On the Role of Protocol-Driven Resilience in Coupled Infrastructure and Natural System Resilience

Royce Francis[1]* and Domenico Amodeo[2]

[1]Associate Professor, Department of Engineering Management and Systems Engineering, The George Washington University, Washington, DC, USA

[2]Graduate Research Assistant, Department of Engineering Management and Systems Engineering, The George Washington University, Washington, DC, USA

Corresponding author email: seed@email.gwu.edu

ABSTRACT

Lifeline infrastructure systems have always been crucial to the social, economic, and military security of societies. Because lifeline systems are critical to societal coherence and economic operations, assessing and mitigating risks to lifeline system operations is crucial. However, attention has shifted from risk assessment to resilience assessment due to the exceptionally large adaptation and mitigation needs implied by the geographic and temporal scope of natural and man-made hazards. The goal of this commentary is to introduce the concept of protocol-driven resilience. Protocol-driven resilience refers to the way in which the network of human relationships, operating protocols, evolving objectives, and information sharing processes produces resilient system behavior. Protocols are the formal and informal rules, and formal and informal processes that govern the nature, quality, and quantity of connectivity and interaction between the coupled system's physical and human components. Protocols are crucial to resilience of coupled infrastructure and natural systems because the although the physical components of the infrastructure are relatively static, the protocols are dynamic and decomposable. We assert that the resilience of a system should be assessed by studying the range or diversity of conditions under which a protocol set preserves relationships.

KEYWORDS

Infrastructure resilience, macrocognition, system architecture, natural hazards

Lifeline infrastructure systems have always been crucial to the social, economic, and military security of societies. Lifeline infrastructure systems are services such as electric power, natural gas, telecommunications, water and wastewater, and emergency services systems. Although infrastructure systems are crucial to societal function, infrastructure systems *per se* have only recently begun to receive sustained research attention (Meerow and Newell 2015). The initiating event driving the attention was the attack on the World Trade Center in New York City, USA on 11 September 2001 (9/11). As the United States struggled to determine how to best respond to this event, American society revisited the ways in which infrastructure security was managed. Shortly afterwards, Rinaldi, Perenboom, and Kelly (2001) published a seminal analysis of the extent to which lifeline infrastructure systems such as power and water supplies had become interconnected and interdependent. Moreover, this analysis outlined the criticality of solving the challenges involved in modeling interdependent infrastructure systems that result from the integration of technological advances with social and economic capabilities. Rinaldi et al. made two principal findings relevant to our discussion: i.) infra-structure systems are networked, complex adaptive systems (CAS); and, ii.) infrastructure systems are characterized by four categories of interdependencies—physical, geographical, cyber, and logical.

Early efforts to assess the risks of infrastructure systems focused on intentional man-made terrorist events. For example, the Bioterrorism Act of 2001 focused on changing the ways that vulnerabilities were identified in water infrastructure, supporting intensive investigation into vulnerability assessment and risk management methods (Redhead, Vogt, and Tiemann 2002). However, water infrastructure managers and operators began to realize that terrorism vulnerabilities represented a relatively small portion of the types of vulnerabilities faced by their utilities. Towards the end of the decade, industry attention shifted to focus on all-hazards assessment because it became increasingly clear that the adaptation and mitigation needs implied by the geographic and temporal scope of natural hazards and demographic changes might also be effective against man-made hazards. Moreover, the temporal and geographic scope of man-made hazards—at least for water and wastewater systems—would be dwarfed by the temporal and geographic scope of natural hazards (Kwasinski et al. 2017).

As this realization set in, focus began to shift to infrastructure resilience. Resilience was defined by the United States Department of Homeland Security (DHS) as “the ability to adapt to changing conditions and withstand and rapidly recover from disruption due to emergencies” (The White House Office of the Press Secretary 2013). Prior to resilience, large-scale socio-technical system design and management was influenced by a focus on risk—the likelihood of sustaining consequential impacts as a consequence of a vulnerability having been breached by an external initiating event (e.g., (US EPA Office of Water, US EPA Office of Ground Water, and US EPA Office of Drinking Water 2015)). While risk and resilience are related, they are not necessarily interchangeable. First, while both concepts are emergent properties of systemic interactions among components of the system under consideration, risk entails a focus on the system itself while resilience extends beyond the system to other entities interacting with it (Kwasinski et al. 2017; Kwasinski, Lavelle, and Trainor, n.d.; NIST 2015). Second, while risk and resilience are both anticipatory, risk involves the assessment and mitigation of contingencies that could reasonably be anticipated; whereas resilience involves the assessment of response capabilities that could facilitate improvisation and responsiveness to unforeseen circumstances (Epstein 2007). Resilience became the focus of forward-looking water utilities as it became clear that the development of response capabilities and focus on other interacting systems would improve their preparedness, situational awareness, and relationships with other governance and infrastructure system partners (Kwasinski et al. 2017; K. M. Morley 2010; K. Morley 2006).

Since 9/11, significant progress has been made to understand the risks to lifeline infrastructure through in-depth risk analysis of all key infrastructure systems, assessing the full range of hazards and severity of the possible risks. In addition, important inroads have been made into understanding the coupling of engineered infrastructure with the natural systems and processes supporting it. Nonetheless, this coupling has been understudied. We believe that one potential reason that the engineered infrastructure and natural system coupling has been understudied is that we have not yet achieved deep enough coupling of cognitive systems sciences with infrastructure system resilience measurement science.

In this commentary, we hope to encourage researchers to extend the perspective of Rinaldi, Peerenboom, and Kelly (2001) and others (e.g., (Woods 2015; Hoffman and Woods 2011),(Klein et al. 2003)) that critical infrastructure systems are socio-cognitive systems. Broadly, we understand this to mean that: i.) infrastructure resilience is a property that emerges from the human relationships and operating protocols that are produced from the interaction of natural topology and human values; and, ii.) both infrastructure-environment interdependence and infrastructure system interdependence (e.g., multi-modal inland waterway transportation systems) are characterized by the mechanisms through which lifeline systems exhibit mutual cognition. In this context, mutual cognition involves the many ways in which data are collected and processed between lifeline systems through human and instrumented (e.g., sensors and data acquisition systems) mechanisms. We call the way in which this network of human relationships, operating protocols, evolving objectives, and information sharing processes produces resilient system behavior *protocol-driven resilience*.

Protocols are the formal and informal rules, and formal and informal processes that govern the nature, quality, and quantity of connectivity and interaction between the coupled system's physical and human components. In this context, these formal and informal processes can include set procedures, informal conversations or unwritten agreements, real-time information collection and improvised decision-making, legal requirements, chains of command, relationships of trust, etc. Protocols are crucial to resilience of coupled infrastructure and natural systems because the although the physical components of the infrastructure are relatively static, the protocols are dynamic and decomposable. To understand the role of protocols in system resilience, it is fruitful to briefly revisit the language of Holling (1973) contrasting the qualitative view of systems with the quantitative view of systems focused on stability and robustness (p.1): "If we are dealing with a system profoundly affected by changes external to it, and continually confronted by the unexpected, the constancy of its behavior becomes less important than the persistence of the relationships." As Holling writes in the same article (p. 17): "Resilience determines the persistence of relationships within a system," while "Stability … is the ability of a system to return to an equilibrium state after a temporary disturbance." If we can use Holling's words, with which our readers are likely to be much more familiar than our own, protocols are the relationships providing system resilience. Although resilience can be produced by systems that have low stability due to the persistence of their protocols, most research in infrastructure system resilience has not focused on characterizing these protocols, but has been focused on measuring stability. We assert that resilient systems have protocols that can preserve relationships over a broad range of environmental conditions. The resilience of a system may be assessed by studying the range or diversity of conditions under which a protocol set preserves relationships.

Perhaps the focus on metrics and stability is due to the societal dependence on lifeline infrastructure systems. In fact, Holling also seems unable to escape the desire to "measure" resilience and includes some proposals for contrasting measures of stability and resilience in the same seminal article quoted above. If we view infrastructure, loosely, as the result of coordinated political actions then it is clear that instability is completely unacceptable. It is an outcome that we, at least in Western societies, have not been willing to tolerate. Hardness and robustness, i.e., absorptivity and recoverability, are the chief design objectives. At the same time, it is no longer controversial to assert that the environment and natural processes in which our engineered infrastructures are changing. In some ways, these changes may not have been anticipated by the designers of the original physical infrastructure configurations. Consequently, a reformed focus on resilience will be required in order to facilitate adaptation to changes in natural processes; the degree to which this focus should be vigorously engaged is in direct proportion to the infrastructure's direct interdependence on natural processes (e.g., (Park, Seager, and Rao 2011; Mu et al. 2011)). This reformed focus must bring protocol-driven resilience to the foreground, prioritizing the persistence of relationships and the likelihood that systems will need to be designed with greater ability to accommodate regional instability while still retaining their fundamental identities, and using traditional measurement-based approaches to resilience to support the new focus.

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