Measuring the Resilience of Infrastructure Systems[i]

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Introduction

The U.S. economy depends on effective, reliable, and affordable infrastructure that delivers energy and information to support productivity, water to meet basic needs, manufacturing to produce raw and finished materials, and transportation to connect communities. However, infrastructure is vulnerable to many threats and hazards that threaten the services it provides. Several events over the past few years highlight the range of challenges that infrastructure systems must address and illustrate how communities are responding to some of them.

In 2012, Superstorm Sandy left more than 8.5 million customers without power, with outages persisting more than one week (U.S. Department of Energy, 2012). While communities recovered, residents faced shortages of gasoline that persisted during the same period (National Association of Convenience Stores, 2013). In 2015, multiple airlines suffered computer failures where even delays of a few hours cancel dozens of flights, delay hundreds of others, and strand thousands of passengers (see for example LA Times, 2015 and The Guardian, 2015). Finally, in 2016 the Louisiana Coastal Restoration and Planning Authority released its 2017 Annual Plan, which documented the state's current efforts towards implementation of its master plan to achieve long-term sustainability given threats from hurricanes, coastal erosion, and sea-level rise (LACPRA, 2016).

To improve the resilience of infrastructure in contexts like these it is critical to understand how resilience can be measured. This requires defining resilience – meaning both what it is and what aspects of the system must be measured –and understanding why resilience is being measured.

Defining Resilience for Infrastructure Systems

Resilience has been defined in many ways. A few recent definitions define resilience as the ability:

> Of the system to withstand a major disruption within acceptable degradation parameters and to recover within an acceptable time and composite costs and risks. (Haimes, 2009)

> To prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. . . . [It] includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents. (White House, 2013)

> To prepare and plan for, absorb, recover from, and more successfully adapt to adverse events. (Committee on Increasing National Resilience to Hazards and Disasters; Committee on Science, Engineering, and Public Policy; and The National Academies, 2012)

These definitions, while each different, reveal four aspects of the system being addressed. These aspects are described in detail in a Framework for Measuring Energy System Resilience, proposed by the Rand Corporation (Willis & Loa, 2015).

 First, resilience describes the state of service being provided by a system in response to a disruption. When assessing resilience, key questions would be whether the service has been degraded, how much of the service has been degraded, how quickly the service has been restored, and how completely the service has been restored. Therefore, resilience does not describe a dichotomous state of whether or not a disruption has occurred. Rather, resilience describes the degree of disruption across multiple dimensions, which could include type, quality, time, and geography of service provision.

Second, the state of a system depends on how it was designed and how it is operated. These choices influence whether and how service is degraded during a disruption, how quickly it recovers, and how completely it recovers. For example, an electricity grid system that is designed with more redundancy, operated with more contingencies for backup, and designed with recovery in mind might experience a lesser and briefer disruption and, if so, would be more resilient than a system that has less redundancy, has fewer backups, and is more difficult to rebuild.

Third, different responses will lead to different resilience at different costs. For example, it may be possible to redesign a supply chain information system after a glitch with more effective knowledge management, and as a result, the quality of service provided after recovery exceeds the original level of service provided.

Finally, resilience of a system also depends on the timescale. If repair of a flood protection system replaces levies where they were and how they were originally designed, over a period of years, the system may experience repeated disruptions if climate change leads to greater frequency of intense flooding. If the system is continually maintained and upgraded, the protection could improve, but at a cost.

Aligning Resilience Metrics to Decision-making

We track metrics to be able to keep score, to tell whether goals have been met or whether success has been achieved. We track metrics to improve quality, to tell where improvements are possible and whether progress is being made. We also track metrics simply to account for resources, to tell whether budgets are met and to know where assets reside.

Metrics of resilience are used for many purposes and at many levels. Some of the reasons for metrics are more relevant to a national perspective and others to a local or facility perspective. For example, at a national or regional level, it may be important to know how resilience affects economic output or economic damage stemming from disasters. For a refinery operator, it may be more important to know how many spare parts are in stock and what options exist for backup power generation.

These different purposes for measurement have an important implication for resilience metrics. There is no single set of metrics that supports all decision-making needs. Instead, each purpose may demand a unique set of metrics, yet organized in a consistent way across purposes.

Logic models provide a consistent framework for organizing metrics in the fields of program evaluation and quality improvement (Rogers et al., 2000; Greenfield, Williams, & Eiseman, 2006; Willis & Loa, 2015). From an operational perspective, a logic model explains how activities, budgets, and people (i.e., *inputs*) ultimately contribute to desired outcomes. From a strategic perspective, a logic model explains which inputs are needed to support strategy. From either perspective, a hierarchy of metrics exists to connect inputs to outcomes and improve understanding about how to achieve outcomes more effectively and efficiently (Figure 1).
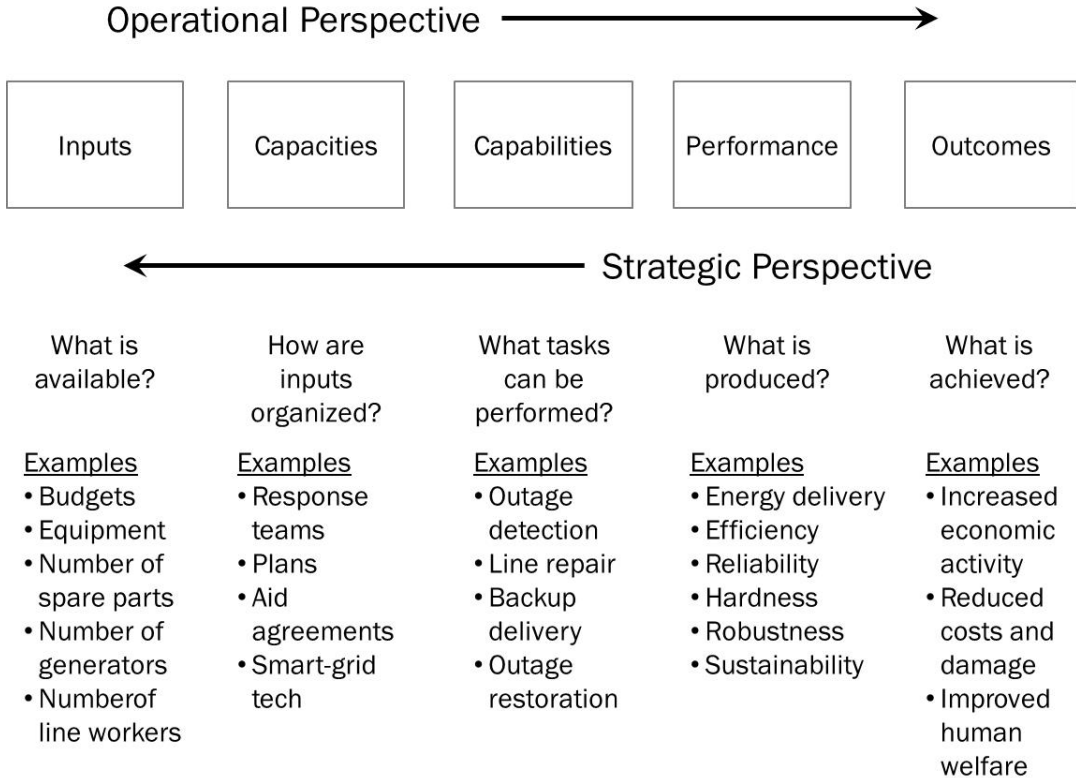

Figure 1: Metrics Can Serve both Operational and Strategic Decision-making

The building blocks of resilience are *inputs*, which define what is available to support resilience. As an example, in the context of power systems, inputs include budgets, equipment, spare parts, and personnel to support recovery operations. On their own, these inputs do not provide resilience unless they are organized to support functions or tasks.

In a logic model framework, the ways in which inputs are organized to support resilience are called *capacities*. Examples of capacities for power systems include response teams capable of repairing equipment, recovery plans that can be implemented following a disaster, or advanced technologies that can be used to reroute power and reconstitute portions of a grid during disruptions. Having these capacities in place is not the same thing as being able to use them, however.

Capability metrics reflect how well capacities can serve a system when they are needed. Ultimately, capability metrics describe how proficiently tasks can be performed. For some responsible for managing infrastructure, some capability metrics address the provision of services and thus measure resilience itself. Others measure capabilities that support resilience. Continuing with the case of energy infrastructure, examples include the ability to detect leaks or outages, to repair damaged power lines or pipelines, or to restore power outages.

Capabilities are ultimately desired because they improve system *performance*. Performance metrics describe what is produced by an engineered system. In the context of energy systems, examples of metrics include the amount of energy delivered (i.e. a service) or operating characteristics of the system (i.e. characteristics of that service that support resilience), such as efficiency, reliability, fault tolerance, sustainability, or robustness.

In the end, the performance of infrastructure depends on how the systems generate the *outcomes* that society is seeking to achieve. Resilience of infrastructure can be measured by many outcomes, such as reduced damage or deaths and injuries from disasters or increased economic activity.

As communities and infrastructure owners and operators continue towards improving the effectiveness, reliability, and affordability of infrastructure services, these principals for measurement can help them track whether they are achieving desired effects on improving the resilience of their infrastructure.

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