Extreme Events and the Sustainability of Civil Infrastructure Systems

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ABSTRACT

The impact of extreme events is in reality the interaction among three systems; the natural environment, the human community, and the built environment - the infrastructure that supports human activities. The sustainability of our infrastructure depends upon knowledge of the natural environment – for example, the research on global warming and its impact on meteorological events such as storms, droughts and floods. Sustainability also depends upon the demographic composition and distribution of population. Shifts in population require expanded infrastructures; people moving into hazardous regions like coastal areas may require new infrastructure.

The events of September 11, 2001 show once again the vulnerability of our civil infrastructure systems. However, the on-going attention may provide the opportunity to increase the sustainability of civil infrastructures while reducing their vulnerability- the focus of this paper.

The paper first presents background related to sustainability and vulnerability of infrastructure systems. A systematic procedure including an optimization algorithm is presented to incorporate sustainability concerns into the vulnerability analysis. An illustrative example is given, followed by concluding remarks on its integration with past research on vulnerability of civil infrastructure systems.

Keywords: Civil Infrastructures; Sustainability; Extreme Events.

1. Introduction

Human beings have always been beset by threats to their well-being. Yet, with each new headline announcing an earthquake, a storm, a terrorist attack or other crisis, it appears that the vulnerability of our infrastructure to extreme events is increasing. In fact, some studies have documented that losses and potential losses in the United States from various hazards are rising at an alarming rate.

Despite the headlines, many of these occurrences are perfectly “natural” events – some of which have been happening for millions of years. Flooding river deltas is one; the threat of attack on food supplies by neighboring tribes is another. These events become “extreme” i.e., catastrophic, when we:

- Move our activities in life, work or play into high risk areas, and
- Build complex, tightly coupled infrastructures to satisfy our needs and wants.

We are doing both. People are moving to suburban and exurban locations, many of which are in unpredicted flood plains, seismic risk areas, and exposed coastal locations and we are building infrastructures to support their life, work and play. In addition, advances in communications and computing technologies are being employed to create both new infrastructures, e.g., cellular communications and the Internet, and to make existing infrastructures safe and more productive, e.g., intelligent transportation systems.

Typically, engineers have been responsible for the planning, design construction and maintenance of the civil infrastructure systems and decide where, how and when facilities will be built. Fundamentally, the engineer's job has been to provide the most cost-effective system to fulfill the goals, interests and objectives of the organizations they represent. Transportation engineers focus on the needs of users and increasing demands for service; water quality engineers focus on maintenance of an adequate supply while maintaining an aging delivery and distribution system. Sanitary system engineers focus on the collection and treatment of ever-increasing amounts of waste with fewer disposal locations(Wright 1996).

Our infrastructures have been planned and built by public and private agencies, each focused on the performance of only their agency. Within each agency, there is competition for limited funds. Operations and maintenance departments focus on keeping today's systems running while planning and design departments are concerned with building the capability for tomorrow.

Many of these utilities achieved greater efficiency by establishing relationships to other utility companies. Power generating and distribution utilities allowed for greater development than was possible from many small generating systems. Control and monitoring systems have made possible the remote operation and control of system components allowing safe and coordinated operations over large geographic areas. Each system was able to take advantage of the expertise of other utilities and no longer relied on as many "in-house" support departments.

However, this reliance on other companies has increased their interdependence. Failures, no matter the cause, in one locale may have far reaching effects across many systems. The reliance of one system on another relates to their interdependence. This reliance was made very evident following both the September 11, 2001 attacks on the World Trade Center and the August 14, 2003 power failure in the Northeastern United States and Canada. Following the events of September 11, reports published in the Metro edition of the New York Times for the period September 12 to December 12, 2001, documented 215 incidents involving a civil infrastructure, and over 20% of these (46) involved more than one system(Wallace et al. 2003). The power failure resulted in more than fifty million people in the U.S. and Canada losing electricity with economic damage in excess of five billion dollars(Eisenmann and Willis 2004).

So, the challenge is this: how does one system find suitable alternatives to add new capacity for growth or add redundancy to reduce vulnerability while not making other systems more vulnerable and while working to increase the sustainability of all the systems, within the financial constraints of budget?

Sustainability looks to meet the needs of the present without compromising the ability of future generations to meet their needs. This requires managing the use of natural and physical resources in a way that enables people and communities to provide for their social, economic and cultural well being while :1) Maintaining the potential of natural resources to meet the needs of the future and 2) avoiding adverse effects on the environment.

Reducing vulnerability consists of examining a system’s probability of damage from natural, human-caused, or willful acts. Solutions work to increase the robustness of the system and can include hardening key components to reduce potential damage and adding new components to increase resilience

The inherent weakness for infrastructure system managers is the inability to “see” beyond the boundaries of their own system. This is clearly stated in “*The National Strategy for the Physical Protection of Critical Infrastructures and Key Assets”* (The White House 2003).

> *Most industry officials have a fairly complete understanding of their own operations and associated vulnerabilities. However, many of these enterprises require assistance to identify their dependencies on other sectors and the degree of risk to which they are exposed as a function of those interdependencies. The potential impact of such interdependencies hit home for the banking and financial services sector on September 11, when the collapse of the World Trade Center towers interrupted telecommunications services in lower Manhattan. The disruption brought electronic financial transactions to a halt, with long-term economic impacts still being felt more than a year later. (The White House 2003, p. 34)*

This lack of vision beyond the boundaries of a single utility system affects the vulnerability and sustainability of all infrastructure systems.

2. Vulnerability

Recent events, in particular the September 11, 2001 attacks, have increased concern over the vulnerability of infrastructure systems, those that provide the basic services of transportation, power, communications, etc. Alternative designs are being proposed to reduce vulnerability, typically by introducing redundancy – often at a substantial cost. However, any reduction in vulnerability may not be forthcoming if the designers do not consider the interdependence of infrastructure systems. For example, a proposed redundant path for a telecommunications network may be connected to the power system at a different point than an equivalent path in the present network – but the source of power may be the same for both connections. The result is, if the power source is disabled, both paths will fail and telecommunications service will be not be available.

The issue of the vulnerability of our civil infrastructures has been addressed in a multitude of forums – the most prominent being the President's Commission on Critical Infrastructure Protection. Researchers have studied the survivability of infrastructure systems by modeling them as independent networks and analyzing the impact of disruptions on the service provided by the infrastructure. As examples, Balakrishnan et al. (1998) and Chamberland and Sauso (2001) focused on telecommunications networks, and Haimes et. al. (1998) studied water systems.

In all cases, the research addressed one infrastructure system and the service it provides and did not consider interdependencies among infrastructure systems. Notable exceptions are work by Rinaldi et al. (2001) and Amin (2001) that focus on the issue of interdependent infrastructures and provide very useful definitions and discussion of the ramifications of disruptions to interdependent infrastructure systems. The work by Haimes and his colleagues is also very relevant to the issue of vulnerability of infrastructure systems (Haimes and Jiang

2001; Longstaff and Haimes 2002). In Longstaff and Haimes (2002), hierarchical holographic modeling provides the holistic schema to address the survivability of infrastructure systems; while in Haimes and Jiang (2001), a Leontief-based input-output model is used to understand the interconnectedness among infrastructure systems. This work does provide important insights needed to begin to address the design issues of survivability of infrastructure systems.

Our past research has focused on modeling the interdependency of the civil infrastructure systems and using this model to identify vulnerabilities due to interdependence before disruptive events occur and as a tool for managers during the recovery and restoration phases following a disruption(Lee et al. 2004).

3. Sustainability

Sustainability takes on a global view of the activities of society. There are many definitions in the literature and the definition has changed with time. One definition which seems to reflect the essence of most definitions is the following:

> *Humanity has the ability to make development sustainable--to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs. The concept of sustainable development does imply limits--not absolute limits but limitations imposed by the present state of technology and social organization on environmental resources and by the ability of the biosphere to absorb the effects of human activity(Brundtland 1987).*

Much effort has been expended in working toward a consensus of balancing today’s local needs of business and society against global views and the needs of future generations. B. Stigson (Stigson 1999) notes” There is a strong shift from a few years ago when the environment and sustainable development were viewed by business as risk factors. The situation today (and even more in the future) is that these are seen as responsibilities and opportunities – sources of competitive advantage.”

The 1992 United Nations Conference on Environmental Development in Rio de Janeiro focused on the issues of global sustainable development. International organizations such as the World Business Council are seen to be at the forefront of these efforts. Journals such as the Journal of Urban Planning and Development, Journal of Water Resources Planning and Building Research and Information publish many articles and papers on the sustainable development of our infrastructure systems.

In general, sustainability includes a “birth-to death” assessment of the products and services used daily. One framework for these analyses is found in Streamlined Life Cycle Assessment by T.E. Graedel (Graedel 1998). In this book, the author breaks down the life cycle into five stages and evaluates each over five environmental impact areas. The life cycle stages are pre-manufacture, product manufacture, product delivery, product use and refurbishment, recycling and disposal. The five impact areas are materials choice, energy use, solid residues, liquid residues, and gaseous residues. Each combination of stage and impact is graded on a 0-4 scale with 0 representing an environmentally unfriendly performance and 4 representing excellent environmental performance. It is acknowledged that this process is rather subjective but the author encourages the documentation of justification for each score assigned. The use of this environmental rating will be discussed later in this paper.

4. An Analytical Approach to the Incorporation of Sustainability in Vulnerability Analysis

Many tools and methods are available for systems mangers to evaluate the vulnerability of their system of concern or across multiple interconnected systems. The choice of tool is not relevant to this discussion. Once a vulnerability is found, a method for evaluating alternatives is needed that takes into account economic, social and environmental concerns. A methodology for this is presented next.

Let us assume an analysis has been done on a civil infrastructure system in some geographic region with a focus on impacts on other systems. Each system's management set minimum criteria for operation of his system and analyses were run to uncover key components among the set of systems whose failure would not sustain this minimum satisfactory operation criteria. Let N be the set of vulnerable components and M are the set of alternatives for each component in N. Let c_{mn} be the economic cost of alternative m for component n

$$c_{mn} = f_{mn} + (o_{mn} * t)$$

(1)

where f_{mn} are the fixed charges associated with alternative m and component n (this includes purchase and installation) and o_{mn} are the annual operating expenses over the period of interest, t. The values of c'_{mn} are based on the values of c_{mn} scaled over the maximum value for one component n. The highest c'_{mn} is scaled to 100; the remaining alternatives for component n would range from 1-100.

Let E_{mn} represent the environmental score of alternative m and component n where

$$E_{mn} = \sum_{ij} e_{mn}^{ij}$$

(2)

and e are the elements of the matrix comprised of the five life stages and five environmental areas for alternative m and component n. As stated earlier the values of e range from 0 to 4, so the maximum value of E_{mn} is 100 (see section 2).

Let S_{mn} represent the social score of alternative m and component n. If there are j areas of societal concern under consideration, then each area s would range over a value from 0 to 100/j.

$$S_{mn} = \sum_{j} s_{mn}^{j}$$

(3)

(If there are 3 areas of concern, the upper limit on s_j is 33.3 and the maximum value for S is 100).

Let k_n^{econ}, k_n^{env} and k_n^{soc} be the weighting factors for the decision maker between the economic cost, environmental score and social score for component n (it is assumed that the weights would be the same across all alternatives) and that the sum of the k is 1.

Each alternative in *mn* has its total score TS, and limiting our choices to one alternative we include y_{mn} ,

where y_{mn} is a binary variable that takes on a value of 1 when alternative m for component n is chosen, and is 0 otherwise.

$$TS_{mn} = y_{mn}(k_n^{env} E_{mn} + k_n^{soc} S_{mn} - k_n^{econ} c'_{mn})$$

(4)

$$\sum_{m} y_{mn} = 1$$

(5)

(High environmental and social scores are preferable with low economic cost which is why the first two terms are added and the last is subtracted.)

The set of y_{mn} indicate to the decision maker which alternative has been chosen for which component. There will likely be constraints on the total budgets and limits on operating costs.

Combining the decision variable y_{mn} with the fixed cost f_{mn} would give us the set of fixed costs which will be incurred in completing the chosen alternatives for all the components. The sum of these can be constrained to be less than or equal to the allowed budget, B.

$$\sum_{mn}(y_{mn} * fc_{mn}) \le B \tag{6}$$

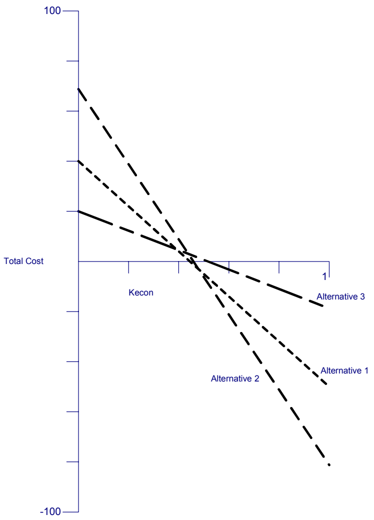
Similarly, the annual operating costs can be constrained to their limit OC

$$\sum_{mn}(y_{mn} * o_{mn}) \le OC \tag{7}$$

The objective function becomes

$$\max \sum_{n} TS_{mn} \tag{8}$$

Once the choices of alternative for each component have been made, then the decision maker can evaluate how changes to the values of k_n^{econ}, k_n^{env} and k_n^{soc} affect the alternatives chosen. He could raise one weighting factor while lowering another and looking at the new set of alternatives chosen and the new total score



Alternatively, the relationships between k_n^{econ}, k_n^{env} and k_n^{soc} for each n can be determined. This will be easier to describe and visualize in a two-dimensional case. If there were three alternatives for equipment n, alternative 1 has c' of 50 and E of 40; alternative 2 has c' of 80 and E of 70 and alternative 3 with c' of 20 and E of 20. If only k_n^{econ} and k_n^{env} were being considered, there would exist the following relationships. If $k_n^{econ} + k_n^{env} = 1$, then $k_n^{env} = 1 - k_n^{econ}$. So the total score of alternatives 1, 2 and 3 are:

$$TC_1 = 40(1 - k^{econ}) - 50k^{econ}$$

$$TC_2 = 70(1 - k^{econ}) - 80k^{econ}$$

$$TC_3 = 20(1 - k^{econ}) - 20k^{econ}$$

Graphically, as k^{econ} ranges from 0 to 1, we obtain the following graph. When k^{econ} is less than about .44, it can be seen that Alternative 2 dominates. When k^{econ} is greater than .44, alternative 3 dominates. In three dimensions a set of surfaces would be derived that would show the dominant solution based on the choice of k_n^{econ}, k_n^{env} and k_n^{soc}.

5. An Illustrative Example

Consider the case of four components and alternatives *a* through *f.* Not each alternative is possible for each component. Table 1 lists the fours components and the available alternatives.

Table 1: Components and Alternatives

	a	b	c	d	e	f
1	X	X	X			
2		X	X	X		

3			X		X	
4		X	X		X	X

As discussed earlier, each alternative has a fixed cost and operating cost which are shown in Tables 2 and 3

Table 2: Fixed Costs

	a	**b**	**c**	**d**	**e**	**f**
1	150,000	200,000	300,000			
2		75,000	90,000	110,000		
3			100,000		140,000	
4		20,000	30,000		25,000	15,000

Table 3: Operating Costs

	a	**b**	**c**	**d**	**e**	**f**
1	50,000	40,000	35,000			
2		75,000	60,000	72,000		
3	X		25,000		45,000	
4		10,000	15,000		25,000	35,000

Each alternative also has environmental and social scores listed in Tables 4 and 5.

Table 4: Environmental Scores

	a	**b**	**c**	**d**	**e**	**f**
1	55	40	66			
2		55	74	42		
3			40		77	
4		56	45		43	23

Table 5: Social Scores

	a	**b**	**c**	**d**	**e**	**f**
1	40	40	65			
2		40	50	60		
3			56		54	
4		45	65		56	45

This example has two budget constraints. The sum of the fixed costs for the alternatives chosen can not exceed \$150,000 and cannot exceed an operating cost of \$550,000. The decision maker selects k_n^{econ}, k_n^{env} and k_n^{soc} to be 0.4, 0.4 and 0.2, respectively, placing priority on economic and environmental concerns and less on social. The optimization selects alternative *a* for component 1, alternative *d* for components 2 and 3 and alternative *c* for component 4, which costs $145,000 in fixed costs and $360,000 in operating costs and an objective value of 20.33. The decision maker wonders how changing the values of k_n^{econ}, k_n^{env} and k_n^{soc} affect the alternatives chosen. Changing them to .3, .5 and .2 places greater emphasis on a more environmentally sound set of alternatives. However, this results in the same set of alternatives, with the same fixed and operating costs and an objective value of 69.79. Changing k_n^{econ}, k_n^{env} and k_n^{soc} to .2, .6 and .2 results in a new set of alternatives to be preferable. Now, the set of choices is alternative *c* for components 1 and 2, alternative *e* for component 3 and alternative *b* for component 4 and an objective value of 138.12.

When the selection of alternatives for a set of components is complete, the vulnerability analysis can be completed. As noted in our previous work (Lee et al. 2004), redundancy cannot be assured without looking across the complete set of infrastructure systems with special consideration to the interdependencies among them. Once the set of alternatives are chosen, they must map the present and proposed infrastructure system with its associated (interdependent) infrastructure systems. Each of the interdependencies is then identified (if they exist) and the procedures presented in Lee, Mitchell and Wallace (2004) followed to assure vulnerability has in fact been reduced and new vulnerabilities have not been introduced. If one or more of the alternatives is found during the analysis based on interdependencies, to not have reduced the vulnerability as expected, the set of alternatives from the sustainability analysis can be revisited and one or more alternatives selected. The result will be a set of alternatives that both reduces vulnerability of a civil infrastructure system and increases its sustainability.

6. Concluding Remarks

We have proposed a procedure for conducting vulnerability analyses that incorporates sustainability. The first step is for the management of each infrastructure to analyze their system and select the set of vulnerable components. They must next propose a set of cost alternatives that can reduce the vulnerability of each component. With these data as input, they would conduct the sustainability analysis described in Section 4, resulting in a set of alternatives for reducing vulnerability and increasing the sustainability of the components in the civil infrastructure system(s) being analyzed.

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