A Generic Framework for Resilience Assessment[i]

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From pre-event to (pre+post)-event strategies

Quantitative risk assessment emerged in the 1950s, characterizing risks as a frequency distribution over the consequences. Modelling the tail of those distributions, extreme value theory has been the dominating approach to predict low-probability – high-consequence events, thus answering the questions "what can go wrong? What are the consequences?" In this case**, risk assessment is a pre-event strategy**, based on the precautionary principle. The ongoing urbanization led to increasing coupling strength and decreasing heterogeneity, both within and between systems. Those trends are pushing many socio-technical systems to critical states, at which they are moving into a behavioural domain that we did not observe in the past, and which is providing 'outliers' (Black Swans, Dragon Kings) in the tail of distribution, making reliable predictions of extreme events challenging or even impossible. This calls for novel approaches, among which **resilience assessment and management – a post-event strategy** - is a first importance to boost system's recovery, reconfiguration and adaptation.

A resilience framework based on eight generic functions

In the last decade, the resilience concept gained much attraction, and policymakers, practitioners and academics have been using it widely and enthusiastically (McAslan, 2010). It has been around for quite some time (Jackson, 2015), having its origin in the engineering of materials, emerging later in the area of psychology, and becoming an important paradigm in ecology. In its essence, resilience is the "capacity of a system to absorb disturbances and to reorganize so as to retain essentially the same structure, function and feedback loops" (Walker & Salt, 2012). The resilience and policy committees of the National Academy of Sciences (NAS) defined resilience as the ability of the system "*to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events*" (Cutter et al., 2012, Cutter et al. 2013). The two definitions are embracing two fundamental properties that are interacting symbiotically, systems' resistance and systems' resilience. The traditional engineering approach has been to design systems for resistance such that

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they can withstand characteristic exogenous and endogenous actions. Going back to the Latin word resilire, resilience on the other hand means to spring and rebound.

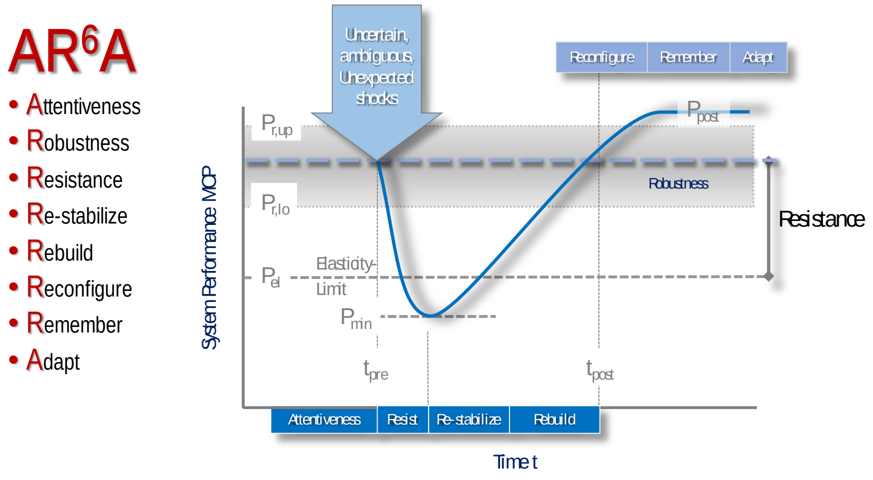

Figure 1: Resilience concept based on eight generic functions: attentiveness, robustness, resistance, re-stabilization, rebuilding, reconfiguration, remembering, adaptation

We propose a resilience framework (figure 1) that is based on eight generic system functions: attentiveness, robustness, resistance, re-stabilization, rebuilding, reconfiguration, remembering, and adaptiveness, which we characterize with the AR^{6}A acronym. We measure systems performance (MOPs), represented as the y-axis.

- **Robustness** refers to that range of performance – defined by an upper and lower limit – that guarantees a continually expected flow of services.
- **Resistance** is the ultimate limit of a system to withstand actions that are straining it during its lifecycle. Structural engineering resistance often equals the elasticity limit, beyond which non-recoverable deformations will occur. If a disruption is straining a system, its performance will decrease down to a minimum (P_{min}), which can become zero in a worst-case. Resilience stems on resistance.
- The recovery phase consists of the two functions, **re-stabilize** and **rebuild**, aiming to re-establish critical systems functions up to a range that enables survivability, to rebuild all the functions and to re-establish normalcy, respectively. We have to emphasize that system recovery is an active concept that is mobilizing additional resources, which differs from a 'laissez-faire' approach.
- **Reconfiguration** means to adapt and change systemic properties by introducing or deleting interdependencies, or introducing or deleting components. Our experience shows that reconfiguration rarely happens with man-made systems. It also requires to change or enhance the system boundaries to address the key issue "how should we adapt the topology of the system" to make it more resistant and more resilient.
- **Adaptation** means to continue to enhance a system's abilities to improve the fitness to cope with disruptions and to increase survivability.
- **Attentiveness** and **remembering** are two 'cognitive' functions, encapsulating the ability to anticipate, and to detect endogenous and exogenous disruptions, and to memorize and learn from earlier disruptions, enabling a system to respond more rapidly and more effectively to future disruptions.

Scholars have been using sets of functions and attributes to operationalize the resilience concept (Bruneau et al., 2003; Cimellaro et al., 2010: Ganin et al., 2016; Linkov et al., 2014; Madni & Jackson, 2009; Planz & Levis, 2015; Tierney & Bruneau, 2007). The earthquake engineering community usually relies on four attributes - robustness, resourcefulness, redundancy, and rapidity - while the NAS resilience and policy committees proposed six functions (Cutter et al., 2012, 2013) that are quite different, which demonstrates that resilience assessment is still emerging. All of the proposed approaches are stemming on the resistance function, characterizing it with attributes such as the capability to absorb, or to provide redundancy. They are additionally characterizing the capability to recover with attributes, such as rapidity, resourcefulness, response, or recovery. The NAS definition additionally considers awareness and adaptation. Our approach brings in two 'cognitive' functions – awareness and remembering –, which we borrowed from the biological immune systems, which are a model for business resilience (PWC, 2015). It additionally splits the recovery function into re-stabilizing and rebuilding, which are typical phases in the wound healing process. Since our eight-function concept is generic, it should be easily transferable to any kind of system. Our experience with stakeholders shows that they can easily understand the eight functions, whereas it is difficult for them to understand the resilience concept based on a specific definition.

Transferring the resilience concept into socio-technical systems

Infrastructure systems are a compound of engineered, organizational and user subsystems, at which we have to look as a whole. Considering that social components triggered many system failures, the implementation of a resilience framework has to address the human factors within a system first. The first step consists of raising awareness and of developing a new mindset how to combine pre-event and post-event strategies to cope with future disruptions. In a second step, key people have to walk systematically through the eight generic system functions. The restabilising, rebuilding and reconfiguring functions need special attention because they often happen under a 'laissez-faire' regime, while tool-supported, active intervention can make them much more effective, supporting systems to recover much faster. Resilience is a dynamic phenomenon that we can only observe if there is a reliable body of time series data, which is unfortunately often missing. A third step should consist to develop a 'sensing concept' to capture key system performance indicators that will allow us to quantitatively characterize and assess resilience in the future.

Assessing and Measuring Resilience

The quantification of resilience stems from work done in the earthquake engineering community (Bruneau et al., 2003; Cimellaro et al., 2010; Tierney & Bruneau, 2007). It looks at how systems' performance is falling down after a disruption and how it is recovering afterwards, mapping the resistance and the recovery functions on some metrics. The term robustness is used mostly instead of resistance, which we are convinced is more appropriate because it is the essential concept in the engineering standards, requiring a system to resist against a set of actions. Scholars have been using this "bathtub" resilience metrics, but there is still a demand for a more comprehensive approach. Looking at our eight resilience functions, we are striving for an index, into which five functions - resistance, robustness, recovery (restabilize, rebuild), and reconfigurability - are going in. We assume that plotting such an index as a time series will be a representation of the adaptability in a longer run. Additionally, there is a need for an assessment of the "cognitive" resilience functions – awareness and remembering.

Annotated Bibliography

Bruneau, M., Chang, S.E, Eguchi R.T., Lee, G.C., O'Rourke, T.D, Reinhorn, A.M., Shinozuka, M., Tierney, K., Wallace, W.A., and von Winterfeldt, D. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra*. 19(4): 733.
Paper that framed and conceptualized the "bathtub" resilience metrics and defined four resilience attributes - robustness, redundancy, resourcefulness, rapidity. The first general engineering resilience framework proposed.

Cimellaro, G.P., Reinhorn, A.M., & Bruneau, M. (2010). Framework for analytical quantification of disaster resilience. *Engineering Structures*. 32 (11): 3639-3649.
Based on four resilience functions - robustness, redundancy, resourcefulness, rapidity - the paper provides an alytical framework. Loss functions have been in use in the earthquake engineering community, while recovery functions have to be developed. The authors proposed three types of recovery functions: linear, exponential and trigonometric.

Cutter, S.L., Aheard, J.C., Amadei, B., Crawford, P., Galloway, G.E., Goodchild, M.F., Kunreuther, H.C., Li-Vollmer, M., Schoch-Spana, M., Scrimshaw, S.C., Stanley, E.M., Whitney, G., and Zoback, M.L. (2012). *Disaster Resilience - A National Imperative.* Committe on Increasing National Resilience to Hazards and Disasters, Committee on Science, Engineering, and Public Policy, Vol. Washington, DC. The National Academic Press. 244 p.
Report of a US National Research Council (NRC) to address the issue of increasing resilience to disasters. Had to (1) define "national resilience", (2) to provide goals, baseline conditions, or performance metrics for US resilience; (3) to describe the state of knowledge about resilience to hazards and disasters; and (4) to outline issued to be addressed. Defined resilience as a set of six functions: (1) prepare and (2) plan for, (3) absorb, (4) recover from, (5) adapt to actual or (6) potential adverse events.

Cutter, S.L., Ahearn, J.A., Amadei, B., Crawford, P., Eide, E.A., Galloway, G.E., Goodchild, M.F., Kunreuther, H.C., Li-Vollmer, M., & Schoch-Spana, M. (2013). Disaster resilience: A national imperative. *Environment: Science and Policy for Sustainable Development.* 55 (2): 25-29.
Article on the 2012 US NRC report on disaster resilience.

Ganin, A.A., Massaro, E., Gutfraind, A., Steen, N., Keisler, J.M., Kott, A., Mangoubi, R., & Linkov, I. (2016). *Operational resilience: concepts, design and analysis.* Nature Scientific Reports. 6 (19540): 1-12.
The paper proposed quantitative measures to capture and implement the definition of engineering resilience advanced by the US NAS. The paper demonstrates the formulation on two classes of models: 1) multi-level directed acyclic graphs, and 2) interdependent coupled networks. Interesting recovery process model in coupled networks.

Jackson, S. (2015). Overview of Resilience and Theme Issues on the Resilience of Systems. *INCOSE Insight*. 18 (1): 7-9.

The paper discusses resilience from a systems engineering perspective, emphasizing that the scope is either on socio-technical systems - a compound of engineered, organizational and user subsystems, or on systems of systems, both governed by interdependencies. Proposes a set of principles, on which resilience should stem: function, cohesion, interaction, emergence, hierarchy, communication, control, satisficing, viability and parsimony.

Linkov, I., Bridges, T., Creutzig, F., Decker, J., Fox-Lent, C., Kröger, W., Lambert, J.H., Levermann, A., Montreuil, B., & Nathwani, J. (2014). Changing the resilience paradigm. *Nature Climate Change*. 4 (6): 407-409.
Opinion paper, proposing a roadmap for enabling the development of resilience capabilities, including: (1) specific methods to define and measure resilience; (2) new modelling and simulation techniques for highly complex systems; (3) development of resilience engineering; (4) approaches for communication with stakeholders. The authors emphasize that resilience is a complementary attribute to improve traditional risk management that uses strategies of adaptation and mitigation.

Madni, A.M., & Jackson, S. (2009). *Towards a conceptual framework for resilience engineering.* Systems Journal, IEEE. 3 (2): 181-191.
The contributions is based on the assumptions that disruptions are a result from webs of ongoing interactions and adaptations" that characterize complex systems behavior in the realworld. In the view of the author's resilience is a means of coping with system complexity, and dynamically maintaining control in the face of ongoing disruptions. It is a continuous, adaptive effort enabling a system to survive and to recover from unexpected perturbations, disruptions, and operational environment degradations. The control engineering view is interesting.

McAslan, A. (2010). *The concept of resilience. Understanding its origins, meaning and utility.* Torrence Resilience Institute. Accessed [Feb-02-2016]. [http://www.torrensresilience.org/images/pdfs/resilience%20origins%20and%20utility.pdf]
Although grey literature, the paper compiled the historical roots of the resilience concept most comprehensively.

Pflanz, M.A., & Levis, A.H. (2015). *On Evaluating Resilience in C3.* INCOSE Insight. 18 (1): 29-33.
An approach to resilience based on four attributes - tolerance, flexibility, capacity, and inter-element collaboration.

PWC. (2015). *Entreprise resilience. Boosting your corporate immune system.* The executive paper series, (1). PWC. Accessed [https://www.pwc.com/sg/en/risk-assurance/assets/gc-enterprise-resilience.pdf]

Tierney, K., & Bruneau, M. (2007). *Conceptualizing and measuring resilience: A key to disaster loss reduction.* TR news, (250).
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Walker, B., & Salt, D. (2012). *Preparing for Practice: The Essence of Resilience Thinking.* In *Resilience practice: building capacity to absorb disturbance and maintain function*, B.H. Walker and D.

Salt, Editors. Island Press: Washington, D.C.: p. 1-25.
Good overview how resilience looks from an ecologist's point of view.