IMPACT OF INTERDEPENDENCIES BETWEEN INFRASTRUCTURE SYSTEMS IN THE OPERATION OF HEALTH CARE FACILITIES DURING DISASTER EVENTS

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ABSTRACT

Infrastructures systems cover a large number of sectors, including the national power grid, oil and natural gas production, transportation, and distribution networks, telecommunications and information systems, water systems, transportation networks, the banking and finance industry, the chemical industry, agriculture and food systems, and public health networks. These systems do not exist in isolation of one another – telecommunications networks require electricity, transportation networks require systems information to operate, generation of electricity requires fuel, emergency systems require transportation networks, and so forth. Interdependencies give rise to numerous challenges that do not exist in single infrastructure models.

During a disaster event, health care facilities are expected to operate efficiently in order to provide care to injured patients. Traditionally, it has been assumed by disaster planners that these facilities are capable of providing services under the most extreme circumstances. However, medical care for injured patients can be affected if health care facilities do not have sufficient supply of electric power, water supply, or effective access to road transportation networks, etc.

This paper presents two mathematical models that may be used to assess the level of interdependencies between the health care facility and the primary infrastructure systems linked to the facility. These models use linear programming to determine the unsatisfied demand in the major infrastructure systems and the impact of this shortage of resources on the operation of the hospital. The models described in this paper show the impact of a disruption when interdependencies among infrastructures are considered and supports strategy development and decision making during the restoration process. The framework and modeling used in this paper can assist in determining cost-effective operational strategies in a health care facility in order to respond to a disaster event considering the

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interdependencies between infrastructure systems and taking into account different capital investment alternatives that can be used to improve its response capability during disaster events.

KEY WORDS

health care facilities, infrastructure systems, interdependencies, optimization, capital investments.

INTRODUCTION

The National Strategy (2003) defined a set of essential infrastructure systems that cover a large number of sectors, including the national power grid, oil and natural gas production, transportation and distribution networks, telecommunications and information systems, water systems, the banking and finance industry, the chemical industry, agriculture and food systems, and public health networks. The operation of these infrastructure systems is impacted by the interdependencies among them. According to Rinaldi (2004), "omitting interdependencies will at best limit the validity of analyses and at worse lead to bad or inappropriate policies and decisions during crises or severe infrastructure disruptions."

As the tragedies of September 11, 2001 and Hurricane Katrina in August 2005 demonstrated, individual infrastructure systems are interconnected in such a way that failures cascade from one subsystem to another and from one system to the next. Electricity outages curtail compressor stations in natural gas pipelines which supply the fuel they need and stop pumps at water and wastewater treatment plants. They also disrupt traffic signals and transportation infrastructure. Water can neither be delivered by pipelines for irrigation and fire suppression nor by trucks in bottles. Emergency crews cannot get to the sites where their services are needed. The telecommunications sector is halted without electricity: no landline phones, jammed cell phone switches, no internet and computing, no SCADA (supervisory control and data acquisition), or control systems (Heller 2002, Lee et al. 2003, Brown 2004).

Health care systems play a critical role in mitigation and recovering from effects of natural disasters or deliberate attacks. These facilities are required to operate efficiently during an emergency, which includes treating a significant number of patients simultaneously. Health care facilities are not isolated, rather, they are part of a community's infrastructure systems. Therefore, any planning decision or preparedness strategy should be defined in accordance with the offered service level of the existing infrastructure systems close to the facility. For example, as a consequence of the flooding after Hurricane Katrina in August 2005, health care facilities in the city of New Orleans were evacuated because it was not possible to operate power generators located in the lower levels of the hospitals and also because the delivery of medical resources was delayed as a result of the flooding of the road network.

Since health care facilities rely on infrastructure systems to operate (i.e., water, energy, roads), it is necessary to assess the impact on the health care facility due to disruptions of these infrastructure systems during disaster events. The vulnerability analysis should incorporate the analysis of interdependencies between the health care facility and these infrastructure systems, including the effects of disruption on these systems in the operation of the facility and its flow of patients.

INTERDEPENDENCIES BETWEEN INFRASTRUCTURE SYSTEMS

An interdependency can be defined as a bidirectional relationship between infrastructures through which the state of each infrastructure is influenced by or correlated to the state of the other (Rinaldi 2004). Interdependencies give rise to numerous challenges that do not exist in single infrastructure models. For instance, when an infrastructure fails due to natural or man-made actions, the consequences are not just for the infrastructure itself. There might be significant consequences to other systems connected to the failed infrastructure. As a result, the evaluation of the consequences should include not just the direct effects, but all the possible consequences to other interconnected systems.

The analysis of interdependencies requires examining at different dimensions for describing the existing interdependencies. Rinaldi et al. (2001) describes six different dimensions for the analysis of interdependencies, as shown in Table 1. The various areas of interactive infrastructure networks (Table 1) present theoretical and practical challenges in modeling, prediction, simulation, cause and effect relationships, analysis, optimization, and control of systems. Infrastructure interconnections create chains of interdependencies that can propagate disturbances across many infrastructures (i.e., power blackouts in the operation of water pumping stations) and over long distances, and the interdependencies may also tend to propagate, amplify, or dampen these disturbances (Brown et al. 2004).

Table 1: Dimensions for describing infrastructure interdependencies (Rinaldi et al.2001)

Dimension	**Elements**
Infrastructure characteristics	Organizational, operational, temporal, spatial
State of operation	Normal, repair/restoration, stressed/disrupted
Types of interdependencies	Physical, cyber, logical, geographic
Environment	Economic, legal/regulatory, technical, social/political, business, public policy, security, health/safety
Coupling and response behavior	Adaptive, inflexible, loose/tight, linear/complex
Type of failure	Common cause, cascading, escalating, human cause

MODELING OF INTERDEPENDENCIES IN INFRASTRUCTURE SYSTEMS

Several modeling and simulation (M&S) approaches have been developed to understand the interdependencies between infrastructure systems. However, according to Brown (2004), no single method or best method currently exists for the infrastructure assessment process, given the complexity, interdependency, uncertainty, and adaptability of the infrastructure systems. M&S approaches that have been utilized to model interdependencies are as follows:

AGENT-BASED MODELLING AND SIMULATION (ABMS)

In ABMS the decision processes and actions of individual agents (e.g., consumers, companies) are simulated, rather than the aggregate system behavior patterns and trends, as in traditional approaches (Macal and North 2002, 2005). ABMS attempts to capture the complex, non-linear, self-organizing, emergent, and sometimes chaotic patterns of interaction exemplified by complex systems. Using an ABMS approach, the physical and behavioral aspects of the infrastructures are represented as a system of highly connected, interacting agents. Organizations that control the various parts of the infrastructure and their decision-making behaviors are modeled explicitly as collections of agents or form spontaneously in response to the physical and economic environment (Macal and North 2002, 2005).

LEONTIEF-BASED MODEL

Input-output analysis has been extensively used since its introduction by Leontief (1936). Although this approach was originally developed to model national economies, it has since been extensively used to model regional and multiregional economies, environmental impacts, water resources planning, flood control infrastructures, disaster planning, and others. Haimes and Jiang (2001), Haimes et al. (2005a, b) applied the original Leontief input-output model (i.e., interdependence among the various parts of the economic system) to analyze the interconnectedness between critical infrastructure systems. They considered a system consisting of m critical complex intraconnected and interconnected infrastructures, such as water networks and power generation, with the output being the risk of inoperability that can be triggered by one or multiple failures due to complexity, accidents, or acts of terrorism.

PERFORMANCE OF INTERDEPENDENT INFRASTRUCTURES MODEL

Nozick et al. (2004) developed a mathematical framework to represent interconnected infrastructure networks and a collection of algorithms that can be used to estimate performance and optimize investment in the different networks. The authors represent interconnected infrastructures by the use of networks (graphs of nodes and arcs). The graph models capture probabilistic information; they characterize interconnected networks with probability distributions of link capacities and correlations between link capacities. The arcs represent components or subsystems in an infrastructure or the connection between infrastructures. They have capacities that may be uncertain and evolve over time. These changes in link capacity may include both random failures (that reduce arc capacity) and repair actions of uncertain duration (that restore capacity).

NETWORK FLOWS MODEL

Lee et al. (2003) developed three mathematical models of network flows to represent the interdependencies between infrastructure systems (i.e., power and telecommunications). The first representation describes each system during normal operations. The second provides support to the managers of the individual systems and to emergency response officials in assessing the impact of a disruption and determining if service can be provided without extensive restoration operations. The third model shows the impact of a disruption when interdependencies among infrastructures are considered.

NETWORK FLOWS MODEL

The models described in this section are represented as Minimum-Cost Network Flow Problems (MCNFP) (Lee et al. 2003, Winston 2004). This representation captures the movement of the commodities (water, power, medical resources) corresponding to flows and also services corresponding to a desired level of these flows (the required supply to satisfy a given demand). Each infrastructure system is defined as a collection of nodes and arcs with commodities flowing from node to node along paths (arcs) in the network.

NORMAL OPERATIONS MODEL

This model describes the functioning of the infrastructure systems (i.e., power generation, water supply, transportation network) and the internal capabilities of the health care facility (i.e., emergency room, intensive care unit, surgery, etc.) under normal operating conditions which means that a disaster event has not occurred. The objective function is to minimize the cost of the operation of the infrastructure systems. It is assumed that all demands on all infrastructures are being met and that there are sufficient resources available to respond to typical emergencies in the facility (fewer than 500 casualties) (Barbera and Mcintyre 2002). Figure 1 describes the framework of the Normal Operations Model.

Parameters and Sets

S	set of infrastructure systems
V	set of nodes of the network
A	set of arcs of the network
b_k^s	demand at node k of infrastructure s, $k \in V$; $s \in S$
c_{ij}^s	unit cost at arc (i,j) of infrastructure s, $(i,j) \in V$; $s \in S$
u_{ij}^s	maximum capacity at arc (i,j) of infrastructure s, $(i,j) \in V$; $s \in S$

Variables

x_{ik}^s	flow in arc (i,k) of infrastructure s, $(i,j) \in V$; $s \in S$

Objective

$$min \sum_{s \in S} \sum_{i,j \in V} c_{ij}^s x_{ij}^s$$

such that

Flow equilibrium at node k of infrastructure s

$$\sum_{s \in S} \sum_{j \in V} x_{kj}^s - \sum_{s \in S} \sum_{k \in V} x_{ik}^s = b_k^s \quad (i,k,j) \in V;\ s \in S$$

Limited capacity in arcs

$$x_{ij}^s \leq u_{ij}^s \quad (i,j) \in V;\ s \in S$$

Positive flow in the networks

$$x_{ij}^s \geq 0 \quad (i,j) \in V;\ s \in S$$

Figure 1: Normal Operations Model Framework

RESPONSE TO A DISRUPTION MODEL

This model helps to assess the unmet demand, including new demand, when a disaster event occurs. It is possible that some of the infrastructure systems and/or internal capabilities would be damaged because of the disaster, thereby reducing the normal response capability. This model helps to determine how much demand is unmet given the changed capacities (after the event occurs) and the changed operational conditions of the infrastructure systems. The response to a disruption model (Figure 2) requires data regarding the revised conditions of the infrastructure systems after the disaster event (i.e., additional demand, new capacities, new supply, new operational constraints, etc.). The results of this model help to assess the vulnerabilities of the health care facility in case of a disruption of the infrastructure systems, quantifying the reduction of supply due to the disaster event as a percentage of the normal operations flow. This reduction in the level of supply affects the flow of patients within the facility. If there are insufficient resources at the hospital, there is an increase in: (a) the number of patients waiting to receive medical care, (b) the length of stay of the patients in the service areas, and (c) the work pressure in the medical personnel (Arboleda et al. 2006).

Parameters and Sets

S	set of infrastructure systems
V	set of nodes of the network
A	set of arcs of the network
b_k^s	demand at node *k* of infrastructure *s, k∈ V; s∈ S*
c_{ij}^s	unit cost at arc *(i,j)* of infrastructure *s,(i,j)∈ V; s∈ S*
u_{ij}^s	maximum capacity at arc *(i,j)* of infrastructure *s, (i,j)∈ V; s∈ S*
p_k^s	weighting factor for node *k* in infrastructure *s*, *k∈ V; s∈ S*

Variables

x_{ik}^s	flow in arc *(i,k)* of infrastructure *s, (i,j)∈ V; s∈ S*
d_k^s	unsatisfied demand at node *k* of infrastructure *s*, *k∈ V; s∈ S*

Objective

$$min \sum_{s\in S} \sum_{i,j\in V} c_{ij}^s x_{ij}^s + \sum_{s\in S} \sum_{k\in V} p_k^s d_k^s$$

such that

Flow equilibrium at node *k* of infrastructure *s*

$$\sum_{s\in S} \sum_{j\in V} x_{kj}^s - \sum_{s\in S} \sum_{k\in V} x_{ik}^s - d_k^s = b_k^s \qquad (i,k,j)\in V;\ s\in S$$

Limited capacity in arcs

$$x_{ij}^s \le u_{ij}^s \qquad (i,j)\in V;\ s\in S$$

Positive flow in the networks

$$x_{ij}^s \ge 0 \qquad (i,j)\in V;\ s\in S$$

Unsatisfied demand

$$d_k^s \ge 0 \qquad k\in V;\ s\in S$$

Figure 2. Response to a Disruption Model Framework

RESTORATION MODEL

The purpose of the restoration model is to reflect the interactions between the infrastructure systems and the internal capabilities in the analysis of each restoration strategy. The objective function in this case minimizes the operational cost and the shortfall of demand identified in the response to a disruption model. The definition of restoration strategies requires input from experts in the health care industry and emergency management services in order to validate their feasibility. These strategies are associated with the resources available and the network's topology. For example, a restoration strategy could be the installation of additional power generation plants at one of the nodes linked to the hospital. The definition of strategies and the mathematical formulation of this model are in progress at this time.

ILLUSTRATIVE EXAMPLE

The first two optimization models described in previous sections are used in this example to evaluate the impact of a disruption in the infrastructure systems that provide water, power, and medical supplies to a health care facility. These systems were selected because of their importance during the medical response operations after the occurrence of a disaster event. Figure 3 shows a set of three networks that have supply, transshipment and demand nodes.

Some of the nodes are part of two or more networks. For example, node 5 is a water pumping station which requires electric power to operate correctly. If there is insufficient supply of power at this node and no electric backup is available, there are restrictions in the supply of water as well. Of special interest are the nodes associated with the operation of the hospital (nodes 15, 16, 17, and 18). These nodes are the demand nodes within the facility.

The analysis of the normal operations model showed that all the demands are satisfied for every node in the set of networks (Table 2). In addition, some arcs do not have any flow because the demand is satisfied using other arcs. These arcs may be used during the restoration operations, especially because these arcs are already in place.

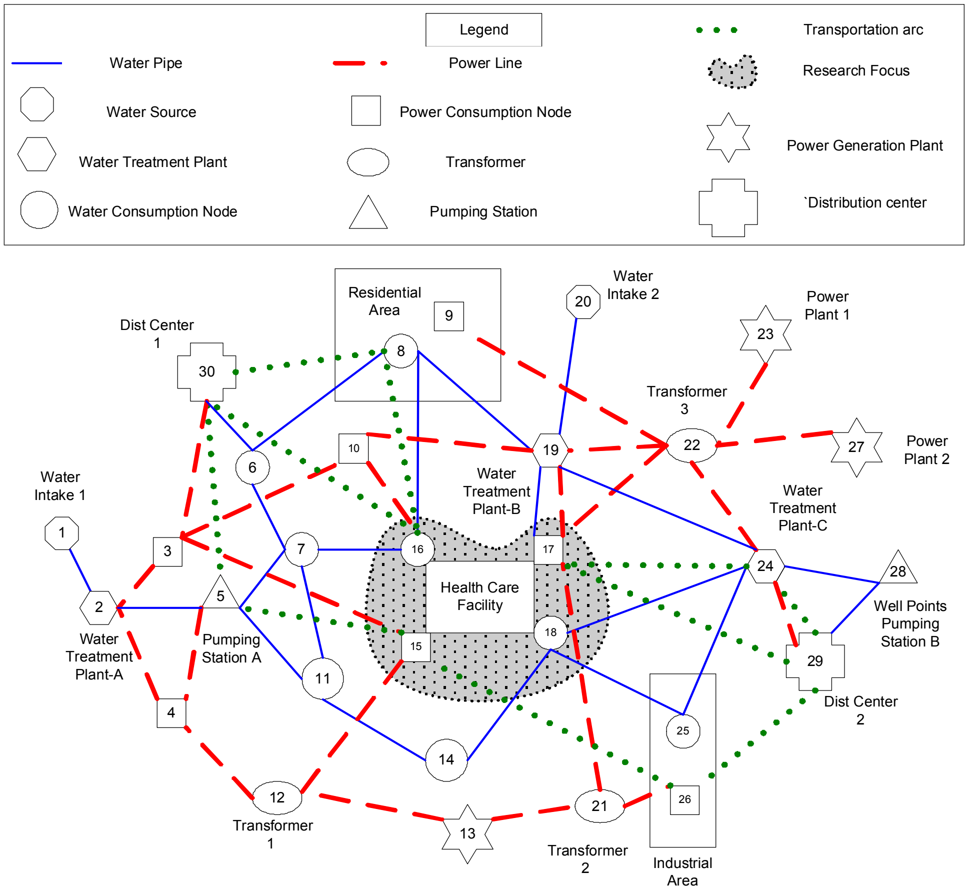

Figure 3: Water, Power and Transportation Networks

Table 2 Satisfied demands at hospital nodes (Normal Operations Model)

Node	Water (m^3/hour)	Power (kW/hour)	Transportation (units of medical supplies / hour)
15	-	5,000	100
16	1,000	5,000	50
17	1,000	10,000	100
18	700	-	-
Total	**2,700**	**20,000**	**250**

Assume then, that a disaster event is reported and as a consequence of this event, there are disruptions in the level of supply at some nodes. An assessment of the condition of the nodes affected by the disaster shows that the hospital requires additional medical resources (50 units of medical supplies/hour) to manage the surge of capacity at node 15. Besides, node 29 (distribution center No. 2), node 28 (pumping station B), node 27 (power plant No. 2), and node 23 (power plant No. 1) have only 10% of its original supply capacity. The results of the response to a disruption model show that there are unsatisfied demands at some of the nodes in the network, which affect the operational conditions of the health care facility.

Table 3 shows the impact of the disaster event at the nodes associated with the operation of the hospital. The operational capacity at the water and power system decreases by 25% when compared with normal operations. In addition, the supply of medical resources decreased by 68% due to the disruption of the distribution center 2. This reduction in the operational capacity affects the flow of patients within the facility, and hence it is necessary to implement strategies to reinstate the supply of resources to the facility. These strategies can be evaluated utilizing the restoration model and taking into account the network topology and resources available.

Table 3 New operational capacity at the hospital (nodes 15, 16, 17, and 18)

	Water (m^3/hour)	**Power (kW/hour)**	**Transportation (medical resources/hour)**
Required demand	2,700	20,000	300
Demand deficit	700	5,000	205
New Operational Capacity	**74%**	**75%**	**32%**

CONCLUSIONS

Physical damage to health care facilities or disruption of their operations or supply chain could prevent a full, effective response and exacerbate the outcome of an emergency situation. An essential component in the vulnerability assessment of health care facilities is the analysis of interdependencies between the different infrastructure systems that supply resources for the operation of the facility. The interconnectedness between these systems may create additional demand needs during a disaster event, but may also be used for restoration efforts. The models described in this paper can help hospital administrators to determine critical components of the infrastructure systems that require additional redundancy in order to maintain the operation of the facility after the occurrence of disasters.

REFERENCES

Arboleda, C. A, Abraham, D. M., and Lubitz,R. M. (2006). Simulation as a Tool to Assess the Vulnerability of the Operation of a Health Care Facility, 1st Specialty Conference in Disaster Mitigation, CSCE, Calgary, Canada (under review)

Barbera, J. and Macintyre, A. (2002) A Medical and Health Incident Management (MaHIM) System: A Comprehensive Functional System Description for Mass Casualty and Health Incident Management. Report for the Institute for Crisis, Disaster and Risk Management, The George Washington University. Washington, D.C.

Brown, V. A., Beyeler, T., and Barton, D. W. (2004) Assessing infrastructure interdependencies: the challenge of risk analysis for complex adaptive systems, Int. J. Critical Infrastructures, Vol. 1, No. 1, pp.108–117.

Haimes, Y. Y. and Jiang, P. (2001). Leontief-Based Model of Risk in Complex Interconnected Infrastructures, Journal of Infrastructure Systems. ASCE, Vol. 7, No. 1, pp. 1-12

Haimes, Y. Y., Horowitz, B. M, Lambert, J. H., Santos, J. R, Lian, C., and Crowther, K. (2005a) Inoperability Input-Output Model for Interdependent Infrastructure Sectors. I: Theory and Methodology, Journal of Infrastructure Systems. ASCE, Vol. 11, No. 2, pp. 67-79

Haimes, Y. Y., Horowitz, B. M, Lambert, J. H., Santos, J. R, Crowther, K., and Lian, C. (2005b) Inoperability Input-Output Model for Interdependent Infrastructure Sectors. II: Case Studies, Journal of Infrastructure Systems. ASCE, Vol. 11, No. 2, pp. 80-92

Heller, M. (2002). Life Cycle Infrastructure Risk Management: R&D Needs. Risk Management Strategies in an Uncertain World. Columbia-Wharton/Penn Roundtable, New York

Lee, E. E., Mendonca, D., Mitchell, J. E., and Wallace, W. A (2003). Restoration of services in Interdependent Infrastructure Systems: A Network Flows Approach. Technical Report 38-03-507, Decision Sciences and Engineering Systems, Rensselaer Polytechnic Institute, Troy, NY.

Leontief, W. (1936). Quantitative input-output relations in the economic system of the United States., Review of Economics and Statistics, MIT Press, 18, 105-25

Macal, C., North, M. J., (2002) Simulating Energy Markets and Infrastructure Interdependencies with Agent Based Models, *Social Agents: Ecology, Exchange, and Evolution Conference*, University of Chicago, October 8-9, Chicago, IL USA, pp 1-20

Macal, C., North, M .J., (2005) Tutorial on Agent-Based Modeling and Simulation. Proceedings of the 2005 Winter Simulation Conference, M.E. Kuhl, N.M. Steiger, F.B. Armstrong, and J. A. Joines, eds., Orlando, FL, December 4-7, Institute of Electrical and Electronic Engineers, Piscataway, NJ, U.S.A, pp. 2-14

National Strategy for the Physical Protection of Critical Infrastructures and Key Assets. (2003), The White House, February http://www.whitehouse.gov/pcipb/physical.html Accessed Dec 2005

Nozic, L. K, Turnquist, M. A., Jones, D. A, Davis, J. R. and Lawton, C. R. (2004) Assessing the Performance of Interdependent Infrastructure and Optimizing Investments. Proceedings of the 37th Hawaii International Conference on System Sciences, IEEE, pp. 1-7

Rinaldi, S. M.; Peerenboom, J. P.; Kelly, T. K. (2001). Identifying, understanding, and analyzing critical infrastructure interdependencies; Control Systems Magazine, IEEE, Issue 6, pp 11 - 25

Rinaldi, S. M. (2004). Modeling and Simulating Critical Infrastructures and their Interdependencies. Proceedings of the 37th Hawaii International Conference on System Sciences, Kauai, Hawaii, January 5-8, Institute of Electrical and Electronic Engineers, Piscataway, NJ, U.S.A, pp 1-8

Winston, W. L (2004). Operations Research. Applications and Algorithms. Fourth Ed. International Thomson Publishing, Belmont CA