

## DECISION TECHNOLOGIES FOR PROTECTION OF CRITICAL INFRASTRUCTURES

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## ABSTRACT

*The goal of our effort is to eliminate or reduce the impact of a disruption to our critical infrastructures by protecting the quality of the services they provide. Decision technology supports those responsible for achieving this by:*

- *Quantifying the degradation of services provided by all the systems when one or more component of any system is damaged or destroyed.*
- *Evaluating alternative means to reduce or eliminate the impact caused by an incident.*

*The Interdependent Layered Network (ILN) mathematical model was developed with the support of the National Science Foundation. The ILN model has been embedded in a prototype decision support system, MUNICIPAL, the Multi-Network Interdependent Critical Infrastructure Program for Analysis of Lifelines, to support the design and assessment of protection strategies including:*

- *identifying key elements to reduce the impact.*
- *determining what levels of effort are required to restore service.*
- *designing alternative paths to reduce vulnerability.*
- *determining where to site emergency response resources to rapidly restore services after a disruption.*

*MUNICIPAL supports response and restoration following disruptions, facilitates analysis of threat scenarios and supports emergency preparation and training activities. Research has shown that MUNICIPAL can be used to identify vulnerability, taking interdependency into account, and suggest alternative strategies for protection of infrastructure systems. Data on the lifeline systems for the southern portion of Manhattan and the impact area of the Northridge earthquake are being used to assess the model.*

*This paper will discuss the research needed to develop the ILN model and MUNICIPAL, the decision support system. It will then discuss the components of MUNICIPAL and how it can be used for system design, vulnerability analysis and restoration following a disruption.*

## INTRODUCTION

Americans enjoy their current lifestyle because of the operations and complex interactions of a set of human-built systems and processes. These systems include transportation, electric power, gas and liquid fuels, telecommunications, wastewater facilities and water supplies. This set of civil infrastructure systems has also been included in the broader set of critical infrastructures defined by the USA Patriot Act of 2001 [1]. In the Patriot Act, critical infrastructures are those

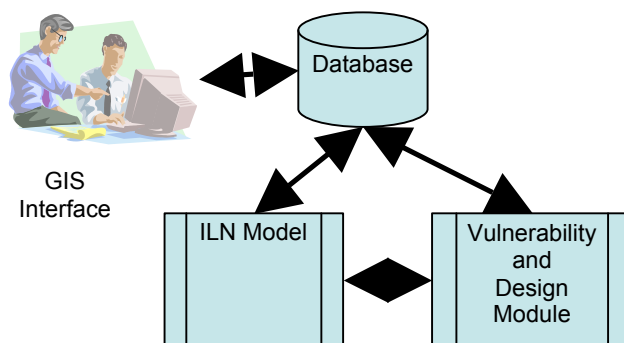
*“systems and assets, whether physical or virtual, so vital to the United States that the incapacity or destruction of such would have a debilitating impact on security, national economic security, national public health or safety or any combination of these matters [1]).”*

This research will focus on the interconnectedness of these systems.

Each of these systems has evolved independently. However as technology has advanced, the systems have become interconnected. The reliance of any of these systems on power is obvious. Failures, by whatever cause, within the communications networks in one locale may have far-reaching effects across many systems. This is specifically noted in *The National Strategy for the Physical Protection of Critical Infrastructures and Key Assets* [2] (referred to later as the “National Strategy”).

As recognized by the *National Strategy*, many emergency managers fail to recognize this “interconnectedness” or interdependence of infrastructures in responding to an incident. Infrastructure management systems did not allow a manager of one system to “see” the operations and conditions of another system. This research provides a “system of systems” view to better understand the interdependent nature of these systems with respect to mitigation and post-disruption response and recovery.

This research has developed a formal, mathematical representation of the set of civil infrastructure systems that explicitly incorporates the interdependencies among them and is called the Interdependent Layered Network (ILN) model. The ILN is a mixed-integer, network-flow based model which has been implemented in software that enables the resulting model to be exercised. The ILN is embedded in a prototype decision support system, the Multi-Network Interdependent Critical Infrastructure Program for Analysis of Lifelines (MUNICIPAL), the subject of this paper. MUNICIPAL consists of a geographic information system (GIS) interface for the user, a database with the attributes of the set of infrastructures, the ILN module, and the vulnerability module.



**Figure 1**

MUNICIPAL provides the capability to understand how a disruptive event affects the interdependent set of civil infrastructures. This capability improves society's ability to withstand the impact of and respond to events that can disrupt the provision of services that are required for the health, safety and economic well being of its citizens. Managers of infrastructure systems will be able to assess the vulnerability of their own system due to its reliance on other systems. Organizations responsible for coordinating emergency response efforts will also be able to model different event scenarios and assess their impact across the full set of systems and the services they provide. With this broader perspective of impact, mitigation and preparedness strategies can be formulated and evaluated for their ability to reduce their effects on society.

The model is not based upon a unique configuration of infrastructures, but is generic and therefore, applicable to more than one location. It is also not specific to a particular type of event, such as an earthquake or hurricane. The only requirements are that the event is possible but unpredictable, the event is of sudden onset, and the event causes damage to the physical components of the infrastructure system.

The intended use of MUNICIPAL was for response and restoration efforts following a disruptive event and as a training tool for personnel who would be guiding response and restoration efforts. As the research progressed, MUNICIPAL was found to be useful in supporting system design, in assessing the vulnerability of a system, in measuring the benefits of pre-staging resources or installing backup power systems and even changing the physical design of the existing systems. This paper will discuss each of the components of MUNICIPAL, with particular emphasis on modeling interdependencies. This research has developed a network flow formulation of interdependent networks which clearly identifies effects of a disruptive event across the set of infrastructure systems. The next section discusses how each of the possible interdependencies was modeled.

### **THE INTERDEPENDENT LAYERED NETWORK (ILN) MODEL**

Following a disruptive event, the first concern of a system manager would be to determine if all demands for service can be met. Based on reports from field observers and experience of system managers, alterations in capabilities of the system components are made. These assessments include operating conditions and capacities. Assessment of new demands must also be made because post-event conditions can result not only in decreases but in increases in demand for services. Examples of increases could include the demand for medical services or volume of telephone calls.

The impact assessment results in a reconfigured network with revised flows for each infrastructure system directly affected by the disruption. Given these revised capacities, supplies, demands and network configuration, the ILN model for this particular system can be run, and a feasible solution would indicate that all demands can be met within system capacity constraints. However, if there is no feasible solution, then there would exist unmet demands for service. This would require the ILN model to be run across the complete set of systems to examine the full impact of this unmet demand.

The objective function of the ILN model incorporates different priorities in addition to modeling interdependencies. On independent nodes, the available supply may be meeting the required demand or there may be some shortfall. This shortfall in meeting demands at independent nodes is referred to as slack. In the model, there is no consideration for partial slack at the interdependent nodes. Because these interdependent nodes control the operation of nodes in other infrastructure systems, if they are not fully operational then they are in a failed condition; there is no benefit to partially meeting the requirement. Following the response phase, when there are unmet demands across one or more systems, one choice for the objective function is to minimize the total cost of flow across all the arcs plus the prioritized shortfall (slack) plus the prioritized, unmet, interdependent demands. Weighting factors will “push” the available resource toward demands which are determined by the system manager to be of higher importance (e.g., meet the requirements of a hospital before meeting the needs of a residential area)

### **Input Dependence**

An infrastructure is input dependent when it requires as input one or more services from another infrastructure in order to provide some other service. As an example, in the case of a telephone switching station, the switching station itself is a transshipment node within the telecommunications network. However, this same switching station from the perspective of the electrical network is seen as a demand node since it needs an adequate source of electricity to operate. This situation may be represented more formally as follows. Denote the demand node for the switching station in the electrical network to be node  $j$ . If there is an adequate flow of electric power into node  $j$ , the switching station can function; otherwise, the switching station fails. A binary variable,  $y$ , is used in this case to represent the two states of the switching station. If adequate power is available at  $j$ , then  $y = 1$ ; if not, then  $y = 0$ . The phone switching station also has some maximum capacity within the telecommunications network. The station’s capacity can be represented as the product of the binary variable  $y$  and the rated capacity. When adequate power is available the station can operate to its rated capacity (since  $y = 1$ ). On the other hand, if adequate power is not available then the capacity of the station is 0. This binary variable  $y$  serves as a virtual connector between the two systems. Its value is set by the conditions existing in one system, and affects the operating characteristics of a second system. Events affecting the power network that have an effect on node  $j$  in turn impact a node in the model of the telecommunications network. The effect on any set of systems can be analyzed in a similar manner. Note that some interdependent infrastructure system failures may result in reducing capacity to some value other than zero. For example, loss of supervisory control systems in a subway system may result in operators exercising greater care and slowing trains. So the post-disruption capacity may be lower than normal. In this case, the connector variable  $y$  would shift from 1 to a lower value.

### **Mutual Dependence**

A collection of infrastructures is said to be mutually dependent if at least one of the activities of one infrastructure system is dependent upon any other infrastructure system and at least one of the activities of this other infrastructure system is dependent upon the first infrastructure system. Consider a natural gas system pump and a gas-fired electric power generator. From the perspective of the natural gas system, the pump is a transshipment node and the generator is a demand node. From the perspective of the electrical network, the generator is a supply node and

the pump is a demand node. The generator needs gas to produce electricity; the pump needs electric power to deliver gas through the system to the generator. Failure of one component causes its corresponding binary variable to be set to zero, thus reducing the effective capacity of the other component to zero. In other words, if the pump were to fail, supply of gas to the generator would be inadequate. If the capacity of the generator is set to zero (since its effective and because the generator is a supply node, all flows on the arcs (i.e., the power lines) leaving the generator would now be zero, by flow conservation. Alternately, a lack of power at the pump demand node in the electrical generating network causes its capacity to be set to zero. To correct this situation, either an alternate source of gas must be found for the generator or an alternate source of power must be found for the pump.

### **Shared (AND) Interdependence**

Shared interdependence occurs when some physical components and/or activities of the infrastructure used in providing the services are shared. Phone lines could be considered in the AND interdependency. Each phone line carries two types of calls, incoming and outgoing. Therefore, each cable section whether it be the connection from a single home to a distribution line or the feeder cable connecting a CEV to a central office, would have some maximum capacity. For example, if the capacity of some section is 50, this could be 50 incoming calls or 50 outgoing calls or some combination totaling 50. This is modeling by limiting the sum of the flows of the various commodities to not exceed the total capacity.

### **Exclusive-or (XOR) Interdependence**

Exclusive-or interdependence occurs when multiple services share infrastructure component(s), but the component can only be used by one service at a time,. In the first few days following the WTC attacks, streets (i.e., shared components) could not be used by both the emergency response personnel and financial district workers. This conflict had to be resolved prior to reopening the New York Stock Exchange [3]. Exclusive-or interdependencies are modeled by selecting additional constraints to restrict flow to one commodity or the other.

### **Co-located Interdependence**

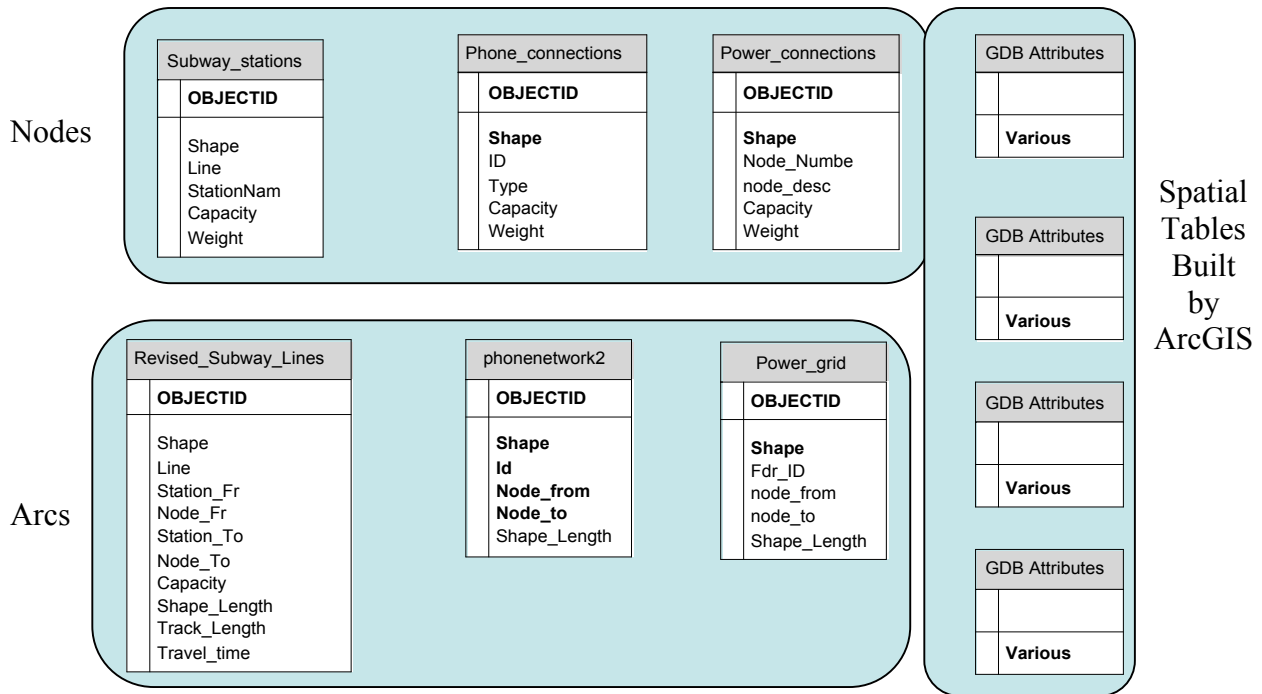
The co-located interdependency occurs when any of the physical components or activities of the civil infrastructure systems are situated within a prescribed geographical region. It was previously noted that managers of individual infrastructure systems would identify the components of their respective system at or near the site of the incident which may have been affected by the event. Based on further investigation, the status of these components will be adjusted. However, since only those emergency response agencies who are responsible for coordinating activities across multiple agencies maintain the complete view of all civil infrastructure systems, it is ultimately their responsibility to ensure that all co-located interdependencies have been considered and the models of the affected infrastructures revised as appropriate.

## **THE USER INTERFACE**

A geographic information system (GIS) was selected as the user interface as this seemed to be the most natural method of displaying systems and determining affected areas. The interface allows the operator to update the conditions of the components of the set of systems modeled, to add temporary systems during restoration and the display areas affected by inability to meet demands.

## THE DATABASE

The database contains the component attributes such as a name, their capacity and their priority, as well as spatial attributes, such as location and length. These spatial characteristics are generated automatically by the GIS software, ESRI's ArcGIS [4] in this case. The remaining attributes are added by the modeler. Changes to attributes due to disruption can easily be made. Some of the tables and attributes are shown in Figure 2. Sample screens from Manhattan and the Los Angeles area are shown as Figures 3 through 8



**Figure 2**

In Manhattan, the goal was to develop highly detailed models in the area south of 60<sup>th</sup> Street of the power, telecommunications and subway systems, three major infrastructure systems impacted by the September 11 attacks. While unable to obtain details on specific components and their locations, Consolidated Edison, Verizon and the Metropolitan Transit Authority were very open in discussing the general construction and operation of their respective systems and have provided feedback during the model's construction.

The subway system includes 115 stations and 338 local and express track sections.

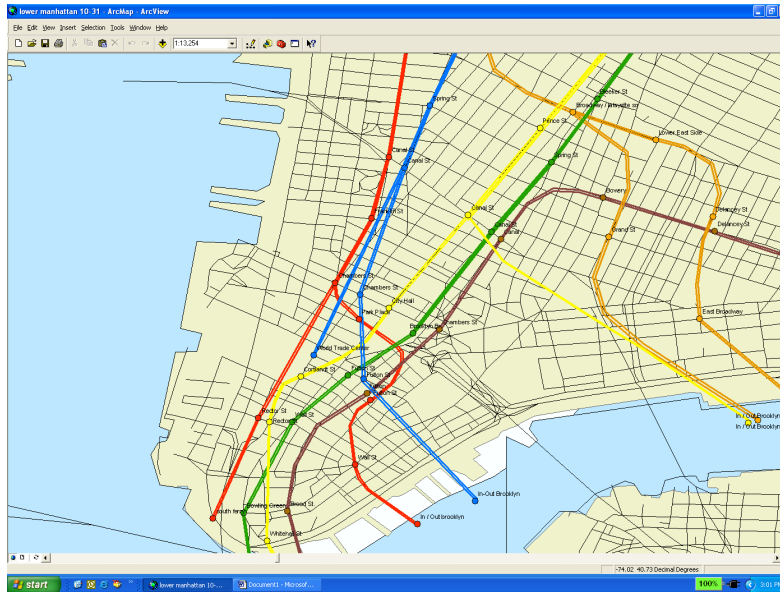


Figure 3

The phone system includes 18 switching centers and their associated service areas, 72 controlled environmental vaults where distribution cables are joined into larger feeder cables and the all the associated wiring. Below Canal St., approximately 500 blocks of phone service were modeled in detail.

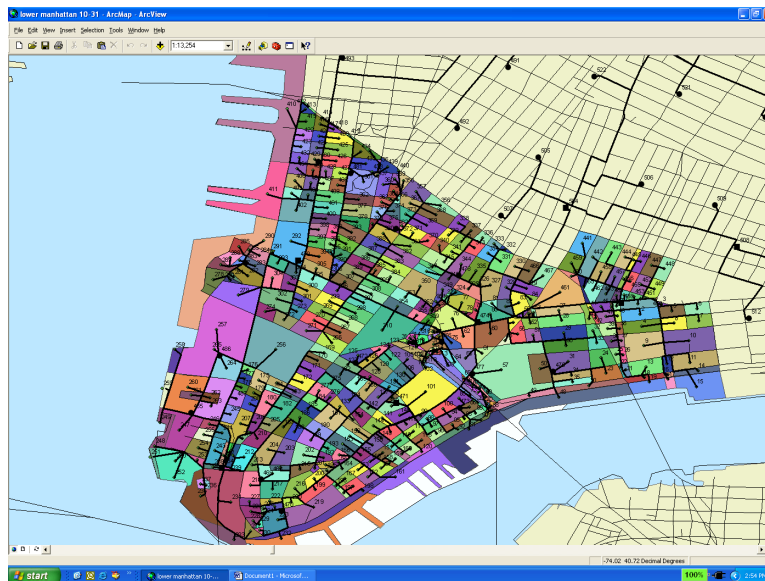
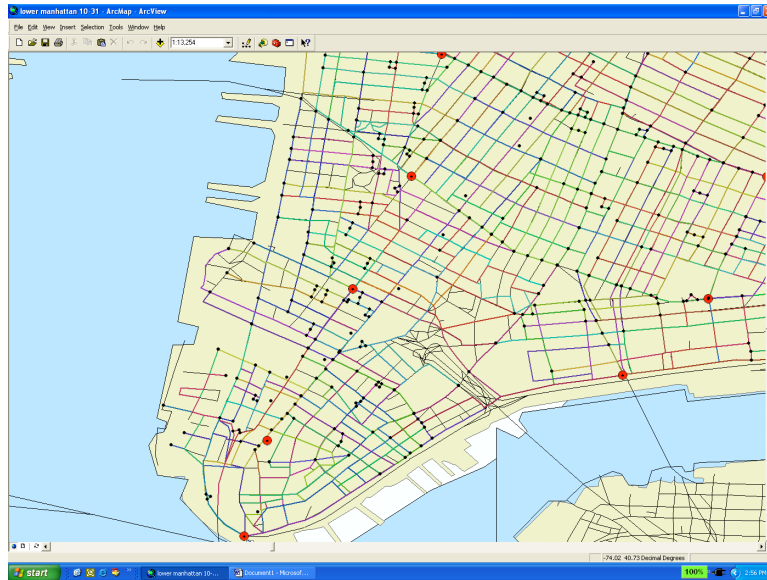


Figure 4

The power system as modeled includes 16 substations and 32 service areas. Each substation distributes power along 8-24 feeders to 18 phone switching centers, 178 AC/DC rectifiers for the subways and service to all residences and businesses in the area.





**Figure 5**

In the Los Angeles Area, the goal is to demonstrate the ability to start with a large geographic area and then provide managers the capability to “zoom” in on specific cities or areas. In a proposed solution which is still being built and tested, the model is built in layers of varying scale and detail. Figure 6 shows approximately 800 square miles of the area surrounding Los Angeles and includes the electrical transmission system. The ILN model would extract the appropriate data from the database. In this case, power substations are the demand nodes. Now, it is desired to focus in on the Burbank area. Figure 7 shows the three substations and their respective service areas which provide power to Burbank. Nodes would be added at the red boundary to be able to compute the flow conditions in and out of the area, based on these three service areas. These boundary values would be used to provide detail conditions inside the city of Burbank shown in Figure 8. In each progressive case, the ILN model would extract the appropriate data from its data base.

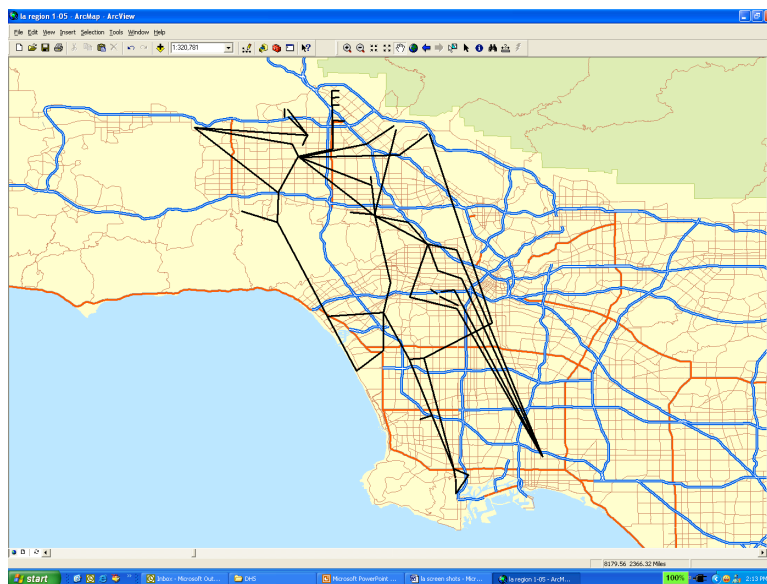


Figure 6

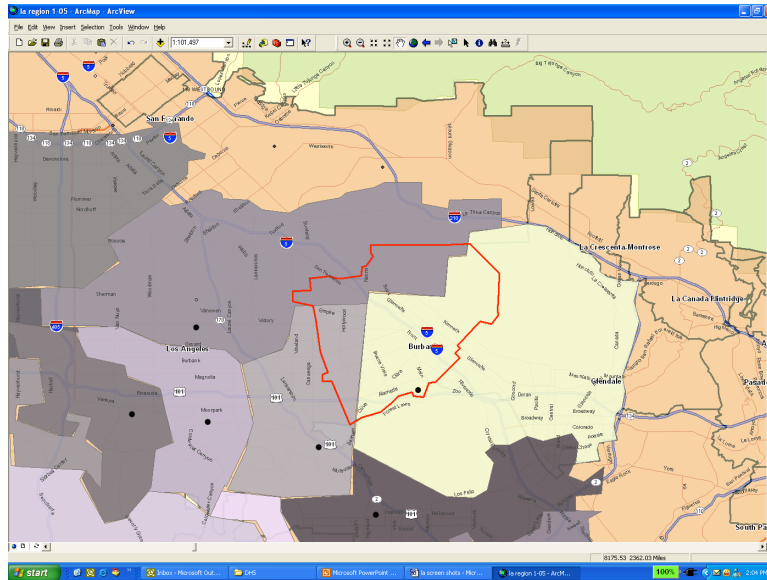


Figure 7

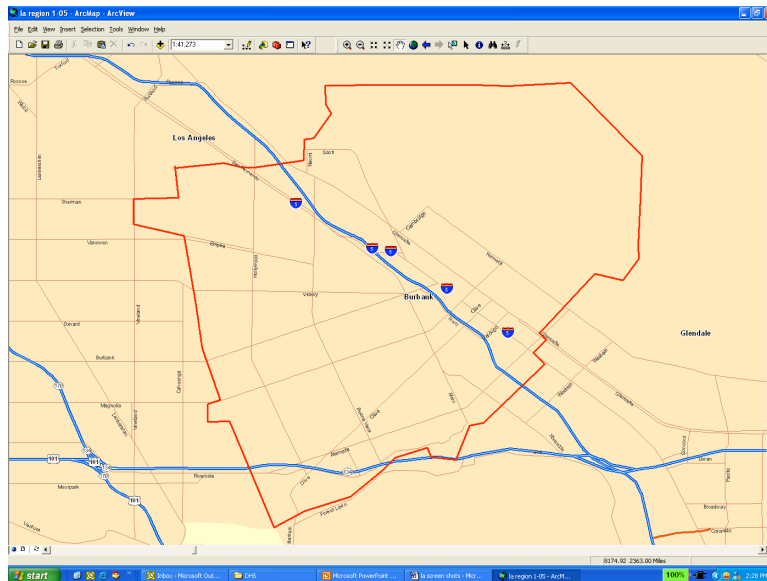


Figure 8

## Vulnerability and Design of Systems

While MUNICIPAL has great value as a tool to support decision making for system restoration following disruptions, these disruptive events can be extremely infrequent. A module has been built to support analyzing vulnerability of systems due to their interdependencies. In general, the system manager identifies paths or components of concern. MUNICIPAL then identifies all the components in the parent system which these paths or components rely on. If the parent system is hierarchal in structure (like power), key components in the parent system are failed one at a

time and the degree of service outage is measured. If the parent is non-hierarchical in structure, key components are failed one at a time. As each is failed, MUNICIPAL determines if an outage of service has occurred and if an outage has occurred, the degree of outage is measured.

MUNICIPAL can also be used to improve the redundancy of systems. First, a path of concern is identified. In this case we will say it is a path in the telecommunications system. Its connections to the power system are next identified. A search is conducted to determine all the components in the power supply that are required for this current telecommunications path to be operational. This set of components from the power systems would be inputted to MUNICIPAL in a failed condition. Running MUNICIPAL would cause all the components in telecommunications that rely on these sections of power to also fail. By proposing new connections within telecomm, MUNICIPAL will be able to determine if a feasible path (or paths) exists and the set of nodes that constitute this path (or set of paths). This information will then be provided to the designer. Additionally, MUNICIPAL can also be used for the addition of temporary or alternative power sources or any other analyses relating to improving reliability by adding redundancy.

## CONCLUSIONS

This paper has described our research to date regarding the development MUNICIPAL, the decision support system for interdependent infrastructure management. We have provided a description of the GIS interface, the database, the Interdependent Layered Network (ILN) model and the design and vulnerability analysis modules. Once the LA area and Manhattan data sets are complete, we will be conducting the mathematical and technical assessments of MUNICIPAL. This will include evaluation by infrastructure system managers, such as Verizon and Consolidated Edison, and with emergency response organizations like the New York State Office of Emergency Management and the California Governor's Office of Emergency Services.

- [1] "USA Patriot Act," in *A*, vol. B, 107th Congress ed, 2001, pp. C.
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- [3] A. Berenson, "A Full Reopening of Stock Trading Is Set for Monday," in *New York Times*. New York, NY, 2001, pp. C1.
- [4] ESRI, "ArcGIS," 9.0 ed. Redlands, CA: ESRI, 2004.