Understanding Complex Systems: Infrastructure Impacts

By Darrin B. Visarraga

Prior to the 1990s, little attention was given to infrastructure interdependencies. However, recent events such as the Baltimore Howard Street Tunnel train derailment (2001), the September 11 attacks on NY & DC (2001), the Northeast electric power blackout (2003), hurricane Katrina (2005), and the increased reliance on SCADA (Supervisory Control and Data Acquisition) systems to monitor and control key system components have brought the importance of infrastructure interdependencies to the forefront (Pederson 2006).

Interconnected and interdependent energy infrastructures are extremely complex systems, consisting of physical facilities (e.g., power plants, refineries, etc.), transmission lines, phone lines, roads, railways, waterways, human decision makers (e.g., consumers, legislators, investors, etc.), etc. Figure 1 shows some examples of interconnected and interdependent infrastructures.

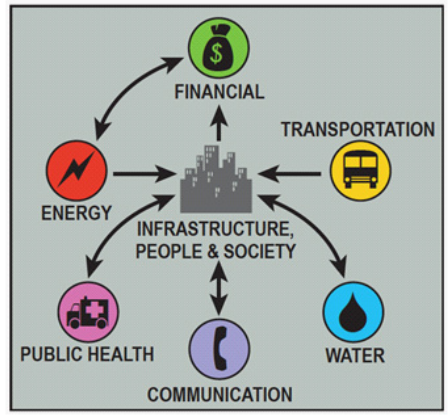

Figure 1. *Interconnected and interdependent infrastructures.*

Critical infrastructures (CI) are arrays of assets, networks (either physical or virtual), processes, and organizations whose incapacitation or destruction would have a severe impact on the nation's security (economic or physical), public health, safety, or any combination thereof. *Key resources* (KR) are any publicly or privately owned resources that are essential to the minimal operations of the economy and government (NIPP 2009). The disruption of any of our CIKR assets, whether deliberate or accidental, could have a devastating effect on our nation's security, public health and safety, economic vitality, and way of life. Therefore, the ability to model and analyze the behavior of these critical infrastructures and their intra/inter-dependencies is of vital importance.

An *infrastructure interdependency* is defined to be a physical, logical, or functional connection from one infrastructure to another, where the loss or severing would affect the operation of the dependent infrastructure. Figure 2 shows a graphical representation of interdependencies and illustrates how they may exist between infrastructure components. In this figure, each plane represents an individual infrastructure. The parallel lines within these planes represent individual sectors or subsets within that particular infrastructure, and the spheres (or nodes) represent key infrastructure components. The solid lines connecting nodes represent internal dependencies, while the dashed lines represent dependencies that exist between different infrastructures. To put this graphical representation into a more realistic context, one can simply recall the events that transpired during Hurricane Katrina in New Orleans. The electric power generation and distribution, and the natural gas production and distribution sectors are all contained within the Energy infrastructure layer. The nodes in that layer represent key infrastructure components (e.g., electric substations, pump stations, city roads, telecommunication hubs, and emergency services), and the solid/dashed lines represent internal/cross-infrastructure dependencies (for example, a water treatment plant utilizing electric power pumps) (Pederson 2006, Toole 2008).

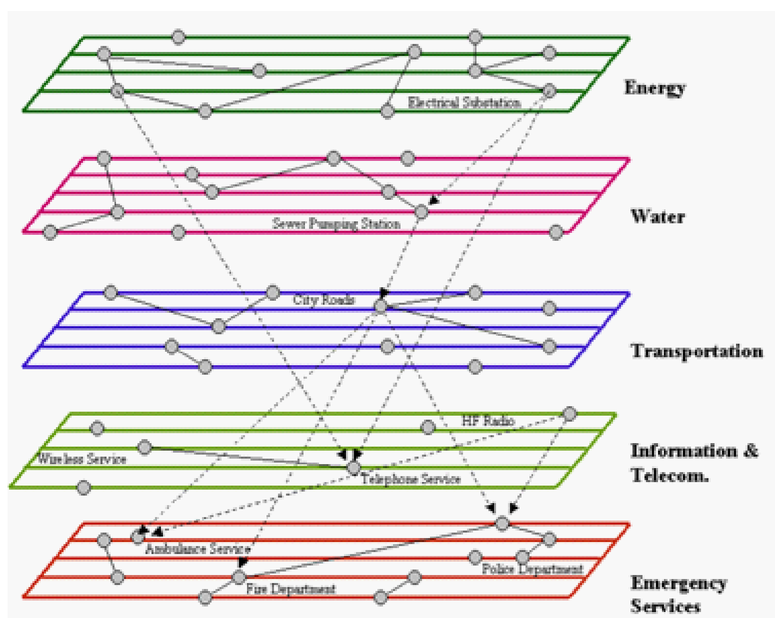

Figure 2. *Infrastructures dependencies and interdependencies.*

Feedback-loops are often utilized in energy infrastructures indicating that these infrastructures depend upon each other for functionality (for example, a gas-fired electric generating plant requires a steady supply of natural gas, and the natural gas pipeline network may possess electric-powered compressors to maintain sufficient pressure). Thus, each system requires the other system(s) to provide an appropriate quality of service. Because a component failure in one infrastructure does not necessarily result in a propagating failure (or problem) into the other infrastructure(s), this type of cascading phenomenon can be difficult to analyze.

In the past, modeling and simulation technologies did very well at analyzing single-domain infrastructures. However, when interdependent infrastructures were considered these technologies had severe limitations, and analysts would often treat interdependencies in an ad-hoc manner. In order to obtain a more thorough understanding of infrastructure interdependencies, LANL has created several software simulation packages to assist homeland security analysts and decision makers in understanding and accurately assessing vulnerabilities (whether intrinsic or from intentional attacks) in critical infrastructures. A few examples of these packages are: Critical Infrastructure Protection Decision Support System (CIPDSS), Electric Restoration Analyzer (EPRAM), Interdependent

Energy Infrastructure Simulation System (IEISS), Logistic Simulation System (LogiSims), and a Scalable Discrete-Event Simulation Framework (SimCore).

The IEISS simulation environment is designed to assist users in simulating the behavior of interdependent infrastructures (e.g., electric power, natural gas, and telecommunications). Simulation results are used to study the effects of cascading failures from one infrastructure into another in order to quantify the synergistic effects and feedback mechanisms between them. An actor-based modeling approach of infrastructures is utilized in IEISS, which allows for each physical, logical, or functional entity in an infrastructure to correspond to a software actor that has a variety of attributes and behaviors that mimic their real-world counterparts. The connections within (or between) infrastructures are represented by connections between the relevant actors and the actors interact in the software through a message-passing protocol (Bush 2003). Mathematically, this means that any infrastructure with a dependency graph representation can be modeled using this actor-based, message-passing process. This approach is suitable for a wide variety of network-like infrastructures.

As urban infrastructures become more complex and interdependent, the probability of large-scale disruptions and/or outages increases. To show how IEISS is used to model and analyze infrastructure interdependencies we introduce a fictitious example shown in Figure 3. In this figure, the IEISS model contains interconnected electric power and natural gas components that operate at different voltage and pressure levels. The simulation process begins by requiring the simultaneous loss of two components (a 230-kilovolt (kv) electric substation and a natural gas city gate). These components are indicated as "B" and "A", respectively, in Figure 3, and are located approximately 30 miles apart.

The loss of the electric substation "B" causes several transmission lines in the local network to be overloaded (including two western-bound 230-kv lines that originate from this substation, as shown in Figure 4). The loss of the natural gas city gate "A" disrupts natural gas delivery to local gas-fired power plants located approximately 10 miles to the south of its location. Due to the overloaded transmission lines, the algorithms used in IEISS, to analyze network behavior, force the utility to shed customer load in order to avoid equipment damage and stabilize the local network. As a result, the shedding action of the utility creates an electric outage area, as shown in Figure 4.

As mentioned above, power is provided to areas west of the electric substation "B" through three 230-kv transmission lines (two of the lines originating from the electric substation "B", and the third connecting to the network east of this substation). Since the loss in natural gas from citygate "A" resulted in a loss in local (electric) generation and the outaged electric substation overloads its two transmission lines, power flow to the western customers can only be supplied through the third 230-kv transmission line, which is severely overloaded. The result is an additional area of customer load shedding, as shown in Figure 5.

In this extended impact area, many businesses and facilities critical to the continued operation of an urban infrastructure are affected. In this example, the total outage area encloses nearly 2,700 square miles. Based on average business densities and sales data, the cost of a three-day outage could total an estimated $150 million dollars. In addition, key emergency facilities such as hospitals, telecommunication end offices, police and fire stations will be impacted forcing extended reliance on emergency backup power (Toole 2008).

References

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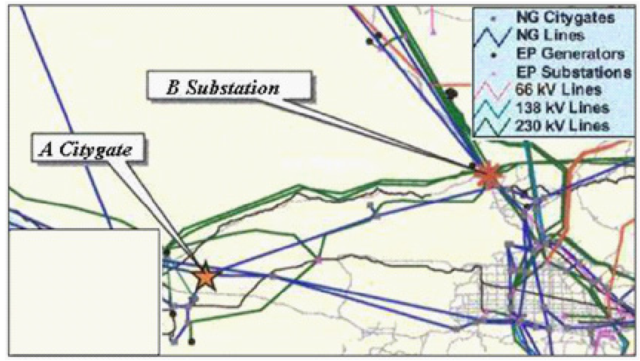

Figure 3. *IEISS model showing electric power and natural gas components, with highlighted locations of outaged nodes.*

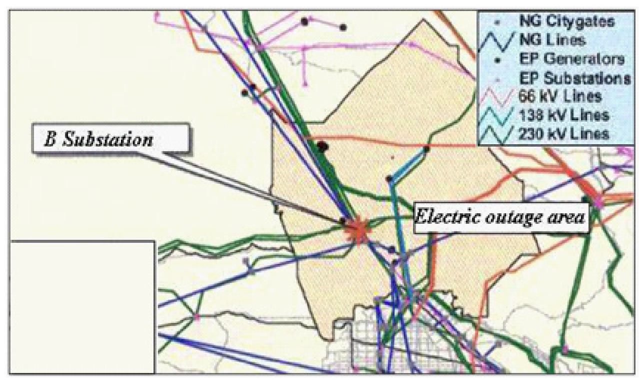

Figure 4. *Interconnected and interdependent infrastructures.*

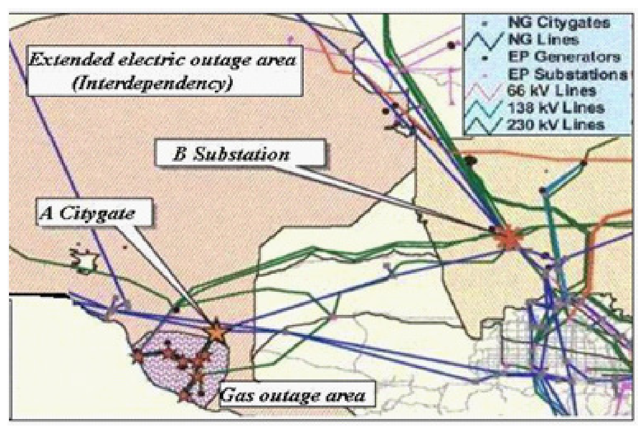

Figure 5. *Additional load shed due to transmission line overload from electric substation "B" results in final interdependent event.*

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