

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ABSTRACT: Considerable work has been carried out in recent years on vulnerability assessment of Critical Infrastructure Systems (CIS). Recent man-introduced hazard, including the 9/11 terrorist attack on the World Trade Center (WTC) in New York highlighted critical need to assess and evaluate the vulnerably of CIS with a focus on providing well coordinated and integrated strategies for public safety and property protection. One can generally group likely attacks, based on their source, into three categories: (1) physical attack, such as that of 9/11 that resulted in the collapse of the WTC, (2) biological, chemical and radiological attacks, and (3) cyber attacks. Most of the recent developments focused primarily on individual infrastructure assets, such as nuclear power plants, bridges, etc. This paper, however, addresses the interdependencies among those critical and vulnerable CIS vis-à-vis the cascading effects that may result as a consequence of natural or man-made disasters in one or more of the CIS network. The paper describes a framework that accounts for and assists in: (1) Identifying of critical components in interdependent urban CIS based on reliability assessment; (2) Modeling the cascading effects of a disaster in an urban CIS; and (3) Developing a decision support system (DSS) for prioritizing disaster mitigation and response strategies. In this framework a CIS network consists of a set of critical nodes, each representing a CIS. The nodes are connected with a set of links, each representing the logical relationship and strength that describe the impact of damage or malfunction associated with the preceding node on that of the succeeding node; capturing the cascading effect through the network being examined. The paper also highlights necessary methods and decision support tools required to perform the individual tasks as well as the implementation environment of the proposed methodology.

1. INTRODUCTION

Cities are complex and dynamic system of systems in which interconnected cyber, physical, social, and organizational components interact in a dynamic nonlinear, probabilistic, and spatially distributed fashion (Haimes and Horowits, 2004; Bruzelius et al., 2002). Planning for resilience in the face of urban disasters requires designing cities that combine seemingly opposite characteristics, including redundancy and efficiency, diversity and interdependence, autonomy and collaboration, and planning and adaptability (Godschalk, 2003). Critical infrastructure Systems (CIS) refer to the physical and information networks, utilities, and services which, if disrupted or destroyed, would have a serious impact on the safety, security or economic well-being of Canadians and/or the effective functioning of governments.

The following two examples will be used to demonstrate problems related to the interdependency of CIS. The ice storm in January 1998 in Quebec caused a huge power failure, disruption of water supply and sanitation systems, and traffic chaos. Without power and water, fighting fire was not an option. The emergency response agencies decided in principle that in the case of a fire, the fire department will raze the entire block to prevent the fire from spreading. Another example of the interdependency of the physical and cyber CIS is the Internet. The growth of the Internet, the increasing number of “mission critical” business functions that rely on communication networks and the emergence of general societal dependencies on communications, all make the survivability of the physical network that our information society depends on essential and of paramount importance. Despite considerable efforts at physical protection of cables, statistics show that metropolitan networks annually experience 13 cuts for every 1000 miles of fiber, and long haul networks experience 3 cuts for 1000 miles fiber. Therefore, we are now almost as dependent on the availability of communications networks as on other basic infrastructure like roads, water, sewer and power.

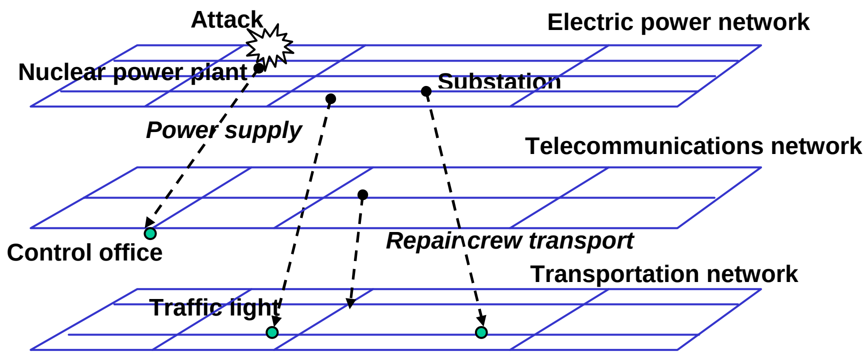

Figure 1. Interdependent Urban CIS

In addition to natural disasters, recent man-made physical attacks, such as the September 11 terrorist’s attack in the US, and cyber attacks, such as Blaster and SoBig computer worms, highlight the unpredictability of the risks facing our CIS and the need for continuous vigilance in preparing for these events. A typical example of a catastrophic man-made disaster is a terrorist attack on a nuclear power plant (NPP) (Nuclear Energy Institute, 2002; Paul et al., 2004). Such an attack would result not only in a high death toll but also would create a series of far reaching cascading effects of damages in multiple other CIS including electric power, transportation, and communication networks (Figure 1). Hence, considerable work is needed to assess the vulnerability of NPP to the likelihood of physical attacks and their cascading effects.

Urban CIS includes transportation, energy, utilities, and communications infrastructure systems. Each of these systems is a complex and challenging system in its own right, but the various interdependencies amongst these CIS complicate things even further. Interdependencies leave CIS vulnerable to collapses or events that may cause hard-to-predict cascading effects that can magnify the impacts of failures and their consequences on society. Therefore, appropriate methodologies are needed to assist decision makers to prioritize and invest scarce resources and to implement rational strategies for the protection of various CIS based on objective and dynamic modeling, simulation, and analysis.

Researchers in different domains have been studying the reliability and vulnerability of infrastructure systems within their specialized domains. Examples of this research include (Akgül and Frangopol, 2003) in the area of bridge engineering, (Bell, 2000, Kiremidjian et al., 2001) in the area of road networks, (Bryan et al., 2004) in the area of water pipelines, and (Assi et al., 2004) in the area of telecommunications network survivability. In addition, recent research papers discussed topics related to the reliability assessment of some of the above systems at a higher level of integration, such as the reliability assessment of a number of bridges belonging to the same road network (Akgül and Frangopol, 2003). However, very little work has been done on the relationship between different infrastructure systems taking into account the interdependency between these systems.

Gilbert et al. (2003) identified a list of major vulnerabilities for cities and the immediate local responses. They argue that planned simultaneous attacks on selected critical components of an infrastructure system (e.g., an electric power grid) could result in a wide spread collapses, with domino-like cascading effects. Examples of vulnerability assessment tools include the Community Vulnerability Assessment Tool (CVAT) (Flax et al., 2002), The risk filtering, ranking, and management method (Haimes et al., 2002), the Natural Hazard Loss Estimation Methodology and a software program, and input-output analysis studies to measure and evaluate the economic impacts of disasters (e.g., Okuyama et al., 1999). However, none of the above mentioned works has presented a comprehensive study on modeling the vertical interdependency of the different components of urban CIS and the inter-vulnerability consequences among these components.

This paper addresses the interdependencies among those critical and vulnerable CIS vis-à-vis the cascading effects that may result as a consequence of an attack or multiple attacks on one or more of the critical CIS in a network. The paper describes a framework that accounts for and assists in: (1) Identifying of critical components in interdependent urban CIS based on reliability assessment; (2) Modeling the cascading effects of a disaster in an urban CIS; and (3) Developing a decision support system (DSS) for prioritizing disaster mitigation and response strategies.

2. PROPOSED APPROACH FOR RELIABILITY AND VULNERABILITY ASSESSMENT OF CIS

We propose to introduce a new reliability-based approach for managing the interdependency of urban CIS by simultaneously analyzing the reliability and costs of the CIS under different combinations of disaster mitigation and response actions while considering the dependency between the different systems. This approach will modify and integrate available reliability models in the different infrastructure disciplines (e.g., transportation, energy, water supply, telecommunications, etc.) at the components, systems, and sub-systems levels. A novel generic interoperable model is proposed to explicitly capture the horizontal (intra-) and vertical (inter-) interdependencies among these systems. Figure 2 shows the steps necessary to realize the proposed approach. Based on this approach, it is possible to develop a DSS for analyzing complex alternative actions (e.g., deploying redundancy in some networks) and determining where to allocate resources and how to manage risks before or after the occurrence of disasters. In the later case, a mobile data collection system is used to update the databases of the CIS and facilitate decision-making in real-time. A by-product of the proposed approach would be in the strategic decision-making process associated with rehabilitation, replacement and renewal of urban infrastructure that account for the interdependencies among these valuable assets.

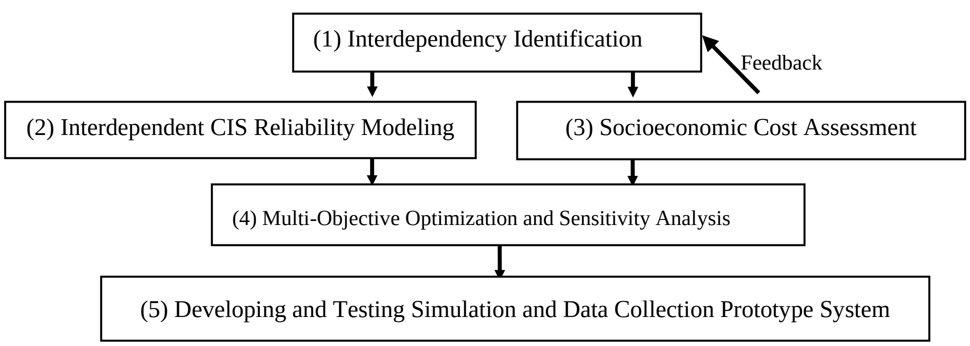

Figure 2. Proposed Approach

2.1 INTERDEPENDENCY IDENTIFICATION IN CIS

The following steps can help in identifying the interdependency between CIS: (1) Reviewing the literature to understand which elements of the various CIS are critical in the context of the urban environment in normal situations and after a disaster, where the criticality can be dynamic; (2) Collecting statistical data from governmental agencies responsible of the urban CIS and from insurance companies. These data can be organized and stored in a database to support the processes considered in identifying interdependencies and cascading effects; and (3) Using AI methodologies, such as neural networks and knowledge-based systems, and other analytical methods, such as the multi-attribute utility theory and the Analytical Hierarchy Process (AHP), to consider the multi-dimensional nature and the attributes of the problem to explicitly represent the degrees of criticality of the nodes involved. The attributes encompassed in this study include: (1) population distribution and density, (2) economic activities in the area, (3) topology of the networks, especially the order of the predecessors and succeeding nodes, and the cost associated with each mitigating scenario. GIS can help in identifying and analyzing the spatial aspects of the interdependency in the infrastructure and their impacts.

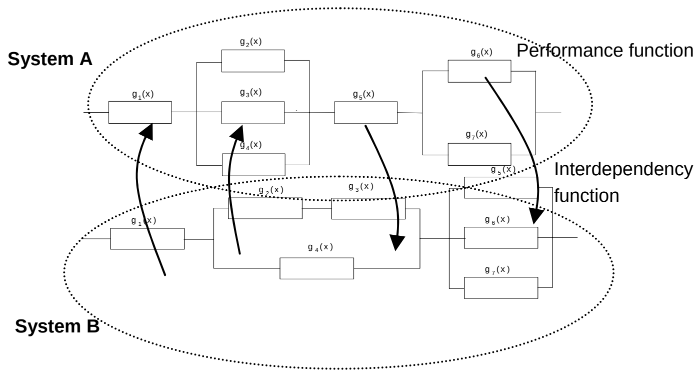

Figure 3. Interdependency Functions between Multiple CIS

2.2 INTERDEPENDENT RELIABILITY MODELING

Element of a CIS may experience different failure modes (*events*) that should be combined statistically to obtain the final result for the entire system. If $f_R(r)$ and $f_C(c)$ are the probability density functions of the resistance R and the capacity C, respectively, of an infrastructure component, then the reliability P_s of the infrastructure component is the volume under the joint probability density function $f_{R,C}(r, c)$ and is given by the integral

[1] $$P_s = P(R > C) = P(R - C > 0) = \iint_{R>C} f_{R,C}(r,c)drdc$$

The term $(R – C)$ represents a random variable referred to as the *performance function* and is usually denoted by $g(\mathbf{X})$. The failure limit state surface $g(\mathbf{X}) = 0$ separates all combinations of **X** that lie in the failure domain from those in the survival domain.

On a single network level, it is often convenient to estimate a single reliability measure that characterizes the overall network performance. Previous approaches proposed heuristic measures of network reliability, such as the arithmetic mean or weighted average of all nodal reliabilities. The interdependency between two or more infrastructure systems can be modeled by modifying the performance functions of the systems so that they include the effects of each system on the resistances and the capacities of the other systems. For example, in the case of a road network including a number of bridges and hosting lifeline systems (e.g., electric and telecommunication wires), the failure of a bridge would reduce the capacity of the road network and the lifeline systems in the immediate vicinity of that bridge, and would indirectly increase the load on other links to compensate for this reduction. By applying this concept, the interdependency between infrastructure systems can be represented by links among the serial-parallel systems with multiple modes of failure as shown in Figure 3.

Depending on the level of integration of infrastructure systems, one whole system can be considered as a component of another system (e.g., a bridge is a serial component of a road network link). This results in canonical graphs of reliability dependency with different levels of complexity. However, explicitly integrating the interdependencies among all infrastructure systems in one graph would result in a very high complexity level that could be very difficult to manage. Our approach is to seamlessly integrate available reliability models in the different infrastructure disciplines (e.g., transportation, energy, and telecommunications) at the components, systems, and interdependent systems levels so that interdependencies among these systems can be explicitly considered and modeled in an interoperable way.

2.3 SOCIOECONOMIC COST ASSESSMENT

The socioeconomic cost assessment includes the assessment of the costs of mitigating and response actions for improving the reliability of interdependent CIS and the costs of the socioeconomic damages that would occur with and without these actions including the capital cost of the damaged asset, social costs, the impact on opportunity costs related to economic activities, etc. (e.g., Kunreuther, 2000). This assessment necessitate the development of a comprehensive socioeconomic cost assessment system for urban CIS including the cost estimates of disaster mitigation and response actions, as well as the overall costs associated with damage of different infrastructure systems. The assessment system would build on previous research work in the area of lifecycle cost estimation for building projects (Jrade and Alkass 2003) and in transportation investment planning (Haider and Badami, 2004, Patterson et al., 2004, Mirza and Haider, 2003). The findings of this assessment will be utilized in for the identification of the critical nodes and in the multi-objective optimization process discussed in the following section.

2.4 MULTI-OBJECTIVE OPTIMIZATION AND SENSITIVITY ANALYSIS

New methods should be developed to study the trade-off between actions for maximizing the reliability of interdependent CIS under disruptive cascading effects and the costs resulting from these actions. In order to increase the reliability of an infrastructure system, the reliability of its dependent links should be increased by one or both of the following methods: (1) increasing the reliability of the supporting links, and (2) providing adequate redundancy for all dependent links in the system network, e.g., a telecommunication network where redundancy improves the service availability against concurrent failures. Genetic Algorithms (GA) can be used for optimizing the overall CIS considering cost and reliability as two separate objective functions (Bryan et al., 2004). The result of the optimization will be the Pareto set of optimal solutions that can be used by decision makers to prioritize and make effective use of their scarce resources based on rational strategies for CIS protection. Based on this Pareto set of optimal solutions, it would be possible to examine a wide range of scenarios and to study the sensitivity of the different mitigating strategies.

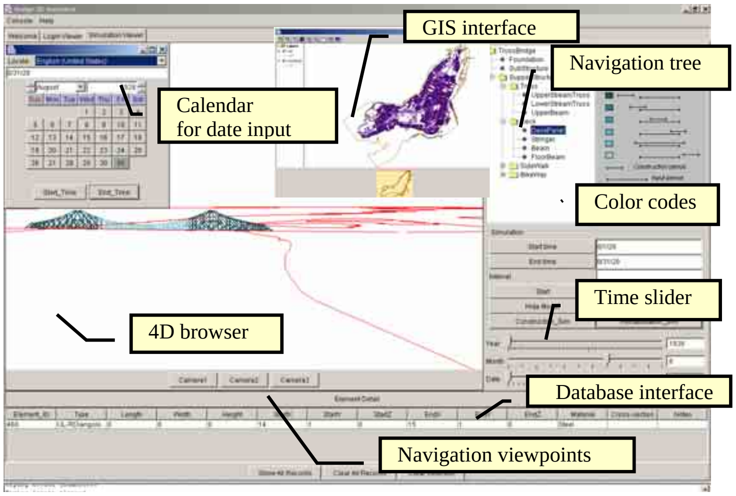

Figure 4. Example of Ongoing Research on Advanced Infrastructure Lifecycle Management Systems

2.5 SIMULATION AND DATA COLLECTION PROTOTYPE SYSTEM

This step aims to develop a prototype system that implements the models described above. It will also provide the test-bed for testing our approach. The system will utilize data related to scalable transportation and telecommunication networks in Montreal metropolitan area as a case study. This system is based on a previous prototype system for mobile model-based infrastructure lifecycle management (Hammad et al., 2004a-b) (Figure 4). This ongoing project is benefiting from the collaboration with Jacques Cartier and Champlain Bridges Incorporated, which is the federal agency responsible of the management of the major bridges and tunnels connecting Montreal Island to the surrounding cities. Post-disaster data collection would benefit from integrating geoinformatics, telecommunications, and mobile computing technologies. Geoinformatics technologies, such as GIS, and tracking methods, such as the Global Positioning System (GPS), can be used in a distributed real-time mobile computing environment. This approach to data collection is especially important in post-disaster situations because of the need to promptly and accurately collect and share the data needed for updating the databases that will be used in the DSS. Java language is most suitable for web-based applications and would allow linking all the information about the CIS (e.g., construction, inspection and maintenance records) to 4D models incorporating different scales of space and time. In addition, this system supports the Industrial Foundation Classes (IFC), distributed databases, and mobile computing by providing user interfaces that could be used on thin clients, such as tablet PCs, equipped with wireless communications and tracking devices, such as GPS receivers. We expect that the underlying requirements for modeling infrastructure interdependencies and on-site information access are general enough to support other infrastructure systems.

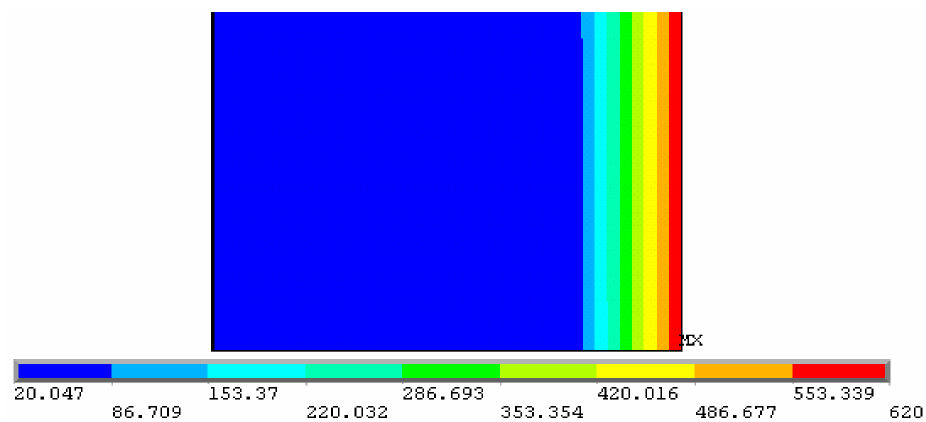

Figure 5. Temperature (C) contour at wall section

2.6 EXAMPLE OF VULNERABILITY ASSESSMENT OF INFRASTRUCTURE FACILITIES

As an example of vulnerability assessment of infrastructure facilities, an automated method has been developed to assist in the assessment of the structural damage of storage and power plant facilities of concrete construction such as NPPs against accidental or man-made hazards (Paul et al., 2005). The hazard considered has two sequential external actions; an impact force arising from a moving vehicle crash and a rise in temperature resulting from the fireball generated from the crash. The moving vehicle could be a truck or even an aeroplane. A sequential coupling method between thermal and structural fields has been developed to analyze the effect of the impact of this type of hazards on structures. A method has been developed to automate the coupling of the two analyses by generating the data files required to perform them. Accordingly, temperature dependent material properties and time dependent loads and boundary conditions are read in automatically. Degradation of material properties due to rising temperatures is also incorporated in the analysis.

A numerical example has been analyzed to test the proposed method. It considers a gasoline truck crashing against the wall of a concrete reservoir, generating an explosion and a fireball. The results indicate that the impact force generated by the crash has very little effect on the overall structure, but the thermal load generated by the fireball has a significant effect on the structural integrity in the vicinity of the crash. The displacements due to the thermal load are several hundred times larger than those due to the impact force. The results (such as those shown in Figure 5) also indicate that, although the heat does not penetrate much into the wall during one hour of heating, it causes considerable amount of plastic strain in the heated area and local damage of the structure. The larger the area of the highly heated zone is, the larger would be the damage, which may ultimately trigger overall collapse of the structure. Considering the particular use of the structure, its vulnerability and safety may, therefore, be assessed from the analysis results. The analysis procedure has been automated and can be applied to investigate a wide range of structural systems made of concrete, steel and other materials of know temperature-dependent properties.

3. CONCLUDING REMARKS

This paper discussed issues related to the interdependencies among CIS vis-à-vis the cascading effects that may result as a consequence of natural or man-made disaster in one or more of the systems in the CIS network. The paper described a framework that accounts for: (1) Identifying of critical components in interdependent urban CIS based on reliability assessment; (2) Modeling the cascading effects of a disaster in an urban CIS; and (3) Developing a decision support system (DSS) for prioritizing disaster mitigation and response strategies. In this framework, it is proposed to represent the CIS network by a set of critical nodes, each representing a CIS. Each node has its own characteristics such as the degree of criticality, vulnerability, and impact on successor nodes in the network. The paper also highlighted necessary methods and decision support tools required to perform the individual tasks as well as the implementation environment of the proposed methodology. The cross-sectoral issues raised by infrastructure interdependencies are essential in understanding and predicting the effects of interdependencies on the resilience and reliability of CIS. In addition, in order to understand the real-world problems and to facilitate the implementation of the research results, we have established contacts with government officials (*Defense Research and Development Canada*) and infrastructure owners and operators (*Hydro Quebec*).

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