Critical Infrastructure Resilience[i]

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Introduction

Historically, U.S. government policy toward critical infrastructure security has focused on physical protection. However, following the terrorist attacks of September 11, 2001; the devastation from Hurricane Katrina in 2005; and a series of other disasters in the early 2000s, the infrastructure security community in the United States and globally recognized that it was simply not possible to prevent all threats to all assets at all times. Consequently, critical infrastructure resilience emerged as a complementary goal to prevention-focused activities. Whereas critical infrastructure security policies primarily focused on prevention of terrorism, accidents, and other disruptions, critical infrastructure resilience activities emphasize the infrastructure's ability to continue providing goods and services even in the event of disruptions. Together, critical infrastructure security and resilience strategies provide a more comprehensive set of activities for ensuring that critical infrastructure systems are prepared to operate in an uncertain, multi-hazard environment.

Though C.S. Hollings is credited with introducing resilience to the ecological and complex systems communities more than four decades ago (Holling, 1973), no universally accepted definition of resilience exists for critical infrastructure. Still, commonalities exist across the dozens of proposed definitions. The most prevalent theme across all definitions is that the infrastructure system is coping with changes that have the potential to affect its operation. Many definitions propose mechanisms by which the infrastructure respond to the changes, and the most commonly listed mechanisms are:

- The ability to absorb or withstand the impact of the change
- The ability to adapt in response to the change
- The ability to recover and restore system functionality rapidly

The efficiency or amount of resources required to successfully respond to a disruption is a less frequently, but important, consideration. In times of crisis, manpower, equipment, and other critical resources for response and recovery operations are in high demand. Hence, a system's ability to perform through disruptive events with less resource consumption than other systems would be a desirable feature and make it more resilient than systems requiring more resources.

Objective & Purpose of Resilience

Risk management has long been used in critical infrastructure planning activities. While it remains a valuable tool, resilience analysis and planning can provide additional benefits. These benefits derive, in part, from fundamental differences between the objectives for risk and resilience analysis.

In the context of infrastructure systems, risk analysis frequently aims to identify the hazards to infrastructure operations and the potential consequences if those hazards are realized. Risk management further aims to decrease either the chance that the hazard will be realized or to decrease the negative consequences that might occur under that realization. Resilience analysis provides a fundamentally different mindset that results in different methodological approaches. Whereas risk analysis and management constructs generally begin with an identifiable (or relatively probable) set of hazards, resilience analysis methods frequently accept that it is not always possible to identify potential hazards and quantify their likelihood of occurrence. Even in the event when this is possible, it may not be possible to reduce the chance that the hazard will occur. Risk analysis methods often include static methods, whereas the temporal dynamics of adaptation, response, and recovery are viewed as essential to resilience. A common, implicit goal of risk analysis is maintaining or returning the system and its structure to the status quo. Resilience objectives focus less on the status quo and more on determining how to achieve a necessary level of infrastructure performance and delivering essential goods or services. Fundamental changes to system structure and operations are viewed as viable, and sometimes preferred, options to maintaining the status quo.

Instruments for Resilience Management

A number of different approaches, methods, and tools exist to support resilience management, but they can generally be grouped into one of two categories: attribute-based and performance-based methods. Attribute-based methods generally try to answer the question "What makes my system more/less resilient?" Thus, they typically include categories of system properties that are generally accepted as being beneficial to resilience. Examples of these categories might include robustness, resourcefulness, adaptability, recoverability, etc. Application of these methods typically requires that analysts follow a process to review their system and determine the degree to which the properties are present within the system. The benefit of these approaches is that their applications tend to be less time and resource intensive and result in either qualitative or semi-quantitative estimates of resilience. However, they do not provide any estimation or confidence in how well the system will operate in the event of a disruption or the effectiveness of potential resilience enhancements and investments. The Supply Chain Resilience Assessment and Management (SCRAM^{TM}) tool (Petit, Fiksel, & Croxton, 2010) and Argonne National Laboratory's Resilience Index (Fisher & Norman, 2010) are two examples of attribute-based methods.

Performance-based methods are generally quantitative methods that try to answer the question "How resilient is my system?" These methods are used to interpret quantitative data that describe infrastructure outputs in the event of specified disruptions and formulate metrics of infrastructure resilience. The required data can be gathered from historical events, subject matter estimates, or computational infrastructure models. These methods tend to rely less on subjective or qualitative evaluations and, thus, facilitate comparative analyses. Because the metrics can often be used to measure the potential benefits and costs associated with proposed resilience enhancements and investments, performance-based methods are often ideal for cost-benefit and planning analyses. A

limitation of performance-based methods is that, alone, they generally do not explain why a system is more or less resilient than another. These methods also often use computational models to generate the necessary data, and those models may require significant time and resources to develop. Consequently, performance-based methods can be rather complex. When deciding which methods to use, the analyst should determine their analysis objectives, evaluate their resources for performing the analysis, and assess their comfort with the varying levels of complexity. The Multidisciplinary Center for Earthquake Engineering Research (MCEER) (Bruneau, et al., 2003) and Rose (Rose, 2007) have developed examples of performance-based methods.

Metrics, Criteria, Indicator for Resilience

Many resilience metrics, attributes, and indicators have been proposed. The Infrastructure Resilience Analysis Methodology (IRAM) provides a comprehensive framework for analysing and managing critical infrastructure resilience (Biringer, Vugrin, & Warren, 2013). The IRAM is a hybrid methodology that includes performance-based metrics to quantify resilience and resilience attributes to inform analysis and improvement.

The IRAM quantifies resilience with two primary sets of metrics: systemic impact (SI) and total recovery effort (TRE). For a specified disruptive event, SI measures the cumulative impact of the disruption on the infrastructure's ability to provide goods and services. TRE measures the cumulative value of the resources expended during response and recovery activities. Together, these metrics quantify the consequences associated with an infrastructure system for a specified disruption. These metrics can be used for deterministic analyses and probabilistic analyses that quantify uncertainties in resilience estimates.

The IRAM contains three resilience capacities, and each capacity contains a collection of resilience-enhancing features. These capacities can be used to identify resilience-limiting infrastructure properties or provide the basis for resilient design activities. The absorptive capacity consists of infrastructure attributes that help the infrastructure withstand or absorb the effects of a disruption. These attributes consist of relatively low effort options, such as redundancy or excess inventory that represent the preferred, go-to options. The adaptive capacity includes system properties that enable the infrastructure to reorganize and change the manner in which it operates in order to overcome the effects of the disruption. Substitution and re-routing are two examples of adaptive, resilience-enhancing features. The restorative capacity is the third capacity and includes system properties that facilitate system repairs and recovery. Examples of restorative resilience-enhancing features include pre-positioning supplies and reciprocal aid agreements.

The last component of the IRAM is a six-step process that formalizes the application of the IRAM. The process guides the analyst in applying the IRAM for the analyst's specific needs. This process has been successfully used to perform resilience analyses for transportation (Vugrin, Turnquist, & Brown, Optimal Recovery Sequencing for Enhanced Resilience and Service Restoration in Transportation Networks, 2014), chemical manufacturing (Vugrin, Warren, & Ehlen, 2011), public health (Vugrin, et al., 2015), energy (Vugrin, Baca, Mitchell, & Stamber, 2014), and other infrastructure systems for a variety of resilience activities.

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