Risk and Resilience Management in Social-Economic Systems[i]

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Risk and Resilience as complementary measures of stress

We propose a definition of resilience as an important complement to risk. Both concepts describe stress within a socio-economic system from two different angles, and together allow for a comprehensive approach to governance and management. **Stress** is an internal response of a system to a perturbation called stressor or stress-factor (Kovalenko & Sornette, 2013). Here, we think of stress as a variable that characterizes the current (or potential) state of a system on a continuum scale ranging from its normal functioning state (e.g. low average level of stress with bursts below certain amplitude and time thresholds) to an unsustainable dynamics leading to a change of regime (e.g. high average stress level with strong upward trend).[ii] In natural sciences, stress can be directly quantified from its observable effects, for instance in the form of physical deformation of a stressed body in engineering or a set of common non-specific physiological changes in living biological organisms. In contrast, stress is hard to quantify in socio-economic systems. As in natural sciences, socio-economic systems are complex and multi-scaled, subjected to a large number of exogenous and endogenous factors, with feedback loops and coupling mechanisms. However, clearly differentiating responses to exogenous from responses to endogenous stressors is made harder by the existence of learning, anticipation and self-fulfilling prophecies, where beliefs govern actions with feedbacks on processes. As an alternative, an indirect approach to measure stress was developed, based on:

1) **Risk** (as the triplet of (i) probability/uncertainty, (ii) potential loss and (iii) mitigation techniques, i.e. counter-measures to reduce vulnerability of a system) characterizes possible environment- and system-specific stressors. By analogy with the Newton's third law, risk is a proxy for a potential internal stress response of a system to these threats;
2) **Resilience** (as the four-level hierarchy of (i) local 'engineering resilience', (ii) non-local 'ecological resilience', (iii) 'viability' enriched with managerial impact and (iv) adaptation and transformation mechanisms) embodies the inner capacity of a system to cope with stressors of any nature (Kovalenko & Sornette, 2013). It characterizes the maximum

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[ii] In the present paper, we do not investigate long-term effects of different levels of stress on ability of a system to respond to stressors. Prolonged extreme levels of stress may result in adverse changes of adaptive capacity of under- or overstimulated system, resembling "poverty trap" and "rigidity trap" resp. (Carpenter & Brock, 2008).

amount of stress a system can bear without a functional disruption, the system dynamics following a perturbation such as the speed of recovery of a traditional functionality, the achieved level of performance or its transformation to a completely different state.

Adding value and filling gaps with resilience

First, as their definitions deriving from their common genesis – stress – attest, resilience and risk are **closely interconnected**:

- The vulnerability of a system, being one of the constituents of risk, bridges it to resilience: indeed, the susceptibility of a system to risks and its ability to sustain stress intersect greatly and may be affected by the same managerial actions (mitigation techniques);
- When trying to balance costly universal resilience and profitable but stripping optimization, risk measures can be important indicators of a required level of resilience.

Second, resilience and risk measures are **complementary**:

- Focusing on the components of risk and resilience that can be expressed in the same units (e.g. risk exposure vs. maximum loss that a system can withstand), *comparison of their relative values* is useful to choose an appropriate response to a stressor. 'Normal' stress, when risks are significantly smaller than the system resilience, induces a 'fight' response with negative feedbacks and return to an equilibrium state. When the risk level becomes comparable to the resilience level, a 'fly' response is often initiated by employing risk-avoidance or environment-adaptation strategies. 'Extreme' stress, when resilience is insufficient, requires a major transformation of the system via positive feedback mechanisms;
- Resilience plays a distinct and crucial role in *uncertain environments* (which resonates with the IRGC view), when standard risk management techniques fail to adequately quantify or even detect existing hazards. This category includes exposure to:
    a) extreme risks, which are characterized by heavy/fat-tailed distributions with undefined mean and/or variance (e.g. existing models for operational risk are often considered to be unrealistic in capturing the peril of human failure or a cyber security breach),
    b) slow-moving risks, which are difficult to identify and monitor,
    c) surprise factors associated with Knightian uncertainty of unknown unknowns (popularized under "black swans" (Taleb, 2007));
- Finally, *complex* socio-economic systems, with nontrivial micro-macro relations, may exhibit:
    d) unsustainable dynamics and gradual maturation towards an instability leading to a bifurcation and potentially large impact events (captured under the concept of "dragon-kings" (Sornette D. , 2009), (Sornette & Ouillon, 2012)).

In any context, resilience serves as a 'safety buffer', i.e. an all-purpose resource to withstand a non-specific stress response of a system to any demand.

Instruments for resilience management

As risk and resilience are interconnected and complementary concepts, their governance and management structures may be similar, but specialized accordingly. We emphasize the following systemic elements for resilience build-up:

- clear statement of (measurable, multidimensional) *goals* to resolve conflicts of interests between time-scales (short- vs. long-term) and beneficiaries (individual vs. community);
- development - via investment, education and regulation - of *fundamental values*, right *incentives* and fair remuneration;
- strengthening of institutions for *contract enforcement*; implementation of *transparency* and *accountability* mechanisms***;***
- *diversification* and fostering of *heterogeneity*, as a reservoir of adaptive capacity;
- *decoupling* of key components to decrease systemic risk and susceptibility to cascade propagation.

Active (biological and socio-economic) systems put stress to use as a driving force of their evolution towards better fitness to changing environments. In particular, stochastic or deliberate stressors are useful for the

- identification and characterization of stress via the system response to perturbations;
- measurement of stress, e.g. via risks and resilience;
- catalysis of learning, which promotes adaptation through feedback mechanisms, and selection of specific favorable features;
- excitation of the system's readiness, maintaining an attentive and engaged state.

Depending on (i) the level of stress induced by environmental demands or endogenous processes and (ii) the degree of uncertainty/predictability of a system, we suggest four **risk and resilience management regimes**, with their corresponding **response mechanisms and management instruments (figure 1)**, which can be grouped into *two subgroups according to the stress elevation, 'normal' to 'extreme'*.

'Normal' stress, when addressed timely, usually does not endanger the very existence of a system. Negative feedbacks are appropriate and adaptation (co-evolution) of a system to (with) stressors occurs.[iii]

- **"Ad hoc management"** can be applied to cope with 'normal' stress for unpredictable complex systems in a highly uncertain environment. This regime is characterized by self-organization, decentralization of management functions and delegation of authority.
- **"Adaptive management"** (Allen & Garmestani, 2015) operates an iterative learning methodology to reduce high management uncertainty in systems with low-to-intermediate spatial and temporal variability. Within this approach, reversible repetitive interventions are preferable, which produce visible effects on a timescale of

[iii] As an interesting illustration, the development of advantageous attributes of human society such as cooperation and exaggerated risk taking by males have been shown to be driven by its *co-evolution* with external and internal stressors, such as competition between groups (Hetzer & Sornette, 2013), (Hetzer & Sornette, 2013) or individual males (Favre & Sornette, 2012), (Baumeister, 2010).

months to years rather than decades. Inclusiveness of stakeholders, strong leadership and community involvement enable this regime.

Extreme stressors truly determine the environmental landscape and the evolution of the system. Thus, positive feedbacks should be employed for the radical transformations needed to adapt to the new conditions.[iv] Centralization, focus on key functionality and mobilization of resources are required. The outstanding importance of extreme events is reflected in the choice of memorable names (Black swans and Dragon-kings) personifying the following regimes.

- The **"Black swan"** regime requires a management approach that deals with unpredictable exogenous disturbances of a large impact. Quantitative estimation is problematic. Critical areas should be identified and accounted for in a contingency plan; strategies to avoid most adverse trajectories must be implemented. The resilience of a system, its ability to react fast and transform when needed is essential.
- The **"Dragon-king"** regime, in contrast, suggests that certain types of extreme events are predictable. These events are the outcome of the system dynamics progressively approaching an instability leading to a transition to another mode. Monitoring and early warning signals should be a part of management practice; interventions are time-sensitive and include preparations to a possible change of course.

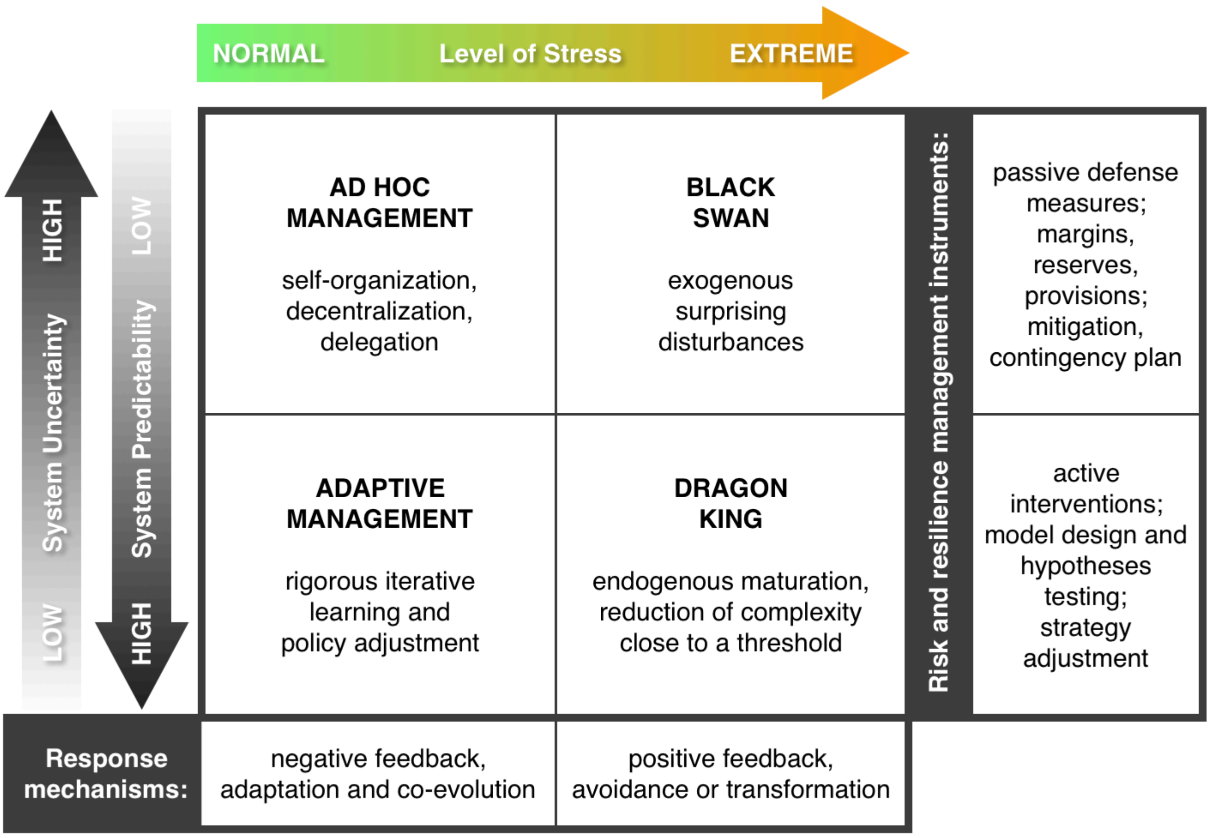

Figure 1: The four quadrants of risk and resilience management regimes corresponding to the system's degree of uncertainty/predictability and stress level within it.

[iv] For example, cardinal political and economic changes are often associated with *extreme* shocks and generic J-curve dynamics (Challet, Solomon, & Yaari, 2009), (Yaari, Nowak, Rakocy, & Solomon, 2008). This type of transitions is characterized by an initial phase of significant recession followed by a recovery, when the renewed system can outperform its preexisting level due to its better evolved fitness.

In all regimes, the resilient evolution of a socio-economic system towards a desired state requires a combination of (i) structured and strict evidence-based assessment and decision-making processes and (ii) flexibility and diversity in the considered alternative policies. The essential ingredients of management success are scientific rigor of implementation and high quality of data. (Chernov & Sornette, 2016) analyses numerous case studies and provides recommendations to facilitate knowledge acquisition and transparent communication in order to prevent distortion and the scourge of *information concealment*.

Metrics of resilience

Development of a complex system resilience calls for a multidimensional measurement approach, corresponding to multiple goals, risk factors and time scales. It includes the following steps.

1) Identification of stressors, their classification (*exo-/endo-factors*). E.g. **specific dynamical patterns observed before or after extreme events were shown to be characteristic of the (exo-/endo-) nature of the triggering factors**. This is relevant to many complex systems (Sornette & Helmstetter, 2003), (Sornette D. , 2005), and have been applied to financial shocks (Sornette, Malevergne, & Muzy, 2003), commercial sales (Sornette, Deschatres, Gilbert, & Ageon, 2004), and YouTube videos views (Crane & Sornette, 2008);
2) Quantification of **dependencies** between risk factors, with increased attention to extreme risks (Malevergne & Sornette, 2006);
3) Integration of both probabilistic measures of stress: (a) risks (observation of event probabilities, losses, vulnerability of the system) and (b) resilience ("exploration" of the stability landscape, e.g. characterized by its latitude, resistance, precariousness and panarchy (Walker, Holling, Carpenter, & Kinzig, 2004));
4) Development of direct measures of stress. E.g. for financial system, the "crash hazard rate" can be interpreted as a direct measure of the level of stress through its theoretical link to the excess bubble price (Johansen, Sornette, & Ledoit, 1999), (Johansen, Ledoit, & Sornette, 2000), (Yan, Woodard, & Sornette, 2012).
5) Quantitative measurement and characterization of the **dynamics**. E.g. different levels of resilience hierarchy can be used for a different time scales.

The following quantitative metrics pertain to each of the four risk and resilience management regimes.

- **"Ad hoc management"**. While the system is here characterized by low predictability and its stressors are stochastic, the high frequency and low severity of the latter allow for standard risk measures, such as *quantile-based approaches* (e.g. *value-at-risk* or conditional value-at-risk, i.e. *expected shortfall*), based on *historical records*, to determine adequate passive defense measures: margin levels, reserves, capital buffers, provisions, and so on.
- **"Black swan"**. The intrinsic uncertainty and the significant impact of these extreme events call for imaginative *'what-if' scenario* analysis, and prudent *stress-testing*. Option and other derivative strategies are typically put forwards for passive defense. However, these countermeasures involve risk-taking (and at the extreme gullible) counter-parties.

- **"Adaptive management"**. Carefully designed and controlled *management experiments* are iteratively maintained to determine effective, and – importantly – scalable, cost-efficient policies. The methodology emphasizes:
    - incorporation of knowledge about different aspects of the system from a broad range of *stakeholders*,
    - *model* development and formulation of alternative *testable hypotheses*,
    - carefully *monitored and controlled experimentation* to test and falsify the working hypotheses,
    - *analysis and evaluation* of the obtained data, *adjustments* of the models and management practices.
- **"Dragon-king"**. The system dynamics close to a change of regime contains early warning signals, allowing for the probabilistic estimation of the time and severity of the incoming transition. The theoretical underpinning of this predictability stems from bifurcation theory applied to dynamical systems: the fundamental reduction theorem states that, close to a change of regime, a system can transit from one state to another one only in a small number of ways, with a collapse from high to low dimensionality of the relevant variables and control parameters. These transitional "normal forms" have been systematically classified (Thom, 1989), (Guckenheimer & Holmes, 1983), (Manoel & Stewart, 2000), (Kuznetsov, 2004). The identification of the relevant control parameter(s) and the characterization of the reduced system dynamics towards a tipping point is of key importance to predict and thus prepare against extreme events in out-of-equilibrium socio-economic systems.

Annotated Bibliography

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- risk and resilience as complementary measures of stress
- classification of resilience measures and possible responses to stressors
- debunking "antifragility" myth
- main ingredients for the resilience of socio-economic systems

Example of a model incorporating adaptive capacity of a system as a function of its stress:

Carpenter, S. R., & Brock, W. A. (2008). Adaptive capacity and traps. *Ecology and Society, 13*(2). Retrieved from http://www.ecologyandsociety.org/vol13/iss2/art40/

Extreme events: "black swans" and "dragon-kings":

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Sornette, D. (2009). Dragon-kings, black swans and the prediction of crises. *International Journal of Terraspace Science and Engineering, 2*(1), 1-18. Retrieved from http://arXiv.org/abs/0907.4290

Sornette, D., & Ouillon, G. (2012). Dragon-kings: Mechanisms, statistical methods and empirical evidence. *European Physical Journal Special Topics, 205*(1), 1-26. doi:10.1140/epjst/e2012-01559-5

Examples of co-evolution with stressors under "normal" stress and transition to a new state under "extreme" stress:

(i) cooperation:

Hetzer, M., & Sornette, D. (2013). An evolutionary model of cooperation, fairness and altruistic punishment in public good games. *PLoS ONE, 8*(11), 1-13. doi:10.1371/journal.pone.0077041

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(ii) beneficial risk-taking of males:

Favre, M., & Sornette, D. (2012). Strong gender differences in reproductive success variance, and the times to the most recent common ancestors. *Journal of Theoretical Biology, 310*, 43-54. doi:10.1016/j.jtbi.2012.06.026

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(iii) generic J-curve dynamics:

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Allen, C. R., & Garmestani, A. S. (Eds.). (2015). *Adaptive management of social-ecological systems.* Springer Netherlands. doi:10.1007/978-94-017-9682-8:

- adaptive management framework;
- suitability criteria and implementation steps (Chapter 6 and 10);
- case studies.

Chernov, D., & Sornette, D. (2016). *Man-made catastrophes and risk information concealment: Case studies of major disasters and human fallibility.* Springer International Publishing. doi:10.1007/978-3-319-24301-6:

- 25+ case studies, including industrial, financial, social and natural catastrophes;
- 5 common factors of information concealment, viz., (i) external environment; internal environment: (ii) communication channels, (iii) risk assessment and risk knowledge management, (iv) ecology of an organization, (v) personal features of employees), and decomposing them further into 30 causes that led to the reviewed disasters.

Dynamical characterization of exogenous and endogenous factors, and its applications:

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Sornette, D. (2005). Endogenous versus exogenous origins of crises. (S. Albeverio, V. Jentsch, & H. Kantz, Eds.) *in the monograph "Extreme Events in Nature and Society", Series: The Frontiers Collection*, 95-119. Retrieved from http://arxiv.org/abs/physics/0412026

Sornette, D., Malevergne, Y., & Muzy, J. F. (2003). What causes crashes? *Risk, 16*(2), 67-71. Retrieved from http://arXiv.org/abs/cond-mat/0204626

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Quantification of risk factors dependences:

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Characterization of a stability landscape by its latitude, resistance, precariousness and panarchy:

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