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STRATEGIC PLANNER INTEGRATING REGIONAL INFRASTRUCTURE TECHNOLOGY (SPIRIT)

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GENERAL ATOMICS

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1. INTRODUCTION

The world's infrastructure systems have evolved from isolated pockets of technology to interdependent networks spanning continents. Meanwhile, the global population has continued to concentrate into dense clusters near urban industrial centers. These populations depend on the support infrastructures that are straining to keep up with demand for energy, water, communications etc. Disruption of the support infrastructure, through natural or man-made disasters, can initiate complex reactions that have been difficult to predict and understand.

2. PROBLEM SPACE

Homeland Security efforts have traditionally focused on procurement of first responders' equipment and command and control systems. This has continued the reactive, response oriented methods shown to be ineffective in the large scale disasters of the recent past. To rise above the reaction process to the level of prediction and prevention will require systematic research and analysis. To date, infrastructure analysis, predictive modeling and planning for disaster impacts are largely academic studies with little operational relevancy.

Hindsight has shown that broad predictions and warnings of damage from natural and man-made disasters have not prepared local planners and emergency managers to protect their local populations. The events throughout the Hurricane Katrina disaster illustrate the importance of preparation and effective response. Federal, state and local officials tracked the hurricane for days prior to arrival. All the responsible officials were informed 56 hours prior to the initial landfall [1], but this highly accurate information did not result in any unified execution of plans. Instead, there was a series of uncoordinated and ineffective actions (and *inactions*) that failed to protect and restore from the storm's immediate and subsequent effects. An operational process is needed whereby local planners, first responders, and emergency managers can understand and predict the impact of regional infrastructure failures.

3. HYPOTHESIS

Emergency management officials will make better decisions if an in-depth assessment is made of regional infrastructures, resulting in prediction of initial and subsequent, cascading effects of infrastructure failures. For example, a regional emergency manager is faced with an explosion at a water treatment plant. The immediate reaction is to rescue and transport the injured victims to the nearest hospital trauma center. However, the missing information for the emergency manager is which hospitals are impacted by the loss of the water treatment plant. Taking victims to a hospital impacted by the water treatment plant sets up a new crisis when the hospital exhausts its backup water supply and patients must be evacuated. This case shows the effects of interdependencies of infrastructure (the hospital function depends on the supply of water), and how better situational awareness of these relationships can help the emergency manager to make informed decisions. Better information could lead the emergency manager to possibly stop the cascade of failure by proactive actions, such as deploying water tankers to the hospital or using a trauma center in a non-impacted area. Analysis and prediction of a disaster's extended impacts, like the loss of a water system, can be tested in drills and exercises, and then be proactively included into policies and doctrines.

A formalized infrastructure analysis process would enhance disaster preparation several ways. The regional planner can assess his infrastructure and lobby for improvements with analytical evidence. The operation center staffs and first responder teams can train with realistic scenarios based on their infrastructure, and the emergency manager can predict the immediate and the impending repercussions during disasters.

4. APPROACH

To establish a standard terminology, some terms first need definition. An *asset* will indicate a specific facility, like an electrical substation, a water treatment plant, a fuel pipeline, a bridge, or a hospital. A group of assets that combine to deliver a collective support service is called a *segment*. Fire Stations, police, ambulance services, and HAZMAT teams are assets that combine to form the First Responders segment. The Department of Homeland Security (DHS) has divided Critical Infrastructures (CI) into thirteen segments, e.g., Energy, Water, Telecommunications, etc. Other segments include Public Health, Waste Water Treatment, and Transportation. Finally, the segments combine to form the CI *System*. The study of the interlocking mesh of these segments comprises CI System Interdependencies analysis.

Numerous reports have been written on how CI should be studied and protected [2]. While DHS has devised separate study groups for each segment, the efforts to assess the interdependencies of each segment as a system have produced generalized papers that address large-scale issues like the effects on national economy and consumer prices.

The Strategic Planner Integrating Regional Infrastructure Technology (SPIRIT) consolidates disparate data, implements NIMS compliant policies, overlays existing infrastructure data onto a geospatial display, and provides a user-friendly, “Video game,” interface to model and analyze potential impacts of natural disaster or terrorist attack for emergency planning and real time response.

The SPIRIT process uses a three-part analysis to resolve these issues.[1]

4.1. SEGMENT ANALYSIS

SPIRIT’s first step is to analyze each infrastructure segment to identify the nodes critical to its “mission.” A segment’s mission is the operational benefit derived from the segment and its collection of assets. For example, the mission of an electrical transmission system is to move electric power from a generating station to distant substations for local distribution to electrical consumers. Not all segments are created equal; two electrical transmission segments may be comprised of identical assets, but may serve vastly different population and industry concentrations. Likewise, differing perspectives and scope of assessments may yield disparate results; a small town may depend directly on a power station that is not a significant asset when viewed from across an entire region.

Segment Specific Assets (SSAs) are assessed for criticality using Density, Capacity, and Structural analysis methods [3], and are assigned ratings of “Mission Compromised,” “Mission Devalued,” or “Mission Uncompromised” status, and are correspondingly colored red, yellow, or green. The rating of an SSA indicates its importance, and the likely impact of

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[1] SPIRIT methodologies and analysis are proprietary to General Atomics Corp.

its loss to the segment's mission. For example, loss of a water treatment plant rated as Mission Compromised will prevent the water segment from achieving its mission of delivering potable water.

Figure 1 illustrates a low resolution functional view of an electrical segment. Symbols used for generation sources are squares, transmission circuits are lines, and substations are triangles. Objects colored black are not listed as critical assets, though they may connect objects that are critical.

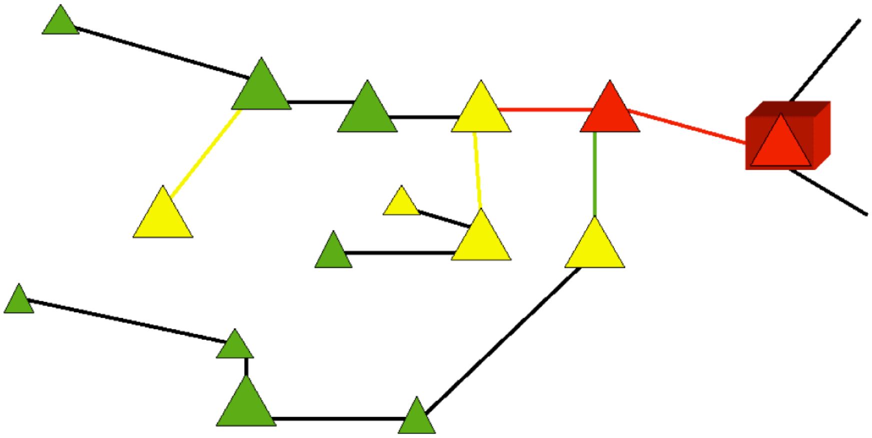

Fig. 1. A functional view of an electrical segment.

The criticality of each SSA is derived by structural and capacity analysis. The power source, its principle transmission circuits and substations are ranked Mission Compromised and Mission Devalued and colored red or yellow. Less critical, but still important assets are ranked as Mission Uncompromised (green).

Figure 1 provides valuable information about the function and hierarchy within the segment and can be used for an analysis of power systems and current flow. But this view does not address spatial or *whole system*-wide relevance of the electrical segment. This view is too narrow for an emergency manager to draw upon for decisions. More analysis is needed to show the spatial relevance of the electrical segment and how that segment affects the whole system infrastructure.

In Fig. 2, these segments are overlaid onto a Geospatial Information System (GIS). This has two advantages; first, a geographic rendering of multiple segments closely shows their interdependencies due to proximity. Additionally, a common map representation brings life to the cold numbers and names onto a specific area with real people and real consequences to hospitals, school and homes. Figure 2 exhibits a part of the electrical segment superimposed on a geospatial image of its urban location.

Figure 2 brings to light some of the details of the electrical system, like the effects of terrain and urban density on the design and architecture of the electrical grid. Some initial indications are evident of the relative locations of substations and large-scale customer loads, but other segments are not included, so this view falls short of a fully representative system depiction.

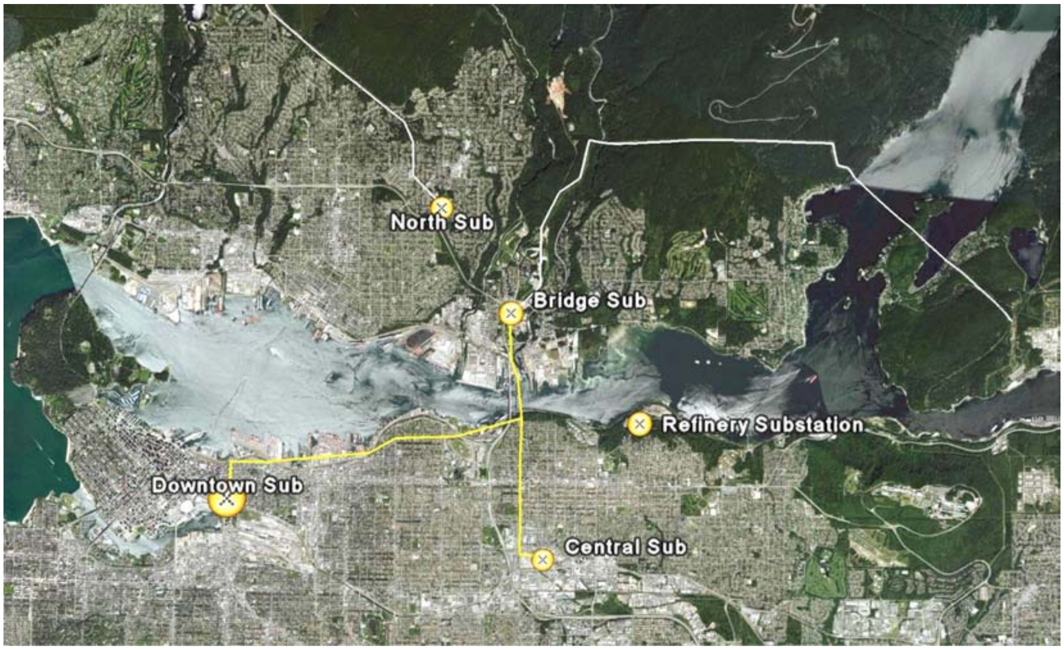

Fig. 2. Single-segment infrastructure geospatial view.

4.2. SYSTEM ANALYSIS

To illustrate the second phase of SPIRIT analysis, Fig. 3 is a small scale example of a whole-system view. The colored backgrounds show the areas, or zones, supplied by specific infrastructure segments (in this case, an electrical substation). Within each zone, icons mark the major CI locations. Local first responder stations, hospitals, transportation hubs and important economic sites are indicated.[2] When available, the locations and right-of-ways used for electricity transmission circuits, gas, water, and petrol pipelines are drawn. Zones can also be drawn for water systems, telecommunication networks, natural gas, and other segments.

Within this view, the zone supplied by the Downtown Substation is highlighted making interrelationships of infrastructure better understood. The water and waste water treatment segments, the health segment, fuel pipeline, and the first responders are shown to depend on a single primary source for electrical power. If a casualty to the Downtown Substation interrupted electrical service in this zone, reference to this view would reveal the neighborhoods and support services impacted.

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[2] All data for this paper was drawn from open sources.

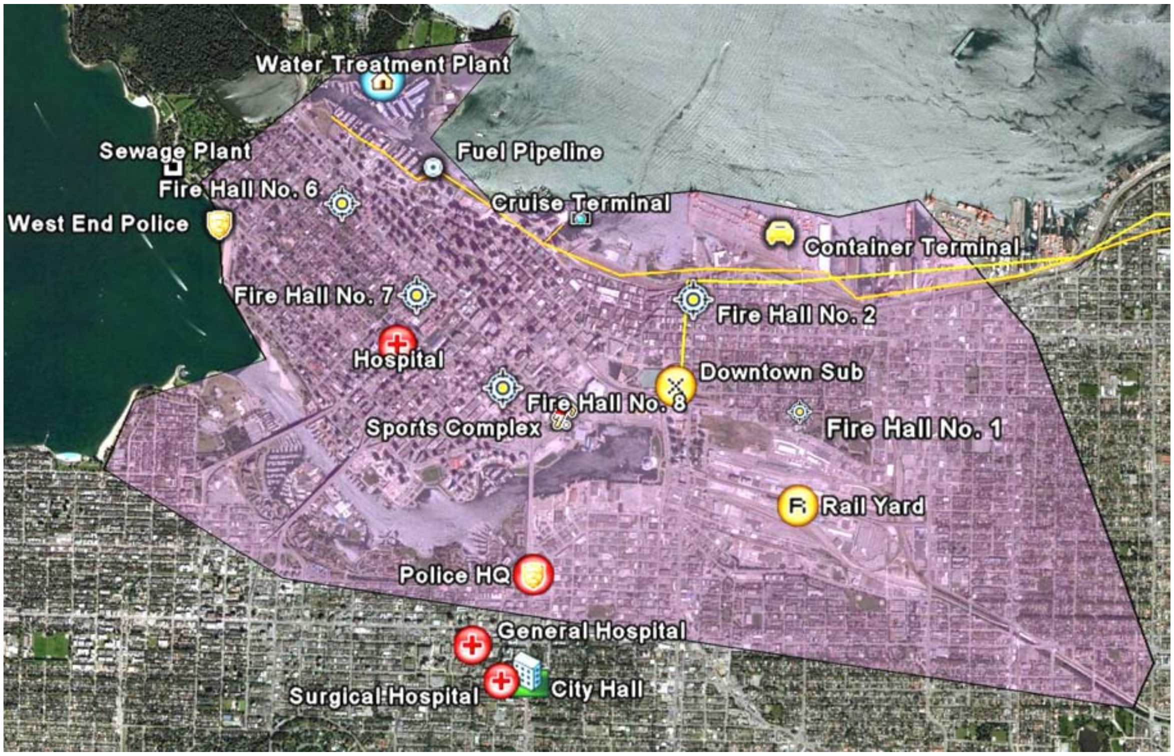


Fig. 3. Whole system view.

This event would present the emergency manager with several challenges; how to communicate to first responders, continuity of hospital operations, and traffic management are only a start. This view gives the emergency manager a strong indication of the area immediately impacted, but this is only the surface layer of several deeper issues.

Combining the research of each individual segment with the geospatial layout of the segments is only part of the solution. The SPIRIT process then analyzes the interdependencies of the CI system and summarizes the effects in a meshed, cause-and-effect matrix (see Table 1). This summary of only a few segments shows that interruption of one segment can have severe consequences across the system.

Some of these segment interrelationships are intuitive. Water pumps need electricity to operate, and transportation requires fuel to operate vehicles. Others may require some reflection, like the need for water for fuel processing.

Some segments, like fuels and electricity, are mutually dependent. In the metropolitan area studied, half of the electricity is produced from power plants that burn natural gas. Conversely, electricity is needed to compress and transport natural gas over the lengthy pipelines from source to customer (in this case, the power plant). Loss of one segment over a large area may interrupt support from the other. Similar matrices can be drawn for other segment failures.

Table 1
Interdependency Matrix

Rows Depend on Columns	**Electricity**	**Fuels**	**Water**	**Waste**	**Public Health**	**Transport**
Electricity	X	Power plant fuel	Hydroelectric, coolant	NA	NA	Parts and fuel deliveries,
Fuels (Petrol)	Pumps, processing	X	Water for refining process	NA	NA	Pipelines, local trucking
Water	Pumps, processing	Fuel for emergency generators	X	Some grey water supplies	Testing and certification	Pipelines, chemical deliveries
Waste	Pumps, processing	Fuel for emergency generators	Water for processing	X	Testing and certification	Pipelines
Public Health	Operation of hospitals, medicine storage	Fuel for emergency generators and vehicles	Water for drinking, cleaning and sterilizing	Testing and certification	X	Emergency services, evacuations
Transport	Traffic signals and controls	Fuel for vehicles and aircraft	NA	NA	NA	X

Returning to the emergency manager's problems once more, the interdependencies briefly outlined in Table 1 will quickly add more disruptions to be addressed. The loss of a key segment (electricity in this case) can lead to subsequent, *cascading* casualties across the entire infrastructure system. The challenge for the emergency manager is to identify current and impending casualties, allocate resources and take proactive steps based on some situation-relevant prioritization. This is a key aspect of disaster management that has not gone well in the past.

Table 1 is an instantiation of the effects of an event, or a series of events comprising a major disaster, but is merely a snapshot in time, and time is a crucial factor. With a few exceptions, disasters do not have discrete start and end points. Rather, there are recognizable timelines associated with nearly every disaster. This is also true of the many individual infrastructure failures that comprise the larger disaster. The emergency manager must have available reasonable representations of these timelines to manage his resources effectively. Table 2 summarizes the timelines associated with infrastructure failures.

Table 2 makes clear the importance of interdependency and time. The initial impacts of lost electricity on this shortened list of segments are lessened by emergency generators that are often installed in major facilities like hospitals and larger water treatment plants. But these generators may offer a false sense of security (see Appendix).

Table 2
Infrastructure Failure Timelines
Event: Electrical Failure

Segment	Initial Impact	Extended Impact	Time to Ex. Impact
Electricity	Loss of electricity, emergency generators start	Generators fail (mechanical failure or fuel exhaustion)	6-12 hr
Fuels (petrol)	Pipelines stop deliveries, service station pumps fail	Fuel shortage	6 hr
Water	Pumps and treatment fail	Potable water shortage	6 hr
Waste water	Pumps and treatment fail	Sewage back ups and spills-health issues	2 hr
Public health	Backup systems at hospitals can minimize impact	No water: no sterilization No fuel: generator fails No waste: public health issues	1-3 days
Transport	Traffic jams	Loss of air traffic control, significant transport delays	6 hr

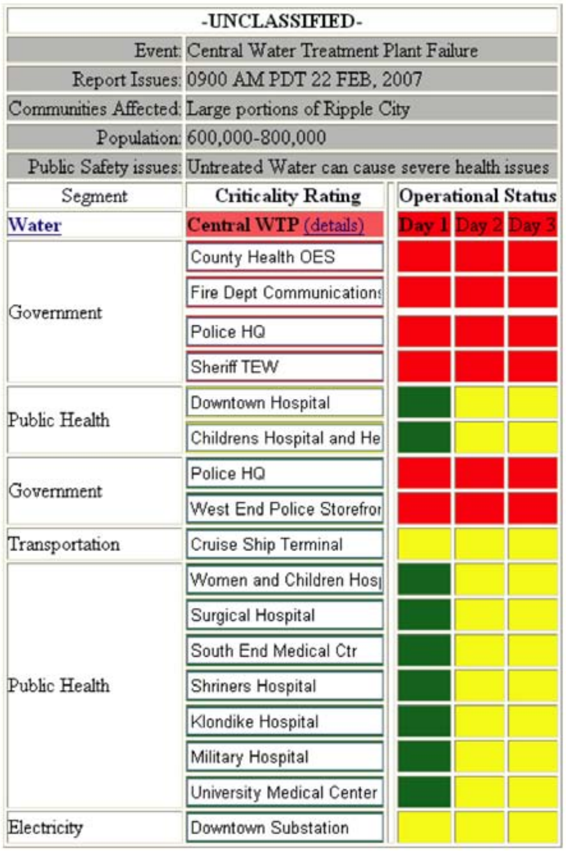
4.3. TIME-DEPENDENCY ANALYSIS

The third phase of the SPIRIT process uses data similar to that in Table 1 to *predict* infrastructure failures based on some generalized interdependencies, and many region-specific details, input to relational models. The SPIRIT process then uses time-dependencies like those shown in Table 2 to identify the most pressing, *most critical* issues. This analysis identifies and critically ranks the main infrastructure, *whole system* nodes.

Criticality, and thus priority, is shown as a function of time to reflect the eventual failure or depletion of backup systems. This provides a time-phased prediction list, from which the emergency manager can work to forestall impending casualties, and actually get ahead of sequential cascading failures.

While the mission criticality of an SSA can be assigned, and for all intents is a static rating, the actual time-dependent effects of cascading casualties can change the Operational Status of the SSA in predictable ways. The complex process of prediction results in a scheme that is simplified for ease of visualization and use. The Operational Status of an asset is classified as Operations Failed if it is incapable of performing its mission. Similar ratings of Operations Impaired and Operations Uncompromised respectively indicate assets running in temporary support or assets that are unaffected.

Figure 4 is just one approach to represent the whole system status in a manageable format. It incorporates the important information in an organized, prioritized, time-phased structure.



-UNCLASSIFIED-				
Event:	Central Water Treatment Plant Failure			
Report Issues:	0900 AM PDT 22 FEB, 2007			
Communities Affected:	Large portions of Ripple City			
Population:	600,000-800,000			
Public Safety issues:	Untreated Water can cause severe health issues			
Segment	Criticality Rating	Operational Status		
Water	Central WTP (details)	Day 1	Day 2	Day 3
Government	County Health OES	🟥	🟥	🟥
	Fire Dept Communication	🟥	🟥	🟥
	Police HQ	🟥	🟥	🟥
	Sheriff TEW	🟥	🟥	🟥
Public Health	Downtown Hospital	🟩	🟨	🟨
	Childrens Hospital and He	🟩	🟨	🟨
Government	Police HQ	🟥	🟥	🟥
	West End Police Storefro	🟥	🟥	🟥
Transportation	Cruise Ship Terminal	🟨	🟨	🟨
Public Health	Women and Children Hos	🟩	🟨	🟨
	Surgical Hospital	🟩	🟨	🟨
	South End Medical Ctr	🟩	🟨	🟨
	Shriners Hospital	🟩	🟨	🟨
	Klondike Hospital	🟩	🟨	🟨
	Military Hospital	🟩	🟨	🟨
	University Medical Center	🟩	🟨	🟨
Electricity	Downtown Substation	🟨	🟨	🟨

Fig. 4. Time-criticality view.

Figure 4 is a condensed report of the effects of an event (loss of a primary water treatment plant) and its impacts across the other segments in the CI system. The segments are listed in the left column, with their component SSAs in the center and each listed SSA's mission criticality indicated by the colored border surrounding the SSA's title. The right-most header lists the Operational Status for each SSA, over a three-day period. The immediate effects of losing the water treatment plant are listed in the first column labeled "Day 1." Subsequent, cascading effects on Operational Status are listed in the "Day 2" and "Day 3" columns.

A scan of the Time-Criticality view in Fig. 4 would show that the Government Sector has been rendered inoperative (the Operations Status is red), while the Public Health Segment will continue to function normally until Day 2, when the hospitals will shift to an Operations Impaired status (green shifts to yellow on Day 2). With this report, the emergency manager has a snapshot of the immediate and impending effects of the loss of a key infrastructure asset. The emergency manager can now take action to restore the initial casualty and take steps to prevent or mitigate the cascading failures.

5. INFRASTRUCTURE ANALYSIS AND OPERATIONS

Many local and regional emergency command centers have invested in expensive command and control systems. These systems typically display the real-time Global Positioning Satellite (GPS) coordinates of first responder units overlain onto GIS displays. The command centers are usually well equipped with communications and computer equipment. These command centers have improved the speed and confidence of disaster reaction and control.

In addition to local government officials and first responder leadership, the command center also hosts local utilities engineers to provide expertise on their respective infrastructures. These representatives provide data on the status of segment damage and answer questions about capabilities and repair efforts.

The weakness of this system is while each engineer is a subject matter expert in his segment, it is unlikely that this group trains together as a unit, or exchanges enough data to form their own interdependency matrix. A water district representative will likely know everything about his water processing and distribution system, but informal research has shown that he will not know much about the electrical substation his district depends on, or the point of origin for his repair parts.

The next evolutionary step for the emergency command center is a map overlay system that can superimpose the critical infrastructure zones (Fig. 3) over the operational, real time GIS plot. With this, the emergency manager can visualize the growing threat of fire or flood, potential infrastructure loses, and locations of first responders that may be affected. This information view can be augmented with the deeper time-dependency analysis of the affected segments and zones to show the consequences of the impending damage. Armed with this, the emergency manager can make highly informed decisions and proactively mitigate the consequences. The command center is no longer reacting, it is now *predicting* and *preventing*.

6. INFRASTRUCTURE ANALYSIS AND TRAINING

Because of indefinite goals and obscure metrics for success, disaster planning has always been an abstract subject. Two important aspects of disaster planning are training and policy development.

Training particularly applies to first responder teams and emergency command center staffs. These training programs have historically addressed the skills the individual fire, police, HAZMAT and medical teams require. An example would be fighting an isolated warehouse fire with all support services intact. This is a useful drill for development of frontline skills, but it is does not reflect the chaotic conditions that will accompany a large scale disaster.

For a higher level of realism, responders and command centers should address whole system effects.

An example scenario: an earthquake or industrial accident has eliminated water pressure and ruptured gas mains over a large area, followed by the same warehouse fire. This scenario can be made more credible through the structured analysis of the actual water and gas grids in the community. This approach can generate realistic scenarios for table top discussions and large scale drills.

By “Video gaming,” or the exploration of cause-and-effect failures through structured analysis, the time-phased repercussions of an event can be spelled out for constructive discussion and policy analysis. Cross-jurisdictional coordination can also be strengthened through table top exercises of cascading failures and subsequent analysis of mutual support agreements and system-wide operational doctrine.

Use of a structured analysis process can standardize situational reporting procedures and can vastly improve the preparation and situational awareness of rescue and assistance teams arriving from outside the area.

7. INFRASTRUCTURE ANALYSIS AND PLANNING

Specific funds have been allocated to harden public transportation, establish buffer zones around chemical plants, and to procure new fire fighting equipment. These enhancements are helpful, but ultimately serve to perpetuate the culture of reaction, and contribute little for preparation and planning. The inexact art of planning and prediction must improve to direct funds to the most important projects.

It has been delegated to the states, counties, and cities to argue for their share of security funding. To improve the chance of support, a regional planner's funding proposal should include a sound cost benefit analysis. In addition to the obligatory graphs and charts, a Time-Dependency analysis of the infrastructure system can add significant value to the proposal package. The benefit of the requested improvements can then be shown by altering the values used to compute asset criticality, and comparing the results of successive Time-Dependency analyses.

By bolstering planning with sound analysis, real infrastructure resiliency can be measured and qualitatively improved. For example, a telecommunications data center for an urban economic zone can be made more resilient with the establishment of an added fiber optic pathway and backup storage networks. With proper modeling, the benefits of resiliency could be demonstrated for inclusion to the funding proposal. The risk of lost telecommunications, possibly caused by cascading damage to a right-of-way or a major facility fire, can then be minimized, and the cascade cycle can be cut short. Another example could be funding for an emergency medical helicopter service, which would also benefit the region long before any disaster strikes.

SUMMARY

Preparation efforts for unpredictable disasters are poorly understood and poorly supported. To augment the steady stream of funding spent for new fire hoses and conference phones, some capability must be developed to assess major infrastructure systems. Prediction of the patterns in which events may combine to interrupt or destroy the critical support services will add valuable direction and balance to planning and prevention. Assessment of static relationships between infrastructure segments is only a start; what must be achieved is a flexible representation of the time-relevant interdependencies that drive the sequential failures of critical infrastructure.

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[3] S. Gorman "A Methodology for Critical Infrastructure Resiliency," *Homeland Security Advisory Council, Report of the Critical Infrastructure Task Force* (2006) p. 23. http://www.dhs.gov/xlibrary/assets/HSAC_CITF_Report_v2.pdf

ACKNOWLEDGMENT

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APPENDIX
GENERATORS

The typical generator set is a diesel engine coupled to a 1.5–2 megawatt ac generator, with a fuel tank capacity for 12 hr of operation. The electrical circuitry of the system will automatically start the generator when voltage to the supported facility drops toward a blackout level.

Research indicates that generators may not be a fool-proof backup. Studies have shown that even fully maintained and supported generator systems fail at the rate of 15% after less than a day of operation [Ap-1]. There are several possible reasons for this. First, startup circuitry may not be effective, so the generator may never be "commanded" to start. Also, emergency generators are seldom started, run, *and loaded* with the power demand for the facility supported.

This is a significant shortfall in regular maintenance and reliability testing, analogous to idling a high performance sports car, but never running it at high speed. Without a test of real performance, there is no guarantee that the generator system is capable sustaining and maintaining high power output.

Finally, once a generator successfully starts and carries the electrical load for its facility, it will run on the limited fuel supply in its tank. Length of the generator's operation is not just an issue of the fuel tank capacity, but more an issue of the fuel volume actually *present in the tank*.

Referring back to Table 2, it becomes apparent that a major challenge for an emergency manager is to replenish fuel tanks for emergency generators to forestall complete infrastructure collapse.

[Ap-1] T. Leonidas, Jr., "Restoring Reliability to Emergency Power Systems," Maintenance Solutions (2006). http://www.facilitiesnet.com/ms/article.asp?id=4325.