Resilience of Systems to Individual Risk and Systemic Risk

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Introduction

The concept of resilience has a short but intense history and is now defined in as many ways as there are corresponding schools of thought (e.g., Ilmola et al., 2013; Keating et al., 2014; Linkov et al., 2016; Mochizuki et al., 2018). The popular understanding of resilience comes from engineering, which traditionally referred to the resistance of a system to disturbance and to the speed at which such a system returns to equilibrium (Davoudi, 2012). C.S. Holling, widely held to be the father of the concept, defined resilience differently, focusing on the "persistence of systems and their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables" (Holling, 1973, p. 14). For Holling, understanding this ability requires a careful assessment of the dynamical interactions between a system's components. Insufficiently resilient systems are exposed to knock-outs, with perturbations potentially triggering large and lasting system-wide collapses, a threat nowadays referred to as systemic risk. A distinguishing feature of such risks is that they emerge from the complex interactions among individual elements or agents and their associated individual risks; systemic risk is therefore also sometimes called network risk (Helbing, 2013). In contrast, individual risk originates from single events that directly affect an agent, in isolation from the rest of the system. It is often defined as the "effect of uncertainty on objectives" (ISO, 2009), and is typically quantified by assessing the probability of an event and its corresponding impacts (UNISDR, 2017).

While the realization of individual risks may lead to a disaster in part of a system, the realization of systemic risks, by definition, leads to a breakdown—or at least a major dysfunction—of the system as a whole (Kovacevic et al., 2015). This has major implications for strategies aiming at increasing resilience. Modern societies typically manage individual risks through insurance (Geneva Association, 2010) or, more generally, through diversification (Kunreuther, 1996; IPCC, 2012). While moderate individual risks, such as car accidents, can be handled efficiently in this way, diversification

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gets increasingly difficult for extreme risks (Kessler, 2014; Linnerooth-Bayer & Hochrainer-Stigler, 2015). For systemic risks, in contrast, fundamentally different approaches need to be applied, e.g., restructuring a network's connectivity (Gao et al. 2016; Poledna & Thurner, 2016). Measures of individual risk and of systemic risk are used not only to quantify risks, but also to identify strategies aiming at increasing resilience. For the latter, an assessment of current resilience levels to absorb, recover, and adapt to adverse events (National Research Council, 2012) is needed. This can focus on different features of resilience (Linkov et al., 2016) including the critical functions of a system, thresholds that if exceeded perpetuate a regime shift, the recovery time from degraded system performance, and the possibility for adaptive management through the anticipation of emerging risks or through learning from past events. Below, we discuss and compare some selected aspects of the most prominent measures and strategies used today. This illustrates differences as well as similarities, and thereby highlights options for developing a joint framework for increasing a system's resilience to both types of risks.

Measures of individual risk and systemic risk

Looking at a system's elements separately, one can assess how they carry individual risks. The most comprehensive quantification of such individual risks is the probability distribution of losses. However, probability distributions are complex objects, so there is a need to capture their most salient features using a minimal number of relevant characteristics. For frequent events, the expected loss or the median loss may provide the most appropriate summary information. For extreme events, on the other hand, tail measures such as the Value at Risk (VaR) or the Conditional Value at Risk (CVaR; also called the expected shortfall) are more appropriate (Pflug & Römisch, 2007). Usually, these risk measures are used to determine risk-management options, e.g., when setting up premium payments, determining the probability of ruin, or making cost-benefit analyses of mitigation measures. In this way, probability distributions and their characteristics have a wide area of application and play a prominent role in discourses about individual risks (Cardona et al., 2012).

Systemic risk results from the interactions of individual risks, and, as any emerging phenomena, cannot be measured by separately quantifying the contributing parts. Studies of systemic risk typically construe systems as networks of interconnected elements and thereby focus attention on the interdependencies among individual risks. In particular, systemic risks result from cascading effects between the interconnected elements—which, in a network perspective, are often referred to as nodes or agents. Recently suggested measures of systemic risk emphasize the role of the structure of the entire network (e.g., Kharrazi et al., 2016) and the contributions of individual nodes to systemic risk, including the dependence of these contributions on their positions in the network (Poledna et al., 2015). In some systems, different types of perturbations can be studied through controlled experiments: so-called pulse perturbations are applied only temporarily, whereas press perturbations are imposed continuously (Dunne et al., 2002; Kondoh, 2003; Scheffer & Carpenter, 2003; Ives & Carpenter, 2007). Measures of systemic risk in such systems quantify a perturbation's full impact, such as the number of secondary species extinctions or biomass reductions resulting from a primary species extinction or biomass reduction in an ecosystem. In other systems, only case studies are possible, which may nevertheless help identify the mechanisms that cause systemic risks. Using insights from such experiments and/or case studies, models can be built to quantify and forecast systemic risks.

Financial systemic risk has become a focus of recent research, not only because of its immense importance for society, but also because of the availability of high-precision and high-resolution data and because financial systems are man-made, and thus—in principle—more amenable to engineering than many natural systems. One of the most prominent systemic-risk measures in financial network analyses today is the so-called DebtRank (Battiston et al., 2012). DebtRank estimates the impact of one node, or group of nodes, on the others and is inspired by the notion of centrality in a network. The centrality of a node takes into account the impact of the node's distress on other nodes in the network, with a high value indicating a more central location of the node. Accordingly, DebtRank can be considered as a warning indicator for a node being too central to fail—an important feature aggravating a node's contribution to systemic risk, in addition to being too big to fail (Poledna & Thurner, 2016). Other measures of systemic risk are also available, such as the Systemic Expected Shortfall, which uses pre-defined thresholds—akin to Value at Risk—to quantify a node's anticipated contribution to a systemic crisis (Acharya et al., 2009).

Enhancing resilience by restructuring networks

As in the case of individual risks, measures of systemic risks have the potential to inform risk-management strategies aiming at decreasing risk. Due to the increasing connectedness within networks—e.g., financial networks—and across networks—e.g., financial systems interconnected with supply chains—it is nowadays becoming more difficult to ensure that a portfolio is adequately diversified, as hardly tractable pathways might connect events. Instead of looking for diversification possibilities, a system's resilience against systemic risk can therefore often more readily be improved by modifying or transforming the topology of the underlying network toward safer configurations.

How a network's structural diversity can enhance its stability has long been analysed in ecology (e.g., May, 1973; Pimm & Lawton, 1978). While this so-called diversity-stability debate has led to fruitful distinctions among conclusions holding for different measures of diversity and for different measures of stability, no generally applicable simple results have been found regarding the impact of diversification on resilience (Tilman & Downing, 1996; McCann, 2000). This is because of several reasons. First, diversification may not only enable risk sharing and facilitate post-failure recovery, but can also multiply the number of pathways through which risks propagate (Gai & Kapadia, 2010; Haldane & May, 2011; Allen et al., 2012; Battiston et al., 2012; Amini et al., 2016). Second, increasing modularity—the degree to which the nodes of a system can be decoupled into relatively discrete components—may decrease risks for most parts of the system, potentially at the expense of impeding resilience for the system as a whole (May et al., 2008). Third, resilience and efficiency, e.g., of road systems, may not go hand in hand (Hochrainer-Stigler & Pflug, 2009; Ganin et al., 2017, 2018). Such trade-offs—e.g., between modular risk and systemic risk or between resilience and efficiency—are implying social dilemmas and creating leverage for moral hazard, as the constituencies bearing the costs or receiving the benefits of tipping trade-offs in either direction typically differ. For example, companies maintaining utility or transportation grids are tempted to make them more efficient to save costs and increase their profits, even when this decreases the networks' resilience—potentially at great expense to the citizenry depending on them. Fourth, strategies to build resilience must take care to avoid so-called erosive strategies that lead to medium- and long-term negative impacts on development and well-being (Keating et al., 2014), e.g., by the short-term over-exploitation of natural resources (Heltberg et al., 2012). Fifth, so-called levee effects, through which increased safety is leading to much larger losses in case of risk realization need to be accounted for, as exemplified by the case of New Orleans after Hurricane Katrina (Kates, et al. 2006).

Hence, instead of one-size-fits-all rules of thumb, the reshaping of a network's topology is therefore best based on examining the specific contribution of each node to systemic risk (e.g., Gephart et al., 2016; Colon et al., submitted). With this approach, managers try to identify those nodes that are too big to fail, too interconnected to fail, and the so-called keystone nodes, which in times of failure cause large secondary effects or lead to a network's complete breakdown (Paine, 1969; see also the critical comments on the latter concept by Mills et al., 1993). Restructuring a network can then be enabled by acting on those nodes. For example, Poledna & Thurner (2016) propose a risk measure based on DebtRank that quantifies the marginal contribution of individual liabilities in financial networks to the overall systemic risk. They then use this measure to introduce an incentive for reducing systemic risks through taxes, which they show can lead to the full elimination of systemic risks in the considered systems. The resultant proposal of a systemic-risk tax is a very concrete measure that can increase individual and systemic resilience (e.g., Adrian & Brunnermeier, 2008; Cooley et al., 2009; Roukny, et al., 2013). In other cases, more broadly-based governance approaches may be necessary (Linkov et al., 2016), which in turn might require changes in human behaviour or cultural norms (as highlighted, e.g., through the current 'loss and damage' debate in the climate-change community; Mechler et al., 2018).

Integrative management of individual and systemic risk

Before proceeding to the management of systemic risks (Cooley et al., 2009), one needs to be able to measure and model them appropriately. Here we have outlined how increasing a system's resilience through the assessment and management of risks differs between individual risks and systemic risks. For individual risks, market-based instruments exist, including insurance and diversification strategies using the law of large numbers, whereas for systemic risk, transformational approaches need to be developed and applied, assessing the contributions of nodes to systemic risk and restructuring networks to reduce these contributions.

Ideally, individual and systemic risks should not be treated in isolation, but in a holistic manner. This challenge has become even more pertinent through experiences showing how individual risks resulting from extreme events can trigger systemic risks (e.g., Massaro et al., 2018). A case in point is the 2011 Thailand flooding and its worldwide consequences (Chongvilaivan, 2012; Haraguchi & Lall, 2015), which has demonstrated the magnitude of potential knock-on effects and inspired the notion of global systemic risk (Centeno et al., 2015). Another example is the self-immolation of Mohammad Bouazazi in Tunisia in December 2010, which started the Arab Spring and caused large-scale consequences as well (Pollack et al., 2011). Indeed, individual risk and systemic risk can be seen as representing two ends of a continuum: with individual risk describing how an event changes a single network node and systemic risk describing the propensity for cascading failures triggered by such events across network nodes, the continuum is spanned by the affected proportion of nodes, with larger proportions characterizing risks at the more systemic end of the spectrum. On this basis, new mathematical methods are currently being developed for integrating measures and models of individual risk and systemic risk, such as the copula method (Hochrainer-Stigler et al., 2018). In addition, a major and yet unaddressed challenge is how to integrate the technical approaches rooted in natural science, which we have outlined here, with innovative governance approaches rooted in social science, which are crucial to build resilience in the face of systemic risks.

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