Function-Based Resilience: Improving Performance through Adaptive Management

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SUMMARY & CONCLUSIONS

Adaptive management through performance measurement is essential for all resilient systems. The authors maintain that the application of resilience objectives aligned with primary functions is the preferred technique for design, evaluation, and performance over the life-cycle of complex systems. It is noted that an approach based on primary functions tends to underemphasize secondary functions and unknown factors that may have meaningful impact on the resilience of systems with longer life cycles. However, the practical aspects of focusing on primary functions outweigh the time required for detailed debate of secondary or unknown factors, especially in the case where there is a culture of performance measurement and a culture for change. Across many sectors, more post-implementation emphasis is needed on performance measurement, analytics, effective communication, and adaptive management.

1 INTRODUCTION

Resilience is an overworked, poorly understood and evolving term in its application to both the built and natural environment. The relationship of resilience to reliability and risk has become increasingly confusing to practitioners in recent years. Much of the confusion stems from applying these terms to a wide variety of contexts in lieu of clear definitions or understanding of time frames. For example, the environmental sector has made the term synonymous with "sustainability" and utilizes a long timeframe. Other sectors that focus primarily on operational resilience, such as the physical security and the aviation sectors, have a shorter timeframe as part of "resilience engineering".

The intellectual overlapping of resilience and risk is understandable, since resilience embodies a system's ability to adjust the way it functions in order to sustain key operations, notwithstanding whether changes are expected or surprising [1]. Resilience and risk depend much on an individual practitioner's perspective. Sound decision making and project evaluation depend on how well the practitioner can establish or confirm the design objectives of the project, as well as those of related systems' functions. Likewise, establishing measurable (and, ideally, quantifiable) performance criteria and communication protocols are essential for adaptation and continual improvement. For both resilience and risk, whoever is framing it, measuring it, interpreting it, and learning from it, are fundamental to the perception of its effectiveness.

Traditionally, risk is commonly expressed as a function of both the severity of outcome and the likelihood that the outcome will occur (See Figure 1). What is missing from this traditional matrix is whether a system can adapt. That is, even an extremely severe outcome, although certainly unwelcomed, may not be devastating if a system can return to the initial state in a reasonable time. To date, the concepts of resilience and risk have both lacked a proper characterization of this factor, i.e. time. While the definition of reliability contains a time element, in practice the time established in the reliability statement, or basis of design, is often forgotten, especially in an age where society asks for its systems to serve long after their design lives have passed. Time is an element that must be established for systems to be perceived as resilient.

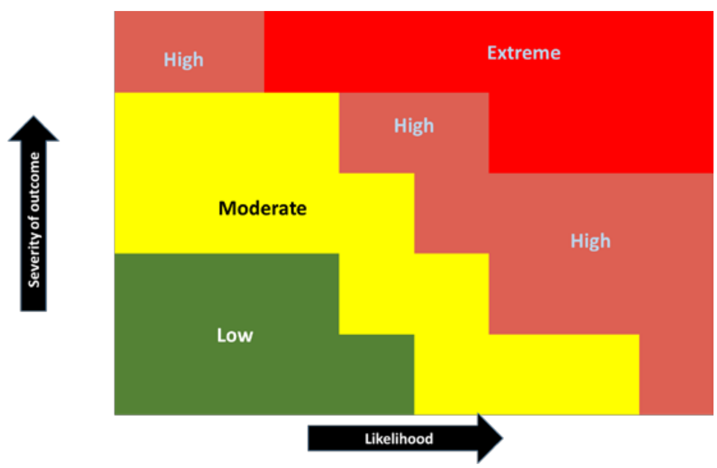

Figure 1. The traditional risk matrix. Adapted from: Hollnagel, E., D.D. Woods, and N. Leveson, Resilience engineering: Concepts and precepts. 2007: Ashgate Publishing, Ltd.

Resilience is traditionally defined as the ability to *return* to the original form or state after being stressed [1]. According to the American Society of Civil Engineers (ASCE) Policy 518 related to critical infrastructure, resilience refers to the capability to mitigate against significant all-hazards risks and incidents and to expeditiously recover and reconstitute critical services with minimum damage to public safety and health, the economy, and national security [2]. Other definitions of resilience, particularly from the built environment that includes buildings and infrastructure, define resilience as the ability to *withstand* stress or disturbance.

Driven in large part to change policy in recent years related to climate change and sea level rise, the US Environmental Protection Agency has been a leader in expanding the definition of resilience to the capacity for a system *to survive, adapt, and flourish* in the face of turbulent change and uncertainty – in essence, to return to a state *beyond* the original basis of design by anticipating future trends and adapting natural systems to those anticipations [3]. This has created some confusion, particularly in the environmental sector, as to whether the end goal of resilience should be *to return* or *to improve* the system beyond its basis of design, or inherent reliability. A practical consequence is the errant perception among many resilience practitioners is that traditional reliability approaches are not sufficient. This has led to a movement for new resilience-specific design standards and approaches.

For the purposes of this paper, the major sectors are generally discussed as the built environment and the natural environment. In practice, these sectors can also be described in six categories: buildings, infrastructure, and vehicles; information systems and cyber security; security and worker health & safety; ecosystems; human health; and social systems.

A foundational element of resilience is establishing the "system" and its desired outputs. Definition helps provide understanding into key issues: system boundaries; scale and scope; timeframe; system objectives/functions to be protected, restored, and/or improved; and performance measurement.

2 KEY DEFINITIONS

A brief overview of key definitions related to key concepts associated with resilience are provided as a basis for common understanding. This overview also demonstrates the potential variability of the meaning of key concepts, even among technical professionals, and to underscore the need for improved facilitation and communication when planning, designing, measuring, improving, and evaluating resilience.

2.1 System

ISO 9000 defines a system as set of interrelated or interacting elements [4]. One leading international systems organization defines a system as a construct or collection of different elements that together produce results not obtainable by the elements alone [5]. One ecosystem-focused reference defines a system as the set of state variables together with the interactions between them, and the processes and mechanisms that govern their interactions [6].

One observation is that different sectors have somewhat different definitions of a "system". A second observation is that defining system (and subsystem) boundaries and interfaces can be subjective. However, an overarching theme associated with most system definitions is that a system should include both its physical and social (human) aspects.

2.2 Function

The SAE JA 1011 Standard defines a function most simply as "what the owner or user of a physical asset or system wants it to do." Functional failure is defined as "a state in which a physical asset or system is unable to perform a specific function to a desired level of performance" [7]. Function is therefore related to both system objectives and system performance. Functions can also be either primary or secondary. For physical assets, a primary function commonly appears on an asset's nameplate (a pump's primary function is to pump). Secondary functions may be such things as regulatory compliance, protection, comfort, appearance, or efficiency.

Function is a key aspect of quality, since quality is indicated by the extent to which a system functions properly. A system that meets its functional objectives is a high-quality system. Function, then, is driven by both efficiency and effectiveness. Of the two, efficiency is more easily measured, at least in thermodynamic terms, i.e. total output compared to inputs. However, effectiveness is the more important metric, i.e. the difference between the initial state and the desired state resulting from the project. Thus, a system may be efficient, yet wholly ineffective, if we are no closer to the desired state, i.e. achieving the desired function, after project completion.

2.3 Adaptive Management

A working definition of adaptive management is simply 'learn as you go'. The US Department of the Interior defines adaptive management as a systematic approach for improving resource management by learning from management outcomes. Adaptive management as a modern management approach is most directly aligned with ecosystem management.

However, a number of sources attribute its roots to Frederick Taylor, the father of scientific management, and on whose work the foundation of Total Quality Management (TQM) is based. The Department of the Interior also cites parallel concepts that have helped shape adaptive management from a variety of perspectives, including business (Senge), experimental science (Popper), systems theory (Ashworth), and industrial ecology (Allenby and Richards). And experts in the field of operational resilience also cite adaption and adaptability as key aspects of resilient systems. "Resilient systems are able to recognize that adaptive capacity is failing or inadequate to the contingencies and squeezes, or bottlenecks, ahead [9]."

2.4 Reliability

Reliability most often is defined as the probability that an item will perform its intended function for a specified interval under stated conditions. This definition was somewhat institutionalized in the post-World War II era by the aerospace and US military sectors. It has been adopted in similar form as the dominate definition among all industry sectors that have formal reliability approaches and standards. However, social sciences often define reliability or analogous to repeatability or dependability.

The most common definition contains four distinct parts from a systems perspective: a probability, which means there is some uncertainty; a function (or functions); a stated interval or time period; and stated or assumed operating and environmental conditions. The definition of reliability is very objective and specific, and in turn lends itself to the ability to assign quantitative numbers. It has also been adapted into what design engineers commonly refer to as the 'basis of design'.

2.5 Risk

Risk is defined by the international risk standard, ISO 31000, as "the effect of uncertainty on objectives." Risk by technical definition can be either positive or negative; however, it is commonplace to consider risk as being a loss or not meeting expectations. Important to resilience, the standard definition states that objectives are related to expectations, and both expectations and objectives can vary depending with the level of an organization or with different types of stakeholders.

3 CONCEPTS AND CONTROVERSIES

This section highlights some common issues around the practical application of resilience in planning, designing, measuring, evaluating, and improving systems.

3.1 Scale and Scope

System definition is established through expression of the of the mission of the system of interests, the needs and requirements of stakeholders, the physical elements of the system, their interconnections (both physical and virtual), human interactions, and operational concepts. Whether in design or whether analyzing system problems/failures, a system map is normally used to create a common understanding of boundaries, physical elements, core processes, feedback systems, inputs, outputs, and outcomes.

Establishing scale and scope is important in the evaluation of system resilience. There is a natural human tendency to decompose larger, more complex systems into smaller system blocks. Achieving resilience in the smaller blocks does not ensure resilience of the overall system, like adequate outputs of each block does not necessarily equate to desirable outcomes of the larger, more complex system.

3.2 Time

Time is also another critical element and often overlooked consideration when evaluating resilience. Human nature, and our core technical training, leads to a tendency to break complex systems into more manageable blocks but also to use shorter timelines in our decision making. Therefore, many physical systems are evaluated for shorter term efficiency and production standards over a few decades, while natural systems or ecosystems may be evaluated in terms of centuries. In crisis situations, systems resilience (better termed as operational resilience) is evaluated in terms of minutes, hours, or days.

3.3 Direct, Secondary, and Cumulative Impacts

System impacts can be viewed as direct, indirect, and cumulative. Direct impacts are typically obvious and occurring in the short term, indirect are usually further in time but still typically foreseeable, and cumulative are further in time, often less foreseeable, and result from actions that are individually minor but collectively significant. Potential impacts can be mapped to system functions. Shorter time scales often drive more focus on primary functions and direct impacts. Long time scales, and arguably resilience thinking, must incorporate all. A practical limitation is being able to predict and properly account for all factors over longer time frames. Probabilistic analysis helps provide better understanding; however, the typical result in practice of looking too long related to less foreseeable impacts is stagnated decision making and inaction.

3.4 Efficiency versus Resilience

Efficiency is a cornerstone of economics and production. One school of thought in resilience is that efficiency, measured over the short-term, is counter to truly resilient systems. Another school of thought is that systems have a natural lifecycle that allows harvesting during certain periods of time but that in other periods the system must be allowed to recover and adapt. In this school of thought, systems can be considered efficient is terms of production as long as such systems are operated below pre-determined thresholds and allowed to recover over dedicated periods of time. Fishery and forest management are often site as examples, but also have their critics. Performance measures and monitoring as well as adaptive management to avoid crossing thresholds is needed to assure resilience.

3.5 Degradation, Sustainability, or Improvement

In terms of resilience, systems can be evaluated under three frames when considering their responses to distress. The classic definition includes the return to a normal state after distress. One perspective is that all systems are degrading, and therefore recovery is to an acceptable level of functionality but never fully to the original state. A second perspective is that a system should fully recover to the original state, and therefore the system is 'sustainable'. A third perspective is that systems should be adaptable over time, and there not only meet their original states but also achieve a state beyond the original basis of design. In reliability theory, this is called reliability growth and occurs as components and human performance improves with time. However, the inherent reliability of a system cannot exceed its inherent design without some form of additional investment and re-design. The slippery slope related to physical systems in terms of adaptive improvement without re-design implies that 'having the right tool for the right job' is not as important as having high performing operators and mechanics.

3.6 Measuring, Monitoring, and Continual Improvement

Human decision making and societal focus on short-term investment efficiencies are in many ways counter to resilience thinking over full system lifecycles. In many industrial settings, system performance is most focused on measuring yearly performance efficiencies (outputs) and maximizing capital investment paybacks. In terms of longer term infrastructure systems and ecosystem enhancement, performance measures directed toward longer-term, lifecycle improvements (or outcomes) are sacrificed for shorter term program needs. However, continual improvement requires some degree of performance measurement.

3.7 Concepts and Controversies Summary

Resilience is a complex topic with many layers for consideration. Like risk, resilience often depends on where one stands. This section outlines a number of key considerations. It underscores the need for improved communication, education, and facilitation related to resilience concepts. Given the many issues associated with resilience thinking, establishing basic system components, primary functionalities, and a reasonable level of measurement are keys to getting decision makers to make investments that lead to more resilient systems.

4 SURVEY

A survey was developed, administered and evaluated in support of this paper. The form of the survey was a modified Delphi format: a brief survey was administered to a collection of resilience practitioners; the results were provided to the respondents and their comments collected; a second round of questions was administered to respondent based on the results and feedback provided from the first round; and respondents were provided with results of the second round with an opportunity to provide additional comments.

The survey was conducted in June and July 2017. The initial survey was provided to a group of 54 resilience practitioners. Resilience practitioners were defined as professionals whose major job responsibilities are related to system development, management, improvement, and decision making. Resilience policy-oriented professionals were not included nor were front-line staff who were not decision makers responsible for the allocation of resources.

Resilience practitioners were based primarily in the eastern United States. A balanced representation from 4 industry sectors was targeted: built systems (buildings, infrastructure, vehicles); natural systems (biological and ecosystems); security and human health & safety; and information systems. A balanced distribution of representation from public and private sector organizations was also targeted.

There were 30 responses to the initial survey (56%). Respondents self-affiliated themselves primarily with the built environment (64% built, 23% security/H&S, 10% information, and 13% ecosystems). The majority of first round respondents also responded to the second round of survey questions.

Some of the key results were:

- 63% had the opinion that resilience was focused on returning to the normal state.
- 70% responded that there was a fundamental difference in evaluating resilience for natural systems versus built systems.
- 93% responded that human factors and human errors have a significant impact on resilience.
- 57% believed that resilience could only be improved by system re-design.
- 83% said their organization had a formal continual improvement program. However, respondents were evenly split on whether their organization had a written root cause analysis process.
- 66% percent responded that the term adaptive management was not well understood by their organization.
- 77% said their organization understood its primary functions to its customers and/or the public.
- 57% responded that their organization were primarily focused on prevention- or risk-based approaches to minimize system failures.

5 CASE EXAMPLES

5.1 Built System

The Orange Water and Sewer Authority (OWASA) is a public, non-profit agency that provides water, sewer, and reclaimed water services to the Carrboro-Chapel Hill community including the University of North Carolina at Chapel Hill and UNC Hospitals. OWASA was officially began operation in 1977. Although improvements and enhancements have been made to the water treatment plant (WTP) since 1977, its fluoride subsystem is 15 years old and primarily manually operated and monitored. There is a high degree of redundancy in the plant, including the fluoride subsystem, since the plant provides public drinking water. OWASA also has a redundant water supply through an interconnection with the City of Durham. There have been no major performance violations or unplanned outages associated with the plant in 40 years.

On February 2, 2017, at 3:22 pm, management decided to shut down the WTP due to an excessive amount of fluoride present within the plant. Immediately following shut down, the interconnection with the City of Durham also failed. The entire service area was without water for 24 hours and had restricted use for three days. In addition to normally expected inconveniences to the service area, including the hospital, the UNC-Notre Dame basketball game was moved to another city and local merchants were also impacted on Super Bowl Sunday.

On February 6, OWASA requested that CH2M conduct a root cause analysis (RCA) of the WTP shut down and provide a draft report by Friday, February 10, 2017. The report concluded that human errors were the primary and secondary causes of system failure.

OWASA's finished water is regularly tested and its operators are certified by the state. Although old and not highly automated by some standards, the plant's design incorporates a meaningful amount of redundancy and other provisions for reliability. OWASA's senior management team tracks and publishes a Key Indicators and Performance Measurements dashboard, including the WTP performance, on its web site. The plant has a well-maintained maintenance management system. The organization has a formal continual improvement program and regularly conducts different levels of root cause analysis in response to system failures, including retaining outside consultants such as in this case.

Most decision makers and stakeholders believe that the WTP performed in a resilient manner. The plant resumed full operations within a short time period, physical and human system deficiencies were improved efficiently, and there was no injury or death from the system distress. However, some observations and questions are worth further consideration:

- A public WTP system is highly monitored. Would the distress have been mitigated as quickly without a high level of performance measurement?
- Would the opinion of resilience have been different if human injury or death had occurred (or UNC lost the basketball game)?
- The system improvements proved to be relatively easy and economical to fix. Was the system truly adaptive? If so, why had the system not been improved sooner?
- Would the opinion of the resilience of the system been the same without the performance of a root cause analysis and quick execution of continual improvement measures?

5.2 Biological System

The resilience of a natural or engineered system must consider be considered for both human populations, such as the ability to adapt to an adverse event, such as an explosion or accident in which toxic agents are released. In many ways, the resilience of these systems is similar to that of the previously discussed WTP example. However, the situation is less predictable in terms of where the stress will occur and how long the stressor is present. For example, recent study showed that if an accidental release of a gaseous contaminant were released in an urban setting, there is a large timeframe range before the gas concentrations were no longer detected [10]. Factors determining this decontamination timeframe included the amount of the gas that penetrated buildings, air intake locations, subway activity and behavior of persons. Interestingly, distance from the gas release location was not always a good predictor of either peak concentrations or decontamination time.

For ecological resilience, the ability to adapt to an insult is best described in terms of biological state, i.e. ability to return to a desired state following the insult. Certain habitats are not particularly resilient, making them vulnerable to adverse outcomes that are irreversible [11].

As for ecological risk, ecological resilience can be expressed as a stressor-receptor relationship. The stressor may be chemical (e.g. DDT causing stress to top predators as it builds up in the food chain), biological (e.g. invasive species diminishing the abundance of native species), or physical (construction of roads that destroy connectivity of habitat which changes predator-prey relationships). If these problems are reversible, the system is more likely to adapt (e.g. a permanent road versus storm damage both diminish connectivity, but the former is permanent). In this sense irreversibility is indirectly proportional to a system's resilience. For example, habitats shown in the lower left-hand region of Figure 2 would more likely endure irreversible harm from exposure to stressors that damage habitat (e.g. acidic rainfall), than those in upper right-hand region.

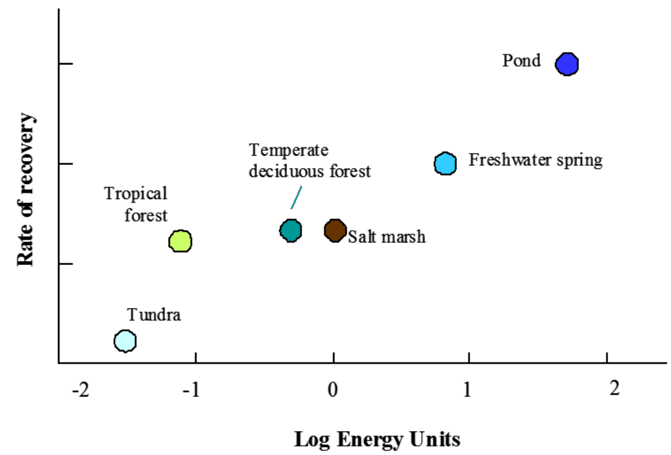

Figure 2. System resilience index calculated from bioenergetics for six community types. Rate of recovery units are arbitrary; energy units = energy input per unit standing vegetation. Source [12]; data [13, 14].

Thus, biological resilience can be considered to be the ability of an organism or an entire ecosystem to withstand a disturbance without shifting to an alternative state and being continue to function as if the disturbance had not occurred [14]. From an ecological perspective, resilience can be quantified as the magnitude of disturbance that is needed before a state shift occurs [13, 15], e.g. if a hypothetical tundra forest system loses 75% of its canopy species with an average decrease of 2 inches of rainfall per year, but a temperate forest loses none of its canopy species with the same rainfall decrease, the temperate forest is exhibiting resilience in its function and structure when confronted with for the drought stress.

Another key metric of resilience is the rate of recovery. Consider two tundra forests that experience a decrease of 50% of their species abundance due to a drought-exacerbated insect infestation. The first does not regain the diversity in five years, but the second recovers in two years. Thus, the second forest is more resilient. The concept of biological recovery is analogous to hysteresis in physics and engineering.

6 CONCLUSIONS

This paper frames and clarifies several aspects of resilience for professionals charged with reliability and maintainability of systems. Establishing common definitions, establishing consensus around timeframes, and implementing monitoring programs are critical for adaptive management and creating resilient systems. Resilience is complicated by subjectivity in terms of who is establishing its basis, who is interpreting it, who is learning from it, and who is adapting from lessons learned.

The authors maintain that the application of resilience objectives aligned with primary functions is the preferred technique for design, evaluation, and performance over the life-cycle of complex systems. It is noted that an approach based on primary functions tends to underemphasize secondary functions and unknown factors that may have meaningful impact on the resilience of systems with longer life cycles. However, the practical aspects of focusing on primary functions outweigh the time required for detailed debate of secondary or unknown factors, especially in the case where there is a culture of performance measurement and a culture for change. More post-implementation emphasis is needed on performance measurement, analytics, effective communication, and adaptive management.

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