ABSTRACT

Park, Jeryang Ph.D., Purdue University, Dec 2012. COMPLEX COUPLED ENGINEERED SYSTEMS: BALANCING RESILIENCE AND EFFICIENCY IN DESIGN AND MANAGEMENT. Major Professor: P. Suresh C. Rao and Fu Zhao.

Ecological impacts of natural systems have increased exponentially since the beginning of the Industrial Revolution, and are evident at increasingly larger spatial scales. Regional and global scale impacts have prompted the experts to introduce a new epoch: the Anthropocene, the Age of Humans. Most of the observed impacts are the outcomes of couplings between two complex systems: the natural systems, and the engineered systems. The connectivity and inter-dependencies between the two systems has also increased, making the impacts from one system to the other larger and causing cascading, unexpected consequences. This thesis focuses on emergent properties, which are the signatures of change in resilience, due to the coupling of complex systems. Two types of coupling are recognized by setting two different initial conditions: (1) ecological systems which are extensively altered and intensively managed to meet human needs (e.g., agricultural landscapes, managed catchments with dams and levees); and (2) human-created engineered systems (e.g., cities, industrial districts), with infrastructure exposed to stochastic, natural disturbance regimes.

The trajectories of complex systems can be described by using an adaptive cycle, in which change in internal processes in response to external perturbations leads to different level of resilience. Numerous examples of power-law are signatures of resilient complex systems that result from optimal diversity, which imparts tolerance to random disturbances, and also optimizes for efficiency in self-organization. Given this fact as a base, following emergent features in coupled complex systems are commonly observed: (1) As the system modifications impart increasing brittleness, the adaptive cycle is accelerated toward K-phase, with increasing precariousness and catastrophe potential resulting from positive feedbacks; (2) System alterations to gain efficiency in delivering socio-economic services contribute to the evolution of functional homogeneity, overwhelming natural spatial variability; (3) Loss of diversity and fragmentation leads to truncation of power-law distributions; and (4) Combination of multiple forcing leads to the emergence of stochastic, non-stationary tipping points, by which conventional risk-based management approaches cannot be sufficient for managing unknown risks. I use case studies of 2011 Tohoku earthquake and tsunami followed by Fukushima Daiichi nuclear power plant explosion, Deepwater horizon oil rig explosion in 2010, and New Orleans flooding by Hurricane Katrina in 2005 to support these common observations.

I argue that resilience of coupled complex systems is not a static property that a system has, but instead it emerges from what the system does in response to stochastic external disturbances and internal process dynamics. Stochastic, non-stationary tipping points examined by using multiple forcing types also convey the idea of irreducible uncertainties in complex systems. Thus, management of coupled complex engineered systems must be based on a recursive process that involves sensing, anticipating, adapting, and learning. A case study of 2011 flooding in Mississippi River Basin is used to scrutinize resilience as an emergent property. Distributed control, anticipatory management, and organizational interaction strategies are also suggested as ways to be better prepared for unexpected shocks. Especially, the comparative analyses of long-term wet-deposition data in U.S. cities and other growing cities in rapidly growing East Asian countries emphasize the important role of distributed controls for managing resilience under strong driving force of rapid economic growth and urbanization. In conclusion, reweighing between resilience and efficiency is necessary during design and management for coupled complex engineered systems such that unexpected shocks and surprises resulting from stochastic forcing are accommodated in a way that reduces compromise in efficiency.