An Introduction to Protocol Driven Resilience

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THE structure of engineered infrastructure systems can be represented by a layered architecture. The relationship between physical components of many types of these systems has been well studied and modelled. The engineered design of these systems can account for some of their characteristics such as robustness, flexibility, reliability. We believe that the resilience, or adaptive capacity, of these systems cannot be described merely by studying the engineered components of such systems. This requires studying what we refer to as the protocol layers. The protocol layer is where humans interact with the engineered elements of the system through the collection and processing of information with the aim of producing a control activity on the system. In the first part of this study we look at several formulations of a generic layered transportation system, to discuss the importance of protocols in adaptive capability. In the second part, we take a brief historical look at an important American intermodal inland waterway transportation system, The Tennessee Valley Authority. From this system we extract some basic protocol layers and discuss how the success or failure of this system has resulted from these protocol layers.

Keywords: Resilience, protocol driven resilience, Infrastructure System Architecture.

1. Introduction

1.1 *Critical Infrastructure Resilience*

The concept of resilience was first introduced by C.S. Holling in an ecological context (Holling, 1973). Since this time the term has been used to describe behaviours across many different disciplines, from critical infrastructure systems to psychology. As the resilience concept gained popularity, the concept was defined and operationalized in new ways. Several reviews of the concept have attempted to trace its evolution (e.g., Henry and Ramirez-Marquez, 2012; Hosseini et al. 2016). Several other works have attempted to broadly orient and direct the conversation on resilience (e.g., Haimes, 2009; Vugrin et al. 2010). Over the past two decades, the importance of engineering resilient critical infrastructure has become a main stream concern due to a proliferation of highly destructive man made and physical disruptions. The term 'critical infrastructure' was first defined by the US Legislative Branch in 2001, as part of the USA Patriot Act (Sensenbrenner, 2001). Subsequent presidential directives by George W. Bush and Barack Obama reasserted the urgency of building better protected and more resilient infrastructure (Bush, 2003; Obama, 2013). In addition to external man-made threats, critical lifeline infrastructure systems are facing natural degradation due to age, and wear. The American Society of Civil Engineers (ASCE) periodically issues an assessment on the state of US infrastructure. In 2017, the ASCE gave an overall assessment of D+ (ASCE, 2017). Newspaper routinely print stories on the cost of aging infrastructure (Kelley, 2016; Flessner, 2017). Infrastructure investment figured prominently in the campaigns of both major presidential candidates in the 2016 US elections (Thompson, 2016). The ability of infrastructure to sustain performance despite age, natural disasters, and human threats is clearly important for society.

Due to the relationship between environment and engineered systems, infrastructure is significantly affected by changes in the natural environment. These changes can take place over the long term—climatic changes—or they can take place dramatically and intensely—immediate natural hazards or extreme events. As a result, infrastructure engineers and managers became aware of the significance of all-hazards risk assessment. Traditionally, engineered system design was primarily influenced by risk analysis based on well-defined operational or environmental scenarios. However, the complexity of environmental hazards that could be faced by infrastructure systems led infrastructure owners and managers in search of ways of understanding the risk their systems faced in light of combinations of multiple natural hazards. These all-hazards approaches recognized the difficulty in identifying

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operationally meaningful risk scenarios that prepare systems for the unique demands imposed during unanticipated events, and opened the door to resilience as a design and management objective, as the impossibility of mitigating all conceivable hazards became clear.

The efforts in understanding all-hazards infrastructure system resilience have made important inroads 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 is understudied is that we have not yet achieved deep enough coupling of cognitive systems sciences with infrastructure system resilience measurement science. In this brief paper, we hope to encourage researchers to extend the perspective of Rinaldi, Peerenboom, and Kelly (2001) that critical infrastructure systems are socio-cognitive systems. In Francis and Amodeo (2018), we write that we broadly 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. 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* (Francis and Amodeo, 2018).

The purpose of this paper is to introduce the concept of protocol-driven resilience by indicating key gaps in the literature, and to define protocol-driven resilience in response to these gaps. The remainder of the paper proceeds as follows. Section 2 describes extant approaches to defining and measuring resilience in the literature. Section 3 discusses key cognitive functions comprising infrastructure systems and conceives infrastructure systems as macrocognitive systems. On the other hand, Section 4 conceives infrastructure systems as layered architectures, and proposes the *protocol layer* as the layer in the system architecture in which infrastructure macrocognitive functions are situated. Finally, Section 5 concludes the paper with our definition of protocol-driven resilience.

2. Resilience

Resilience literature can broadly be categorized into two types. The first category takes a high-level approach toward the development of frameworks for defining resilience. The second category emphasizes the proposition and application of specific measurements for resilience in terms of a specific resilience capability, usually dealing with recovery.

2.1 *Resilience Frameworks*

Authors that focus on developing a framework for resilience tend to propose taxonomies aimed at categorizing the either the realms of resilience or the functions of resilience (Henry and Ramirez-Marquez, 2012; Woods, 2015; Vugrin et al., 2010; McDaniels et al. 2008; Madni and Jackson, 2009; Bruneau et al. 2003). Table 1 provides a brief overview of these resilience frameworks. Some reoccurring themes arise throughout the debate over resilience; the ability of a system to withstand a disruptive event, the ability to recover after such an event, and the ability to adapt the system behavior. While these themes re-occur, different authors may apply variations in terminology across the literature. Differentiating between risk and resilience often plays a significant role in these frameworks.

Table 1. Summary of Resilience Frameworks

Framework	Description	Source
"Engineering versus Ecological Resilience"	Differentiates between ecological resilience focused on "existence of function" and engineering resilience based on "efficiency of function"	(Holling, 1996)
"Four Concepts of Resilience"	A taxonomy of extant resiliency literature based on four areas; rebound, robustness, graceful extendibility, and adaptive capacity.	(Woods, 2015)
"Four Cornerstones of Resilience"	A perspective based on four abilities for resilient performance; respond, monitor, learn, anticipate.	(Nemeth, Hollnagel, and Dekker, 2009)
"Resilience Matrix"	Partitions resiliency into 16 components the interaction of four domains (physical, information, cognitive, social) with the phases of an adverse event (plan, absorb, recover, adapt)	(Linkov et al. 2013a) (Fox-Lent, Bates, and Linkov, 2015)
"Mitigation and Adaption"	An influence diagram framework for socio-technical systems that describes resilience as a process based on decisions made before and after a disaster. Demonstrates improvement in ex-ante decisions by learning from previous experience. Captures influence of uncertainty.	(McDaniels et al. 2008)
"Engineering for Resilience"	Divides resilience into adaptive and reactive category, and develops a framework based on the interaction between system attributes, metrics, management metrics, and methods.	(Madni and Jackson, 2009)
"PEOPLES" framework	Measures resilience over geography and time in terms of seven attributes. Population and Demographics, Environmental/Ecosystem, Organized/Governmental Services, Physical Infrastructure, Lifestyle and Community Competence, Economic Development, and Social-Cultural Capital	(CS Renschler et al. 2010)

Although risk analysis is not the focus of the present work, it is important to acknowledge the relationship between risk assessment and science and resilience assessment (Aven, 2019). While the concepts of *risk* and *resilience* are closely related, they are often conflated. Both risk and resilience are system properties. However, risk properties of systems are functions of risk calculus (Beck 1999, p. 50-53), and can be considered anticipatory in nature. On the other hand, resilience properties of systems cannot be fully captured by risk calculus since systems may also be subject to indeterminate risks. Therefore, resilience properties are reactive. However, when analysing the resilience of a system, resilience analysis relies on risk science in ways that acknowledge that assessing system resilience goes beyond what can be anticipated to evaluate system responses to disruption (Larkin et al. 2015; Park et al. 2013; Linkov et al. 2014). Broadly speaking, resilience is an attribute of the system that describes the system's ability to deal with challenging situations. The framework proposed by Linkov et al. (2013) partitioned resilience into four domains; physical, informational, cognitive, and social. These domains interact across the time-based process of planning for and reacting to an event (Linkov et al. 2013). Bruneau et al. (2003) developed a similar framework of partitioning resilience into four dimensions and four properties. The dimensions are technical, organizational, social, and economic; the four properties are robustness, rapidity, redundancy and resourcefulness. Despite the difference in terminology, these categories and dimensions generally map to the dimensions and phases of the Resilience Matrix proposed by Linkov et al.

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(2013). Madni et al. (2009) develops a framework that includes a division of resilience into reactive and adaptive categories and disruptions into external and systemic categories.

The resilience of an engineered system is, therefore, a system property emerging from the result of disruptions acting upon systems attributes, and system owners, managers, operators, and users reacting to these disruptions to mitigate the impact on system (and sub-system) performance attributes. McDaniels et al. (2008) built on the work of Chang and Shinozuka (2004) and Bruneau et al. (2003) by mapping the influences between decisions and uncertainty. This approach attempts to integrate risk and resilience by dividing decisions into those made before the disruption and those made after the disruption, and those decisions that affect "robustness" and those that effect "rapidity". These four studies recognize that resilience is a capability of the system that derives from the interaction of the physical, information, and human elements of the system. We agree with this concept and seek to investigate it further.

2.2 *Resilience Modelling and Metrics*

While some authors have created frameworks, others have tended to focus on developing metrics to measure a specific function associated with resilience. We find the framework established by Woods (2006) and Woods (2015) useful for succinctly capturing the essence of the resilience functions and for providing a terminology that can used to classify resilience measurement approaches. Woods categorizes the use of the term resilience into four categories, arranged in order of increasing sophistication and relative value; rebound, robustness, graceful extensibility, and sustained adaptability. The first two perspectives have been studied extensively. Rebound studies tend to focus on actions that can be taken to minimize recovery time such as; investments to harden the system (Woods, 2006), sequencing component recovery (Fox-Lent 2015), and parallel versus sequenced recovery strategies (Summers and Shah 2010). These presume a candidate response strategy and compare variations of these strategies. Rebound studies are not concerned with systems' behaviours, but with developing a sense of the effectiveness of various recovery strategies. While useful for assessing the effectiveness of a given or pre-determined strategy, these papers do not address the bigger question on how a system would arrive at selecting these strategies as an adaptive behaviour. Robustness hardens a system by ensuring there is an "absorptive capacity" so that the system can essentially 'take a hit' without requiring modifications (Madni and Jackson 2009; Alderson and Doyle 2010). Robustness must be assessed regarding a specific class of disruptions. For example, an inland waterway may be robust to a one-thousand-year flood, but brittle when faced with an earthquake.

While rebound and robustness have been extensively investigated in the literature, the concepts of graceful extensibility and sustained adaptability are relatively understudied. The concepts of graceful extensibility and sustained adaptability are best suited for exploring the role of human interaction with system architecture in understanding the ability of a system to maintain continued functionality under stress. While robustness is the ability to withstand a change to conditions without changing its form or function, extensibility and adaptability are concerned with the ability of a system to make the required changes to meet a challenge. These are not competing concepts, when a system pushes against the limits of its robustness, adaptation is needed.

We are interested in the functions of resilience referred to as graceful extensibility and sustained adaptability (Woods 2015). These concepts of resilience are concerned with the ability to make short- and long-term adaptions respectively. Sustained adaptability deals particularly with layered architecture systems. Within the literature there is common agreement that resilience is a behavioural attribute of the system. Behaviours are difficult to measure. Park et al. (2013) argue that "resilience in a complex systems context is a dynamic, emergent property that can only be observed in the context of a specific failure scenario" (Park et al. 2013). Alderson et al. (2014) made the case that a more operational view of resilience was required than proposed by Madni et al. (2009), Haimes (2009) and Park et al. (2013) because these authors use qualitative approaches that do not offer methods for improving resilience. The resilience matrix first proposed by Linkov et al. (2014) and first applied by Fox-Lent et al., (2015) took an important step in bridging the gap between frameworks, metrics, and an operational resilience (Baroud et al. 2014). Table 2 provides a selected summary of models that applied metrics to specific inland waterways, coastal, or intermodal transportation infrastructure under duress in order to assess a specific resilience function.

Table 2. A review of recent studies of transportation system resilience demonstrates an emphasis on modeling recovery operations.

Study	**System Type**	**Resilience function Assessed**	**Ex-ante Decision**	**Post-ante Decision**	**Modeling Study**	**Qualitative Study**
Henry and Ramirez-Marquez (2012)	Road Network	Recovery		x	x	
Baroud, Barker, and Hank Grant (2014)	River Port	Recovery	x		x	
Baroud et al. (2014)	Navigable River way	Recovery		x	x	
Baroud et al. (2015)	Navigable River way	Recovery		x	x	
Francis and Bekera (2014)	Power Distribution Network	Recovery, Robustness	x		x	
Alderson, Brown, and Carlyle (2015)	Commodity Distribution Network	Robustness, Recovery	x		x	
Park et al. (2013)	Inland Waterway	Sensing, Anticipating, Adapting, Learning	x	x		x
Cedergren (2013)	Rail tunnel	Recovery	x			x
Nair, Avetisyan, and Miller-Hooks (2010)(Nair, Avetisyan, and Miller-Hooks 2010)	Seaport	Recovery		x	x	
Shafieezadeh and Ivey Burden (2014)	Seaport	Recovery			x	
Miller-Hooks et al. (2012)	Freight network	Plan, Recover	x	x	x	
Chen and Miller-Hooks (2012)	Intermodal freight network	Recovery		x	x	
Hosseini and Barker (2016)	Inland Port	Recovery	x	x	x	
van Westrenen and Praetorious (2014)	Inland waterway(port)	Adapting	x		x	
DiPietro (2014)	Inland Waterway	Adapting		x	x	
Campo, Mayer, and Rovito (2012)	Inland Waterway	Adapting		x		x
Folga et al. (2009)	Inland Waterway	Adapting		x	x	

3. Complexity, Macrocognition, and Trade-off space

All of these resilience measurement studies fail to adequately account for system complexity and macrocognition. A standard definition of complexity has eluded the research community. Some of the various definitions and perspectives on complexity have been reviewed by Summers and Shah (2010) and Alderson and Doyle (2010). In our own research efforts, we find two explanations for complexity particularly relevant. First is the idea of "descriptive complexity", or the idea that complex systems have "internal structures" which are difficult to convey (Broniatowski and Moses 2016). The second is the idea of heterogeneity. This idea is central to our understanding of complexity in infrastructure systems for two reasons. First, infrastructure systems have many diverse components. Second, empirical observation indicates that these are difficult systems to manage because of this diversity. It is common to think of complexity as a system attribute that

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must be managed (Broniatowski 2017; Moses 2002; Moses 2010). However, we believe that complexity, at least in some systems, adds value and may even facilitate adaptive behavior.

Macrocognition describes the real world, "cognitive functions" made in complex contexts, with high uncertainty, and competing goals (Carlson and Doyle 2002). Klein et al (2003) define five attributes that define how these macrocognitive functions operate in the naturalistic context—contexts involving complex decisions made under time constraints and involving "high stakes and high risk", "ill-defined and multiple goals," and decision makers with limited understanding and control over decision variables. Recent research on "normal chaos" attempts to link complexity and chaos by describing seven factors governing the limited ability of humans to fully comprehend a system, predict its behaviors, and sufficiently update our information and address the correct problem (Lauder et al. 2017). Lauder et al. (2017) claim seven factors for "normal chaos" including; the need to establish system boundaries without forsaking realistic effects of external factors, and human limitations as it pertains to learning from past scenarios and our ability to "collect and process information". These authors also point out that an assumption of "logical and consistent" behaviors from humans is incorrect.

The foundational factors of "normal chaos" and the attributes of macro-cognitive decision spaces re-enforce our view that the study of how resilience, as an adaptive capacity is developed and implemented, must go beyond metric-based analytical models. Modern transportation infrastructure systems require macro-cognitive decision-making processes appropriate for the "naturalistic contexts" (Klein et al. 2003). The research on "normal chaos" extends upon the attributes of macro-cognitive decision spaces, by developing additional insights into why these decision spaces are hard to navigate. Due to the complexity and decentralization of these systems, the primary decisions in these systems pertain not to the details of the operations, but more importantly to the high-level trade-offs being made.

Transportation infrastructure systems are macrocognitive systems. According to Hoffman and Woods (2011), these types of systems are bounded by five "fundamental trade-offs". Ultimately, resilience is determined by a set of control activities designed to align system performance with prevailing values, as determined by these high-level trade-offs. Adaptive capacity is the facility within a system that allows it to navigate the trade-off space, determine a control, and implement this control. In this sense even recovery is an adaptation designed to overcome pressing external threats in order to return normalcy. Table 3 provides a summary of the five bounds and discusses their relationship to resilience.

Table 3: Five Fundamental Trade-offs

Bound	Trade-off	**Explanation and Connection to Resilience**
Bounded Cognizance	"Efficiency-Thoroughness of Situated Plans"	Many highly developed and thorough plans—may result in a set of contingencies that have little to no plan in place. This may limit the ability to recover from unplanned events.
Bounded Ecology	*"Optimality-Resilience of Adaptive Capacity"*	Optimizing the performance of one element of the system, may result in other elements becoming "brittle". It is difficult for all components to be robust to all threats.
Bounded Perspective	*"Revelation-reflection on perspective"*	Different perspectives on the system may be required to fully appreciate the nature of the challenge at hand. Committing to many resources to one perspective, and failing to assess from another perspective may lead to bias in the adaptive or recovery process
Bounded Responsibility	*"Acute-Chronic Goal Responsibility"*	Acute goals are concerned with short term benefits that may undermine more "fundamental" goals of the system. Limiting the impact to chronic goals while obtaining benefits from acute goals may impact investment decision guiding robustness and recovery decisions.
Bounded Effectiveness	"Concentrated-Deliberate Action"	Centralized control may enable the system to act quickly, but decentralized control may allow for a broader set of issues to be considered in more depth. In complex interdependent systems, this trade-off may impact the ability of the system to understand the nature of the problem at hand.

4. The Role of Architecture in Resilience

4.1 *System Architecture*

There is a large body of literature discussing the theoretical aspects of *systems architecture.* The aim of this research is to advance our understanding of how system architecture impacts resilience. For our purposes we rely on the definition provided by Selva et al. (2016)—system architecture is "the embodiment of concept, the allocation of function to elements of form, and the definition of relationships among elements and with the surrounding context." Additionally, we approach architecture from the perspective of the users, or the "operational view" (Kossiakoff et al. xxxx). This perspective is appropriate, as the operators have the most direct influence on system's resilience. Systems architecture is used in range of engineering and biological domains, as will be discussed later. Techniques vary as well; from the purely mathematical (Marmsoler et al 2015) to the more narrative and visual (Doyle and Csete 2011; Broniatowski and Moses 2016). Depending on the purpose behind a particular architectural decomposition, many different architectural models may be used such as layered architecture (Marmsoler et al 2015), a networked approach (Alderson et al. 2015), or a purely hierarchal approach (Simon 1962).

4.2 *Network Architecture*

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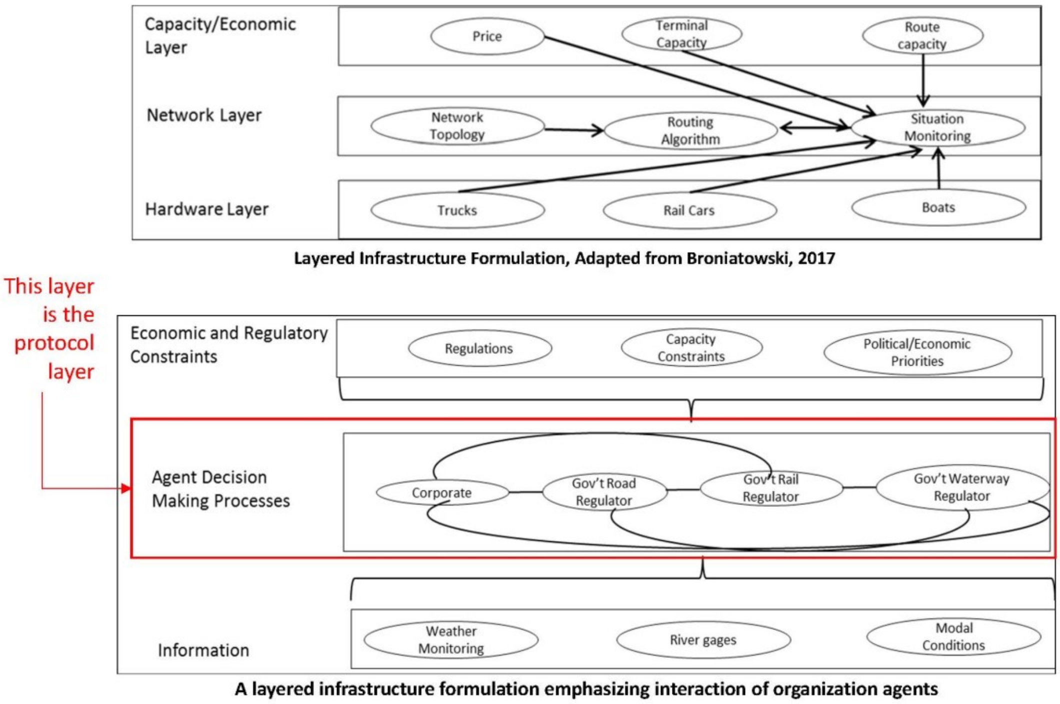

Figure 1. Layered Hierarchy Examples

We can think of multi-modal transportation systems as either a network or a layered hierarchy (Broniatowski 2017). The network formulation requires us to think of an interconnected set of nodes, where each node is connected by a capacitated, modal specific, arc. Network formulations lend themselves well to optimization methods such as linear programming. The complexity arises from the size of the network, and the variety of capacity constraints. Network structures are very intuitive and ease the comprehension of the network. The ease of visualization and optimization has allowed a number of authors to explore system adaptability, recovery, and resilience in the face of disrupted network elements. However, this formulation does not capture all elements of the system such as the technology, information flow, and organization of a system. This is better addressed by a layered architecture.

4.3 *Hierarchal Architecture*

In his seminal work, Herbert Simon, asserts that a hierarchal structure is a key attribute of a complex system (Simon 1962). His definition of hierarchy is "a system that is composed of interrelated subsystems, each of the latter being, in turn, hierarchic in structure until we reach some lowest level of elementary subsystem." Moses (2002) calls these *Tree Structures.* In addition, he observes that other types of architectures, layered for example, can exhibit hierarchal. Layered architectures, discussed in the next section, exhibits attributes of a hierarchy, but with a more flexible and an abstract method for decomposing the system.

4.4 *Layered Architecture*

Several authors discussing the related topics of robustness, complexity, adaptation, and resilience have chosen to emphasize a "layered infrastructure" (Doyle and Csete 2011; Carlson and Doyle 2002; Csete and Doyle 2002; Doyle et al 2005). Similar to Simon, these authors drew upon examples from evolutionary biology and engineering, and the difference between "layered" and "hierarchal" is nuanced, but pivots on the critical concept of "protocols" and "abstractions" (Rasmussen 1985). Layers can refer to a hierarchy of physical dependencies, but also a related set of "abstractions". Although Rasmussen (1985) introduced a relational hierarchy of abstractions ranging from the purely "physical form" to the more abstract "functional purpose", Broniatowski et al. (2017) made the connection between abstraction and layering.

The concept of "layered" infrastructure is centered on the concept of a "layer", both how it is defined, and how it relates to other layers. The concept arises in biology (Gerhart and Kirschner 2007), software development (Marmsoler, Malkis, and Eckhardt, 2015), the internet (Doyle et al. 2005), and transportation (Broniatowski 2016) among other areas. Figure 1 illustrates the layered hierarchy concept. The general idea of a layer is that of a semi-independent process, which does not derive its form or functionality from adjacent processes. Each process or layer may receive input from adjacent layers, but unlike a tree structure, does not rely on on-to-one dependency. This broad definition of a "layer" is drawn from explanations and examples presented by several authors. While Moses (2002) provides the philosophical and algebraic underpinnings of the concept, the most thorough mathematical formulation is presented in Marmsoler et al. (2015).

An alternate perspective is the idea of "layered" architecture as a network of interacting constraints; including, component constraints, protocol constraints, and system constraints (Doyle and Csete, 2011). Components are the individual subsystems which together form the system. Both the components and the whole system are constrained. The system as a whole has a set of constraints which emerge from the interaction of components, and are not equivalent to the additive properties of the components. These components can be considered modules, with "identifiable interfaces", the "potential for independent modification" and the ability to "facilitate abstract modeling".

How components connect within and across layers impacts system performance (Gerhart and Kirschner 2007; Simon 1962); therefore, protocol layers, are the dominant influence on a system's resilience. Lifeline infrastructure systems evolve over time, and are a combination of long-term strategic plans and short term improvised solutions to immediate problems. To explore these connections, we employ a layered architecture approach that allows us to capture the interacting organizational system elements that are non-physical or straddle the boundary between physical and informational.

5. Protocol Driven Resilience

Several of the resilience frameworks discussed above recognizes that resilience is a capability of the system derived from the interaction the physical, information, and human elements with the disaster. We agree with this general concept. The resilience matrix demonstrates that there is an interaction between individual domains and the phase of the disruptive event but does not show the interaction between domains (Linkov et al. 2013). The influence diagram proposed McDaniels et al. (2008) relates decisions to be made throughout the course of the duration event with uncertainties and demonstrates how these impact "robustness" and "rapidity". However, neither of these frameworks discusses how decisions are made, and how system domains interact. Our research program builds upon this line of work by arguing resilience functions, specifically adaptive capacities, result from a system's architecture. Moreover, we call the way in which the human network of relationships, operating protocols, evolving objectives, and information sharing processes produces resilient system behaviour *protocol-driven resilience*.

Protocol driven resilience is the ability of a system to self-organize in the face of disruption or disaster in order to adapt system functionality or configuration to the new events. We assert that the ability of a system to alter its operations to adapt to external stress lies primarily in the human processes responsible for receiving system signals, analysing system compliance with dominant requirements, and directing an activity to bring the system in line with these requirements.

In Francis and Amodeo (2018), we write:

> 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. 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: "If we are dealing with a system profoundly affected by changes external to it, and continually confronted by the unexpected, the constancy of its behaviour becomes less important than the persistence of the relationships." As Holling writes in the same article: "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—even after Rinaldi, Perenboom, and Kelly (2001)—but has been focused on measuring stability.

Society has built and operated critical infrastructure systems, to date, to provide robustness or hardness against disruption or unanticipated events. However, it is possible that we should consider ways in which these systems contain improvisational capacities to respond to disruptions and minimize system brittleness. Moreover, infrastructure cognitive processes—especially those attributable to human systems operating infrastructures—have been understudied. It is critical to extend investigation into the role of infrastructure cognitive processes in providing resilient system behaviour.

For complex layered systems, such as a transportation system, most cognitive processing exists in within the protocol layer. Through these layers humans interact with informational and physical system layers. A system's adaptive capacity emerges from the nature of the interactions between protocol layers and the physical and informational layers. We define this as protocol driven resilience (PDR). Transportation infrastructure is expensive and slow to build. Once the major assets are in place, changing the network structure becomes increasingly infeasible. Therefore, adaptive capacity lies in the ability of the protocol layers to change the way the system is operated. Our ongoing research demonstrates the effect of adaptations in the protocol layer using data from inland waterways in the Southeastern United States.

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