Resilience Analytics for Systems of Systems: Literature and Resource Guide[i]

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Keywords: Resilience analytics, Strategic plans, Systems of systems, Scheduling, Risk analysis, Priority setting, Systems engineering

Overview

This paper identifies literature and other resources for resilience analytics, in particular when the emphasis is the disruption of preferences by alternative system perspectives. It recognizes that multiple, possibly conflicting, perspectives of politics, economics, demographics, technology, environment, etc., are an inherent part of decision-making and plans and processes need to be resilient to emergent and future conditions that might bring one or more perspectives closer to the front.

The literature of *resilience* reflects an interest in the separation of a system from its as-planned or as-expected functionality over time (Connelly & Lambert, 2016; Ganin et al., 2016; Hamilton et al., 2016; Thorisson et al., 2016; Linkov et al., 2014). The National Academy of Science describes the resilience of a system as its ability "to plan and prepare for, absorb, respond to, and recover from disasters and adapt to new conditions" (National Research Council, 2012). A quantification of this definition is proposed by Ganin et al. (2016) by evaluating temporal recovery of the critical functionality of the system when subjected to stressors.

Connelly & Lambert (2016), Hamilton et al. (2016) and Thorisson et al. (2016) describe an approach where resilience of systems of systems, such as hierarchical and interconnected arrangements of infrastructure, health care, manufacturing, economics and environment, can be characterized by separations of time-based priorities or proposed schedules, in particular when a single system comes to the front. Each system has an associated set of factors and conditions, also known as *scenarios*, which might prompt a reevaluation of priorities (Karvetski et al., 2011a; Karvetski et al., 2011b; Martinez, 2011). The priorities of an agency are for projects, existing assets, policies, geographic locations, organizational units, and other entities, known as *initiatives*. A prioritization of initiatives can be viewed as a timeline of implementation or execution, and thus resilience can be characterized in terms of separation of the timeline or milestones of plans from an ideal.

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[i] This paper is part of the IRGC Resource Guide on Resilience, available at: https://www.irgc.org/risk-governance/resilience/. Please cite like a book chapter including the following information: IRGC (2016). Resource Guide on Resilience. Lausanne: EPFL International Risk Governance Center. *v29-07-2016*

A conceptual illustration of the *timeline* view is given in Figures 1a-c. Figure 1a shows the as-planned system in the space of a timeline or milestones. Figure 1b-c then illustrate separations from the as-planned system when subjected to various factors, alone or in combination. In Figure 1b the system recovers and achieves the originally planned end state while in the Figure 1c it adjusts to a new end state. Interpreting Figures 1b-c, the resilience of the system of systems to stress on particular systems is the closeness of the disrupted trajectories to the as-planned trajectory.

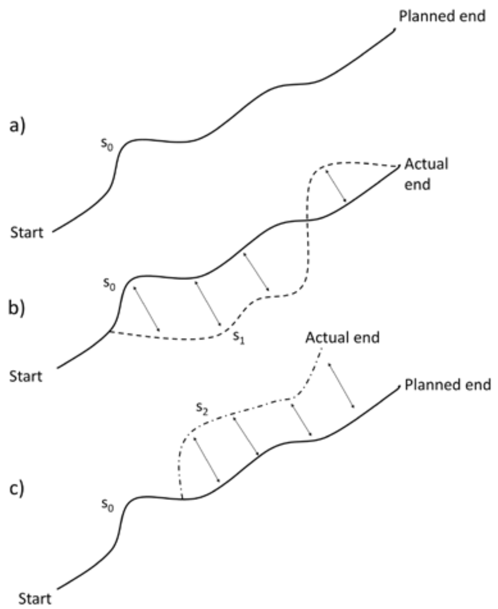

Figure 1: Resilience as the disruption of a timeline of priorities. The resilience of the system is characterized by the separation of the timeline from an as-planned timeline when systems (alternatively recognized as scenarios) influence the higher level system.

R*esilience analytics* as described below focuses on methods for identifying the systems (or particular *scenarios* related to the systems*)*, that, alone and in combination, are most in need of investigation, including risk analysis, simulation, experimentation, data collection and analysis, etc. (Karvetski et al., 2009; Teng et al., 2012). Risk analysis often relies on being able to assess likelihood and consequences of scenarios, while resilience analytics can proceed without that assessment (Thorisson et al., 2016).

Resilience analytics identifies the systems that have the greatest potential to separate the schedule or priorities from an ideal. This allows system owners and operators to focus on mitigating the separative influence of identified systems or build flexibility of milestones into strategic plans.

Resilience analytics should be considered in the context of negotiations (Thekdi & Lambert, 2014) or development of terms for design and operations of systems of systems (Lambert et al., 2012), as follows. By quantifying how various stressors might affect a timeline of priorities the analysis quantifies which systems have the most potential to cause a change of mind about the priorities of a strategic plan within organizations and among stakeholders, which can also be interpreted as scenarios that might prompt renegotiations. Thus, resilience is achieved by anticipating and accounting for these vulnerabilities by including elements that specifically address the systems that are identified to have the greatest potential to have cascading effects on the overall timeline of implementation.

The resilience of the design and operation of a *system of systems* can be quantified, in part, as the *separation* of a *disrupted* timeline of implementation from the *as-planned* timeline, by attention to a system within the *system of systems*. The closer the timelines, the more resilient is the system of systems to the *scenario* of any particular system within it. In the case where elements of the system are ordered in terms of their relative priority or time of implementation, a precondition for quantifying resilience is establishing this order for the *as-planned* system as well as alternative orders that account for different circumstances (*scenarios*) where emergent and future conditions bring one or another system to the front.

In the cited references, *resilience* (as a separation from an initial set of priorities for a system of systems) is represented graphically (Lambert et al., 2013), or quantified as the absolute value of change in prioritization (Connelly et al., 2016; Parlak et al., 2012)), the sum of squares of ordering change (Connelly et al., 2015; Hamilton et al., 2012), Spearman rank correlation coefficient (Thorisson et al., 2016), Kendall tau rank correlation (Hamilton et al., 2015; You et al., 2014a; You et al., 2014b).

Annotated Bibliography

Connelly, E.B., Colosi, L.M., Clarens, A.F., & Lambert, J.H. (2015). Risk Analysis of Biofuels Industry for Aviation with Scenario-Based Expert Elicitation. *Systems Engineering*, 18(2), 178–191.
Applies resilience analytics to initiatives advancing an aviation biofuels industry.

Connelly, E.B., &Lambert, J.H. (2016). Resilience analytics in research and development with application to future aviation biofuels. To appear in Transportation Research Record: *Journal of the Transportation Research Board*.
Describes resilience analytics as an advancement of scenario-based preferences risk analysis and demonstrates the concept for development of aviation biofuels.

Connelly, E.B., Lambert, J.H., & Thekdi, S.A. (2016). Robust investments in humanitarian logistics to support disaster resilience of sustainable community supply chains. *ASCE Natural Hazards Review*. 17(1).
Applies resilience analytics to a portfolio of emergency preparedness investments in Rio de Janeiro, Brazil.

Ganin, A.A., Massaro, E., Gutfraind, A., Steen, N., Keisler, J.M., Kott, A., & Linkov, I. (2016). *Operational resilience: concepts, design and analysis*. Scientific Reports. http://doi.org/10.1038/srep11913
Proposes quantitative measures of resilience, which is based on the evaluation of critical functionality of a system. The approach is demonstrated on two model classes, multi-level directed a cyclical graphs and interdependent coupled networks.

Hamilton, M.C., Lambert, J.H., Connelly, E.B., & Barker, K. (2016). Resilience analytics with disruption of preferences and lifecycle cost analysis for energy microgrids. *Reliability Engineering &*

System Safety.
Introduces resilience analytics with scenario-based preferences as compilations of instantaneous framings of initiatives, objectives, stakeholder preferences, and uncertainties. The paper presents a case study with application to a micro grid investment plan.

Hamilton, M.C., Lambert, J.H., Keisler, J.M., Holcomb, F.H., & Linkov, I. (2012). Research and Development Priorities for Energy Islanding of Military and Industrial Installations. *Journal of Infrastructure Systems*, 19(3), 121011224809006.
Assesses the resilience of a timeline of research and development priorities for energy islanding.

Hamilton, M.C., Lambert, J.H., & Valverde, J. (2015). Climate and related uncertainties influencing research and development priorities*. ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems. Part A: Civil Engineering*. 1(2).
Assesses the resilience of research and development programs within an agency and highlights the role of stakeholder elicitation in the process.

Karvetski, C.W., & Lambert, J.H. (2012). Evaluating Deep Uncertainties in Strategic Priority-Setting with an Application to Facility Energy Investments. *Systems Engineering*, 15, 483–493. http://doi.org/10.1002/sys
Applies methodology introduced by Karvetski et al. (2009) to investments in infrastructure in Afghanistan and emphasizes the role of stakeholder engagement in the evaluation process.

Karvetski, C.W., Lambert, J.H., Keisler, J.M., & Linkov, I. (2011a). Integration of decision analysis and scenario planning for coastal engineering and climate change. *IEEE Transactions on Systems, Man, and Cybernetics, Part A*. 41(1): 63-73.
Describes how resilience analytics can be achieved by integrating scenario planning with multicriteria decision analysis.

Karvetski, C.W., Lambert, J.H., & Linkov, I. (2011b). Scenario and multiple criteria decision analysis for energy and environmental security of military and industrial installations. *Integrated Environmental Assessment and Management*. 7(2):228-236.
Assesses the resilience of different alternative energy sources for military and industrial installations.

Karvetski, C.W., Lambert, J.H., & Linkov, I. (2009). Emergent Conditions and Multiple Criteria Analysis in Infrastructure Prioritization for Developing Countries. *Journal of Multi-Criteria Decision Analysis*, 16, 125–137. http://doi.org/10.1002/mcda
Introduces methodology for prioritizing initiatives and evaluating their resilience to various scenarios incorporating elements from multicriteria analysis and scenario analysis.

Lambert, J.H., Karvetski, C.W., Spencer, D.K., Sotirin, B.J., Liberi, D.M., Zaghloul, H.H., & Linkov, I. (2012). Prioritizing infrastructure investments in Afghanistan with multiagency stakeholders and deep uncertainty of emergent conditions. *ASCE Journal of Infrastructure Systems*, 18(2), 155–166. http://doi.org/10.1061/(ASCE)IS.1943-555X.0000078
Applies methodology introduced by Karvetski et al. (2009) to investments in infrastructure in Afghanistan and emphasizes the role of stakeholder engagement in the evaluation process.

Lambert, J.H., Wu, Y.J., You, H., Clarens, A., & Smith, B. (2013). Future climate change and priority setting for transportation infrastructure assets. *ASCE Journal of Infrastructure Systems*. 19(1):36-46.
Assesses resilience of transportation infrastructure assets in a coastal region to scenarios involving the combination of climate change and other factors.

Linkov, I., Bridges, T., Creutzig, F., Decker, J., Fox-Lent, C., Kröger, W., Lambert, J.H., Levermann, A., Montreuil, B., Nathwani, J., Nyer, R., Renn, O., Scharte, B., Scheffler, A., Schreurs, M., & Thiel-Clemen, T. (2014). Changing the resilience paradigm. *Nature Climate Change*. 4:407–409.
Describes requirements for resilience management and the differences between risk management as a tool to react to known quantifiable threats and resilience management which deals with unknown and unforeseeable threats.

Martinez, L.J., Lambert, J.H., & Karvetski, C. (2011). Scenario-informed multiple criteria analysis for prioritizing investments in electricity capacity expansion. *Reliability Engineering and System Safety*. 96: 883-891.
Assesses resilience of investments in electricity capacity expansion to emergent conditions of electricity consumption rates, price volatility of oil and gas, anti-pollution policies and pressure to move towards green technologies.

National Research Council. (2012). *Disaster Resilience: A National Imperative*. Washington, D.C.: National Academies Press.
Provides a definition of resilience as the ability to plan and prepare for, absorb, respond to, and recover from disasters and adapt to new conditions.

Parlak, A., Lambert, J.H., Guterbock, T., & Clements, J. (2012). Population behavioral scenarios influencing radiological disaster preparedness and planning. *Accident Analysis and Prevention*. 48: 353– 362.
Assesses the resilience of emergency preparedness initiatives to a dirty bomb attack.

Teng, K., Thekdi, S.A., & Lambert, J.H. (2012). Identification and evaluation of priorities in the business process of a risk or safety organization. *Reliability Engineering and System Safety*. 99: 74–86.
Demonstrates a systemic approach to achieve compliance of a risk program with administrative and organizational principles and guidelines for risk analysis. Assesses the resilience of policy initiatives to emergent and future conditions.

Thekdi, S.A., &Lambert, J.H. (2014). Quantification of scenarios and stakeholders influencing priorities for risk mitigation in infrastructure systems. *ASCE Journal of Management in Engineering*. 30(1):32-40.
Describes a form of resilience analytics as a means to achieve stakeholder consensus in negotiations.

Thorisson, H., Lambert, J.H., Cardenas, J.J., & Linkov, I. (2016). *Resilience Analytics for Grid Capacity Planning in a Volatile Region*. Submitted for Publication.
Describes resilience analytics as a complement to risk analysis characterized by likelihood and consequences and demonstrates on a power grid capacity building plan in Afghanistan.

You, H., Connelly, E.B., Lambert, J.H., & Clarens, A. F. (2014a). Climate and other scenarios disrupt priorities in several management perspectives. *Environment Systems and Decisions*, 34(4), 540–554. http://doi.org/10.1007/s10669-014-9525-2
Compares perspectives of several management systems to evaluate the vulnerability of agency priorities to combinations of climate change and other risk scenarios.

You, H., Lambert, J.H., Clarens, A.F., & McFarlane, B.J. (2014b). Quantifying the Influence of Climate Change to Priorities for Infrastructure Projects. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 44(2).
Introduces a modification of the Kendall Tau rank correlation coefficient as a measure of the resilience of project portfolios.