Risk Analysis, Vol. 0, No. 0, 2020 DOI: 10.1111/risa.13657

Systemic Risks from Different Perspectives

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Systemic risks are characterized by high complexity, multiple uncertainties, major ambiguities, and transgressive effects on other systems outside of the system of origin. Due to these characteristics, systemic risks are overextending established risk management and create new, unsolved challenges for policymaking in risk assessment and risk governance. Their negative effects are often pervasive, impacting fields beyond the obvious primary areas of harm. This article addresses these challenges of systemic risks from different disciplinary and sectorial perspectives. It highlights the special contributions of these perspectives and approaches and provides a synthesis for an interdisciplinary understanding of systemic risks and effective governance. The main argument is that understanding systemic risks and providing good governance advice relies on an approach that integrates novel modeling tools from complexity sciences with empirical data from observations, experiments, or simulations and evidence-based insights about social and cultural response patterns revealed by quantitative (e.g., surveys) or qualitative (e.g., participatory appraisals) investigations. Systemic risks cannot be easily characterized by single numerical estimations but can be assessed by using multiple indicators and including several dynamic gradients that can be aggregated into diverse but coherent scenarios. Lastly, governance of systemic risks requires interdisciplinary and cross-sectoral cooperation, a close monitoring system, and the engagement of scientists, regulators, and stakeholders to be effective as well as socially acceptable.

KEY WORDS: Interdisciplinary integration; properties of systemic risks; risk governance; systemic risk

1. INTRODUCTION

The history of societal handling of risk from the 1950s to today has been a success story in almost all Organization for Economic Co-operation and Development (OECD) countries when it comes to conventional risk management (Murray & Lopez, 1996). This success of conventional risk management is well documented. Referring to the situation in Europe, the number of occupational accidents has decreased considerably over time, most notably in the construction sector. The death toll for fatal occupational accidents in Germany decreased from almost 5,000 in 1960 to less than 400 in 2014, the number of traffic accidents from 22,000 in 1972 to 3,700 in 2014, and the number of fatal heart attacks and strokes decreased from 109 cases per 100,000 to 62 in the time period between 1992 and 2002 (Renn, 2014). Although many of these reductions in risk may be due to the improvement of medical treatments, risk assessment and risk management efforts were a key factor in reducing heart attacks and strokes by providing evidence for the connection between diet, exercise, and cardio-vascular diseases,

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0272-4332/20/0100-0001$22.00/1

in particular among men between 50 and 60 (Dankel, Loenneke, & Lorprinzi, 2015).

In addition, the number of chronic illnesses (Nichols, Townsend, Scarborough, & Rayner, 2013) and the number of fatal diseases from environmental pollution or accidents (Health Effect Institute, 2003) have steadily declined over the past three decades, although the health burden from air pollution and lifestyle risks are still highly significant. Conventional risks in terms of accidents and many illnesses have been successfully tamed (Rosa, McCright, & Renn, 2014). However, the situation is quite different for interconnected, nonlinear, and globally effective risks, such as those posed by the global financial system, climate change, or the growing inequality between the rich and the poor. The most recent outbreak of COVID-19 is an example for such global risks that threaten critical functions of society's well-being. In order to take these types of risks into account, the OECD introduced the category of "systemic risk" (OECD, 2003). A widely used definition of systemic risk in the context of finance has been provided by Kaufman and Scott (2003). "Systemic risk refers to the risk or probability of breakdowns in an entire system, as opposed to breakdowns in individual parts or components, and is evidenced by co-movements (correlation) among most or all parts" (Kaufman & Scott, 2003, p. 372). This definition includes some ambiguities that need to be addressed. If one thinks of a car as a system of parts, the total breakdown of a car would certainly not qualify as a systemic risk. Likewise, a partial breakdown of the world's finance system may be severe enough to be called a systemic risk, even if the entire system is not affected. Given this criticism, Aven and Renn (2019) have suggested that systemic risks need to be differentiated on the regional, national, and global level and do not exclusively denote global breakdowns (Aven & Renn, 2019). In the same vein, the 2018 report by the International Risk Governance Council "Guidelines for the governance of systemic risks" emphasizes that systemic risks are characterized by cascading effects that affect the larger system (IRGC, 2018). An Poledna, Rovenskaya, Dieckmann, Hochrainer-Stigler, and Linkov (2020) similarly defined systemic risks as a potential for a threat or hazard to propagate disruptions or losses to multiple connected parts of complex systems (Poledna et al., 2020).

In our understanding, systemic risks refer to potential threats that endanger the functionality of systems of critical importance for society and their scope in time and space. The impacts may extend beyond the system of origin to affect other systems and functions (Renn, 2016). Furthermore, systemic risks can be described by several distinct properties that distinguish them from the conventional risks mentioned above and that involve many interacting elements whose emergent effects are still poorly understood (Lucas, Renn, & Jaeger, 2018). These cumulative effects will be addressed in the next section.

The notion of systemic risks describes phenomena of functionality losses at the macro-level involving multiple agents at the micro-level. In this understanding, agents, in a general sense, are conceptualized as elements of a system that interact with each other and with the system's environment. In technical systems, agents may be part of a technical infrastructure, such as generation, transmission, and control units in the electrical grid. The systemic risk in this case is, for example, the breakdown of the grid as a whole or the release of toxic material due to the failure of electric security systems. In ecosystems, agents, such as harmful chemicals interacting with a fish population in a river, constitute the systemic risk of irreversible destruction of the population. In the global climate system, interacting agents comprise the solar radiation, clouds, greenhouse gases, the oceans, and the earth surface, which in conjunction with each other constitute the systemic risk of climate change. In social systems, humans are the agents interacting with each other and with the system´s environment, with systemic risks manifesting themselves in radical movements leading to social unrest and revolutions (Helbing, 2013).

An adequate analysis of systemic risks and their governance still remains a serious challenge. Beyond empirical investigations and statistical calculations, a closer look into the causal structures, as complex and indeterminate as they may be, seems promising. The main purpose of this article is to demonstrate the value of a multidisciplinary, multiperspective view on systemic risks as a means to gain a more adequate understanding of what systemic risks are, how they emerge in different contexts, and how different future developments of complex system–environment interactions can be captured in a set of scenarios. Furthermore, based on a better understanding of the main properties of systemic risks, the article includes lessons for risk management and governance. The article aims to contribute to the quest for more effective management and governance protocols for reducing systemic risks.

The following sections are inspired by the insight that complex topics need an interdisciplinary approach for capturing the essence of systemic risks. Each coauthor of this article represents a different discipline: Applied mathematics (Scholz), complexity science (Lucas), engineering (Kroeger), evolutionary biology (Laubichler), (human) ecology (Schanze), and social sciences (Schweizer and Renn). These disciplines are closely connected to the assessment and management of physical risks caused by natural hazards, technological operations, (accidents, emission, and waste), and/or social practices (cybersecurity and pandemics). Financial and other risks are not explicitly covered here. The risks that are within the scope of this article interact in a complex and interconnected environment so that all these disciplines (and probably others) provide pieces of the puzzle. The article starts with a review of main properties of systemic risks that form the common foundations for the specific approaches that follow. Section 3 distinguishes two major approaches of how to conceptualize systemic risks when seen from a realist (risks exist independent of the human observer) and from a constructivist perspective (risks are mental models created by humans to cope with threats). Based on this distinction, Sections 4–8 analyze risks by providing different disciplinary lenses. The objective is not to produce a compilation of disciplinary approaches but to provide an integrative representation of complementary insights that enable us to develop a comprehensive and coherent understanding of systemic risks. The comprehensive view is then applied to lessons for risk governance in Section 9. The article ends with the conclusions for further research and practice.

2. MAJOR PROPERTIES OF SYSTEMIC RISKS

The concept of systemic risks encompasses different risk phenomena as well as economic, social, and technological developments and policy-driven actions at the regional, national, and international level. Systemic risks entail endangering potentials with wide-ranging, cross-sectoral, or transnational impacts where conventional risk management and regional or even national risk regulation are insufficient.

Four major characteristics should be considered to identify appropriate analytic entry points for developing a comprehensive understanding of a complex phenomenon such as systemic risks (Aven & Renn, 2019; Klinke & Renn, 2002).

- *Complexity*: Complexity refers to the difficulty of identifying and quantifying causal links between a multitude of potential elements and specific adverse effects. The nature of this difficulty may be traced back to interactive effects among these elements (synergisms and antagonisms), positive and negative feedback loops, short or long delay periods between cause and effect, interindividual variation, intervening variables, and others. It is precisely this complexity that makes sophisticated scientific investigations necessary since the cause–effect relationship is neither obvious nor directly observable. Nonlinear response functions may also result from feedback loops that constitute a complex web of intervening variables.
- *Uncertainty*: Uncertainty comprises different and distinct components, such as statistical variation, measurement errors, ignorance, and indeterminacy (van Asselt, 2000). They all have one feature in common: uncertainty reduces the strength of confidence in the estimated cause and effect chain(s). If complexity cannot be resolved by scientific methods and available data, uncertainty increases. But even simple relationships may be associated with high uncertainty if either the knowledge base is missing or the effects are indeterminate due to the stochastic (randomly structured) nature of the functional relationships.
- *Ambiguity*: Ambiguity denotes the variability of (legitimate) interpretations based on identical observations or data assessments. Most of the scientific disputes in risk analysis do not refer to differences in methodology, data sets, algorithms, models, or statistical procedures but to the question of what all this means for human health and environmental protection (Renn & Klinke, 2012). Emission data are hardly disputed. Most experts debate, however, whether an emission of x constitutes a serious threat to the environment or to human health. Ambiguity may come from differences in interpreting factual statements about the world or from differences in applying normative rules to evaluate a state of the world. In both cases, ambiguity exists on the ground of differences in criteria or norms to interpret or judge a given situation. Ambiguity arises under conditions of

high complexity and uncertainty, but there are also established and well-researched risks that can cause controversy and thus ambiguity.

- *Ripple-effects beyond the source of risk*: Another key characteristic that sets systemic risks apart from conventional risks is the fact that their negative physical impacts (sometimes immediate and manifest, but often subtle and latent) have the potential to trigger severe ripple effects outside the domain where the risk is located. When systemic risks unfold, the resulting ripple effects can cause sequences of secondary and tertiary effects (Kasperson, Kasperson, Pidgeon, & Slovic, 2003). These effects can become tangible in a wide range of seemingly divergent social systems, from the economy to the health system, inflicting harm and damage in domains far beyond their own (DeWitte, Kurth, Allen, & Linkov, 2016). A commercial sector, for example, the food industry, may suffer from the impacts of a systemic risk as has been the case with the financial crisis in 2009 in the form of an increase in food prices or in the case of the COVID-19 crisis in 2020 where labor restrictions in agricultural businesses have resulted in shortages of specific foodstuffs. Another example for a major ripple effect is the BSE (Bovine Spongiform Encephalopathy) debacle in the United Kingdom, which not only effected the farming industry but also the animal feed industry, the national economy, public health procedures, and politics (Wynne & Dressel, 2010). People refused to eat British beef, regardless of tangible evidence showing little threat to their health or safety.

The boundaries of uncertainty and ambiguity are usually well defined in the case of conventional risks. As systemic risks have no clear boundaries with respect to scope, time, and space, there is ambiguity about which other systems are affected and which of these potentially affected systems need to be included or excluded. The COVID-19 crisis has caused ripple effects that transgress from the domain of health risks and extend into economic, social, and political domains causing new risks and opportunities (Aven & Bouder, 2020).

Beyond the four general properties of systemic risks, there are more specific attributes that describe the causal structure of systemic risks. They are directly related to the four properties either as an input or as a consequence (Renn, Lucas, Haas, & Jaeger, 2017; Schweizer, 2019). Systemic risks are

- transboundary or cross-sectoral in scope of their consequences leading to multiple ripple effects;
- highly interconnected and intertwined leading to complex causal structures, high uncertainty, and major interpretative ambiguities;
- nonlinear in their cause–effect relationships showing often unknown tipping points or tipping areas (Scheffer, 2010) that enhance complex and uncertain cause–effect relationships;
- stochastic in their effect structure leading to increased uncertainty that is difficult or impossible to characterize by statistical confidence intervals.

To which degree each of these attributes is met depends on the domain in which the systemic risk originates. However, these four attributes are typical properties of any systemic risk. This typology draws on insights of complexity science on the nature of complex systems (e.g., Nicolis & Nicolis, 2012; Simon, 1991; Waldrop, 1993). In addition, systemic risks tend to be underestimated and do not attract the same amount of attention as catastrophic events despite their potential for catastrophe (Schweizer, 2019; Schweizer & Renn, 2019). First, complex structures defy human intuition based on the assumption that causality is linked to proximity in time and space (Connell & Keane, 2006). However, complexity implies that far-fetched and distant changes can have major impacts on the system under scrutiny. Second, humans learn by trial and error (Helbing, 2010). Facing nonlinear systems with tipping points/areas, people are encouraged to repeat their errors because the feedback received remains positive for a long time. However, once a tipping point has been reached, the consequences are so dramatic that learning from crisis is either unfeasible or often deemed too costly. Third, systemic risks touch upon the well-known common pool problem: as each actor contributes only marginally to the systemic risk, there is no incentive for behavioral change (Renn, 2011). Furthermore, actors who take the free rider position and let others invest in risk reductions have significant advantages since all will reap the benefits equally. Thus, systemic risks are underestimated or, at least, undermanaged compared to conventional risks.

3. TWO CONCEPTUAL APPROACHES TO SYSTEMIC RISKS

Beyond identifying the properties of systemic risks, a conceptual distinction allows for a more comprehensive understanding of systemic risks. When looking at the still sparse literature on this issue, the concept of systemic risks can be seen from both an ontological and epistemological perspective. Both perspectives build upon each other whereby the epistemological perspective unfolds in two variants: the realist and the constructivist version. They represent different degrees of confidence in the human ability to make inferences about causal structures representing reality (Jasanoff, 1998).

The ontological perspective recognizes an increasing complexity and dynamics of (some emerging) risks (Solberg & Nja, 2012). It is based on findings that risks in modern societies may involve multiple interdependent cause–effect interrelations even across social groups and societal sectors, technical components as well as environmental impacts. These risks are real in the sense that they exist independently of the mental representations that humans have developed to understand these risks. However, they cannot be captured by the conventional monocausal model of risk calculations. Nature and magnitude of the resulting effects may remain ambiguous or even unknown (Lucas et al., 2018). Systemic risks in an ontological sense, furthermore, refer to the experience of accelerating spatial and temporal variability and change in the cause–effect interrelations (Forzieri, Cescatti, Silva, & Feyen, 2017; IRGC, 2018). These dynamics enhance uncertainties and thus additionally limit the predictability of future events (De Bruijne, Boin, & Van Eeten, 2010). The combination of high complexity and dynamics affects the predictability and hence the accountability of systemic risks.

The concept of ontological systemic risk is related to—although not dependent on—epistemological possibilities of describing our knowledge about systemic risks. We differentiate between *analytical realism* (systemic risks are no mental constructs but real threats to humans and the environment) and *epistemic analytical constructivism* (models and images of systemic risks are evidence-informed constructions of what the scientific community of risk analysts believes are core elements of complex systems and which variables matter within these systems) (Rosa, 1998). *Analytical realism* refers to the assumption that the systemic threat exists in reality, and its negative physical consequences in terms of losses and associated probabilities can be calculated with some degree of reliability. For example, the ecotoxicological risk for a lake may be characterized or even quantified once risk analysts are aware of the major causal factors and intervening variables as well as their interdependencies. In more general terms, the analytical realism approach depends on the gradual possibility of conceptualizing and observing real-world phenomena using tools of system modeling and simulation.

Epistemic analytical constructivism of systemic risks shifts the understanding of the system from the conceptualization as an empirical fact to an epistemic mental construct. The system is considered as the result of an intentional and creative act with little reference to the (extra-discursive) real world (Becker & Breckling, 2011). Yet, this approach also collects and processes observations and data on the system's behavior; modeling itself is an act of creative selection, structuring, and functional arrangements. Due to the high complexity, interconnectivity, and nonlinear relationships, empirical verification, let alone prediction, is not possible. In spite of the inherent relativism of scientific findings, this perspective has major heuristic value for the comprehension of highly complex and dynamic risks. It allows for an exploration of emergent features and the main characteristics of the system's landscape as anticipated and designed by human mental models. There are various systems theories, such as General Systems Theory, Complex Systems Theory, Dynamic Network Theory, and Cybernetic Systems Theory, that correspond to modeling and simulation concepts, such as equilibrium models, system dynamic models, or agent-based models (Simon & Tretter, 2015).

Both analytical realism and epistemic analytical constructivism are equally essential for analyzing and governing systemic risks. Some aspects of systemic risks may be modeled using the realist paradigm, for example, capturing experimentally tested and validated cause–effect relationships within a complex web of causes and effects. Other aspects may be better captured by constructivist approaches, for example, when anticipating human responses to unprecedented events for which empirical data are insufficient or lacking. Both require substantiated empirical evidence and creative mental processes to select and address the elements and interrelations relevant for painting a comprehensive image of the risk phenomena in question. Respective system-based approaches are already in use in the research practice (Binder, Hinkel, Bots, & Pahl-Wostl, 2013). However, their theoretical foundation is often rather weak and refers to systemic risks only as a side note (Preiser, Biggs, De Vos, & Folke, 2018).

When using this dual approach of combining realist and constructivist perspectives, there are two methodological routes to take. First, the representation of a system in an integrated model (e.g., Laniak et al., 2013) or coupled models (e.g., Schanze, Trümper, Burmeister, Pavlik, & Kruhlov, 2012). The integrated model, also including agent-based modeling (e.g., Giannakis & Louis, 2011), attempts to simulate the entire system or its networks with one consistent approach based on empirical data and simulations.

Second, coupled modeling creates "pipelines" or even networks of interlinked, but distinct and diverse models stemming from different disciplines and methodological traditions. For example, climate change impact assessment is an area where model cascades are well established. One major challenge for integrated or coupled modeling is the degree of representing emergent system features. Those features may be tipping points of the system leading to the system's transition or collapse (Steffen et al., 2015). The way of addressing this challenge, for example, by mimicking an intermediate complexity, can be seen as a key for tackling systemic risks. This pragmatic approach to characterizing systemic risks has been advocated by Aven, Renn, and Rosa (2011). However, risk analysts and risk managers are well advised to respect the limits of probability functions when dealing with uncertainty (by keeping it as a separate category) and the bounded scope of assumptions about causality when designing risk reduction policies.

Hence, ontological and epistemological perspectives are both reflected in risk governance. Increasing complexities and system dynamics influence societal risk perceptions and political and organizational capabilities of assessing, evaluating, and reducing risks (Jasanoff, 1998). As complex causal structures are often influenced by unpredictable and hard to anticipate triggers, it is advisable to focus on the resilience or robustness of the risk absorbing system (target or receptor of risk) rather than on the identification and prevention of risk-generating agents. Hence, systemic risks lend themselves to applications of a precautionary approach due to high levels of complexity and uncertainty (De Bruijne et al., 2010; Renn & Schweizer, 2009) and call for a receptor-centered resilience approach, that is, an approach by which risk assessment and management is focused on preparing the risk receptor for being able to cope with severe stress situations (Schanze, 2016).

A common means for gaining insight into the multicausality of systemic risks is the construction of (causal impact factor-based) scenarios (Bradfield, Derbyshire, & Wright, 2016). Besides defining a system's boundaries, the most important step for the construction of this type of scenarios is the identification of (causal) drivers and impact factors. When selecting a small set of basically different but coherent scenarios, insights can be gained into the variety of functional or causal models of emerging futures that are consistent with state-of-the-art knowledge in the respective scientific fields.

4. SYSTEMIC RISKS FROM THE PERSPECTIVE OF COMPLEXITY STUDIES IN THE PHYSIOCHEMICAL SCIENCES

Complex and dynamic structures that are typical for systemic risks have been studied extensively in the natural sciences (Lucas, 2020). Although the notion of systemic risks is not in common use in physics and chemistry, the elements that compose systemic risks, such as complexity, uncertainty, ambiguity, and dynamic ripple effects, are well known in many areas of the natural sciences. They are embedded in the concept of dynamic structures, notably nonequilibrium dynamic structures. Nonequilibrium dynamic structures, whether manifesting themselves as systemic risks or not, can be observed in essentially all systems of nature, technology, and society. Relatively simple ones can be studied in some model systems of physics and chemistry. In these models, generic mechanisms on the micro-level lead to macroscopic dynamic structures that can be formulated rigorously in mathematical terms. Particular system properties are required for dynamic structure generation to take place, such as feedback processes between the elementary processes on the micro-level as well as between the micro-level and the macroscopic field produced by them. The latter effect is referred to as circular causality. Another major aspect is the self-generation of order under specific circumstances of collective purpose. These observations on behavior in complex systems make it possible to gain insight into the essential phenomena resulting in the emergence of macroscopic dynamic structures due to interactions of the elementary agents on the micro-level. It turns out that the rather diverse and chaotic elementary processes of agents on the micro-level order themselves on the macro-level to widely universal dynamic patterns, which can be formulated in terms of simple macroscopic parameters.

Hence, systemic risks in any system follow the same macroscopic patterns as the nonequilibrium dynamic structures in these model systems. This points to the assumption of a homomorphous structure of the elementary mechanisms behind the generation of universal macroscopic dynamic structures as a basis of a general theory of systemic risks (Lucas et al., 2018). Looking at systemic risks as nonequilibrium dynamic structures in an overarching perspective over all domains, a vast body of empirical facts, indeed, demonstrates the existence of such universal macroscopic patterns, far beyond the systems studied in physics and chemistry.

A typical example for dynamic structure emergence from the technical world is the breakdown of an infrastructure, for example, power grids or a mobility system, such as railway traffic or automobile traffic. On highways, one frequently observes sudden traffic jams when the density of cars is high, normally associated with some external trigger, such as an accident or a construction bottleneck. However, quite often, a traffic jam appears to occur without any apparent reason. Obviously, it is the density of cars on the highway and the related sensitivity to internal fluctuations such as the momentary inattentiveness of a driver that is responsible for the generation of the traffic jam structure (Koonce, Apostolakis, & Cook, 2008). Quite similar events can occur in mass panic situations when there is not enough space for all people to move into one direction (Helbing, Treiber, Kesting, & Schönhof, 2009).

Various kinds of dynamic structures in financial systems are also well researched, such as the stock market crash in 1929 or the global banking crisis following the Lehman Brothers bankruptcy (Hurd, Cellai, Melnik, & Shao, 2016). In such events, agents of the financial markets generate a remarkable pattern of collective behavior. Using the financial instruments available to them in the markets, these agents create a complex web of new instruments, such as structured products, that lead to a market dynamic that they themselves are unable to understand, let alone control. In particular, and similar to epidemic spreading of infections, it is frequently the cascading effect of an original event over the entire system, which characterizes the dynamic process (Helbing et al., 2009).

Most theorists of complex systems are convinced that there are universal patterns in the emergence of dynamic structures (cf. Colander & Kupers, 2016, p. 13f.). It is at the same time surprising since, at first sight, there seems to be no relationship whatsoever between, for example, the refugee problem or the global banking crisis. However, there are common generic mechanisms in dynamic structure generation that are not immediately obvious from a purely phenomenological analysis. These common characteristics refer to self-organization of heterogeneous items when they reach critical thresholds on one of the influential dimensions, the importance of small changes in a complex web of triggers that have the potential to offset an equilibrium situation and the emergence of new patterns that cannot be explained by the summed-up effects of each component of the system.

5. SYSTEMIC RISK FROM AN EVOLUTIONARY BIOLOGICAL AND ECOLOGICAL PERSPECTIVE

Moving from the description of dynamic structures to evolving structures, the perspective of evolution is particularly insightful when conceptualizing systemic risks. Coevolutionary historical dynamics of complex systems are essential for a comprehensive understanding of systemic risk in addition to general dynamical properties of complex systems, such as the consequences of different types of feedback structures, tipping points and general properties of regulatory architectures, scaling relationships, and so on (Lucas et al., 2018; West, 2018).

Coevolutionary perspectives are particularly important when thinking about risk governance and risk management. After all, 3.5 billion years of evolutionary history scientific analysis has provided many insights of how natural systems have responded to internal and external threats and how to develop dynamic learning patterns by means of mutation and selection in cultural evolution (Kleisner & Tureček, 2017). Thus, scientific inquiry can assist risk assessors and managers when studying how natural evolution produced adaptation processes to deal with the intrinsic risks associated with complex systems. Before discussing what evolutionary and complexity theory can contribute to our understanding of each of the features of systemic risks, it is important to pay attention to the main principles of evolution that provide a relevant backdrop for the emergence of systemic risks and their governance.

In short, the basic features of evolutionary dynamics are as follows (Baumgartner, 2006). In order to be able to evolve, systems need to persist and reproduce. And they need to do this in the context of multiple challenges both intrinsic and extrinsic. Intrinsic challenges have to do with vulnerabilities of complex systems—systems failures due to error, decline or breakdowns in parts and components, or network connectivity inside the system. Extrinsic challenges are direct threats or large fluctuations in the environment that adversely affect a system's functioning or survival. While these initially do not fall within the definition of systemic risks, in the context of evolutionary processes, we find a general trend to internalize previously external states (Laubichler & Renn, 2015). The main reason for this is that complex systems gain higher degrees of autonomy from their environments. But, it also means a correspondingly higher degree of systemic risks.

So, how do evolutionary systems manage these risks? On the most general level, evolving systems increase their regulatory structures at a much faster pace than they add completely new characteristics (Peter & Davidson, 2015). For example, the human genome has only a small amount of new, additional genes (defined as protein coding regions) than a fly or a worm. Yet, the phenotypic complexity of humans is much higher. It is a consequence of more complex gene regulation, that is, the blueprint of when and where to express already existing building blocks (genes) (Shubin, 2008). Increasing regulatory structures lead to higher complexity and also increased levels of systemic risks. However, regulatory structures also buffer risks by creating redundancies. The ratio between redundancy and risk is a variable that is itself under selection. This feature is optimized over the course of evolution.

Evolutionary systems manage risk by yet another process, which has to do with the relation between evolving systems and their environment. Rather than just being passively exposed to the whims of their environment, complex systems actively construct and manipulate their environment, a process we call niche construction (Laubichler & Renn, 2015). Niche construction means that internal functional states of organisms get externalized, create more stable environments, and thus contribute to the management of risk.

This brief summary of evolutionary dynamics shows how risk management has been part of evolving systems from the very beginning of life on this planet. It also illustrates two specific elements (internalization and externalization) of regulatory structures that are essential elements of an evolving risk management system.

From an evolutionary point of view, the elements of systemic risks—complexity, uncertainty, ambiguity, and ripple effects—can all be understood as logical consequences of the evolution and emergence of complexity. Increasing complexity is a major trend in the evolution of all systems (biological, social, cultural, technological, and economic). Complexity always has two sides; it tames certain elements of systemic risk through the evolution of regulatory structures while, at the same time, it opens the system to new challenges. In the course of evolution, we generally see selection for an optimum balance of these two sides of complexity. The more parts a system has, the higher its degrees of uncertainty. Again, we see evolutionary trends to reduce uncertainty through regulation and niche construction. This generally works well within certain boundaries, but it can also lead to catastrophic failure. The prevalence of extinction over the course of evolution is a consequence of such systemic risks (except for mass extinction events, which often occurred due to external reasons). With regard to ambiguity, we see a similar dynamic, that is, trends to reduce ambiguity, but also taking advantage of ambiguity as a source of evolutionary novelty and innovation. Ripple effects are a direct consequence of the specific architecture of complexity. As a rule, systems with high degrees of negative feedback tend to prevent ripple effects but are also less flexible and slower to respond to extrinsic challenges, while those with more positive feedback loops show an accelerated adaptive dynamics but face a higher risk of collapse (Tainter, 1988).

What does that mean for dealing with ecological risks, such as climate change, loss of biodiversity, or environmental pollution? Bruce Hope emphasized as early as 2006 the need for assessment and management practices that correspond to the complexity and dynamics of biological evolution. In his analysis, he recommended to treat the environment as a nested system of systems that constantly interact and change over time (Hope, 2006). The theoretical concept of panarchy, specified as the variability of relationships between numerous components of a system (hierarchical, reciprocal, cooperative, and otherwise), captures both the connectivity and the dynamics of natural systems as well as the impacts of human–nature interactions (Allen, Angeler, Garmestani, Gunderson, & Holling, 2014). A panarchy can be regarded as a nested set of adaptive cycles (Gunderson & Holling, 2002), which may be a particularly apt heuristic for framing environmental phenomena that are characterized by complexity and dynamic change (Angeler, Allen, Garmestani, Gunderson, & Linkov, 2016). Human interventions can be described as signals that enter into a specific natural system and promulgate from there into other connected systems with various feedback loops that also extend back into the human sphere. A key management objective in this concept is the enhancement of resilience, that is, capacity of complex systems of people and nature to withstand disturbance without shifting into an alternate regime, or a different type of system organized around different processes and structures (Holling, 1973).

Resilient strategies focus on the risk-absorbing systems and invest into making these systems more adaptive and robust for coping with stress situations (Allen, Garmenstani, Sundstrom, & Angeler, 2016). A series of methods and tools have been developed in the ecological sciences that provide valid frameworks and methodologies to measure and evaluate systemic risks to the environment (overview in Sundstrom, Angeler, Garmestani, García, & Allen, 2014). These methods include Classification and Regression Tree Analysis, and their Bayesian implementation, which identify scaling structure based on size characteristics in ecological (e.g., animal size) or urban (city size) systems (Allen et al., 2016).

6. SYSTEMIC RISK FROM AN ENGINEERING PERSPECTIVE

The patterns of dynamic structures and evolutionary emergence are also typical components of complex technologies, in particular critical infrastructures (CIS). They can also be described by referring to panarchic structures and relationships (Linkov & Trump, 2019) and relate directly to the four components complexity, uncertainty, ambiguity, and ripple effects. The functionality of CIS depends on the ability of human control systems to cope effectively with complex relationships in a dynamic environment (Woods & Hollnagel, 2006, p. 3). These CIS are prototypes for systemic risks as they affect systems on which society depends, and malfunctions of these infrastructures may cause the collapse of the entire system as well as ripple effects on neighboring systems. They form complex relationships among themselves, but particularly with their environments (Heinimann & Hatfield, 2017). The risk of system failure is often difficult to assess due to high uncertainty. Furthermore, CIS are composed of many different units or components that often interact in unpredictable ways. Transport, energy (including the power grid), water supply, and telecommunication systems are examples of CIS. The interactions of these components form a set of conditions that provide the setting in which systemic risks emerge. Such a setting can trigger a breakdown of the entire system in addition to breakdowns of individual parts or components that are normally well captured by conventional risk assessments. Finally, CIS raise issues of ambiguity concerning their acceptability in terms of social, cultural, and ethical criteria. Examples here are nuclear energy, genetic engineering, or nanotechnologies (Kurath & Gisler, 2009).

Most CIS are composed of a plethora of mostly heterogeneous elements of great physical and functional diversity, interacting in multiple ways in a networked structure with interdependencies. Since potential stressors are often not known or may come as a surprise, they require adaptive management concepts that are based on enhanced resilience, such as redundancy, diversity, and decoupling of crucial safety devices (Linkov, Trump, & Fox-Lent, 2016). The key to systemic risk management is to understand and control the variability of performance and not to focus only on single error scenarios as described in fault tree or event tree analysis (Hollnagel, 2006). These complex technological systems are embedded in and open to a multifaceted (social–political–economical–natural) environment, usually managed by different kinds of actors, often with different objectives. Modern CIS often have a hierarchical structure, consisting of a physical layer, which comprises devices that interact with the physical process, as well as the cyberlayer which comprises information and communications hard- and software that are needed to monitor and control the physical process. In conjunction with panarchy theory, the different levels of physical safety and cybersecurity are intertwined and may reinforce each other (Linkov et al., 2013). In addition, CIS are usually geographically distributed and spatially connected.

Most CIS, the power grid in particular, have evolved structurally and technologically over time and have extended their capacity to meet increasing service demands. They have undergone tighter integration and closer coupling and growing (inter) dependencies, respectively. The trend toward a "system-of-systems" will (probably to an increasing extent) continue (Trump et al., 2017). These systems have shown emergent behavior in collective ways. They are difficult to predict from superposition of single elements, difficult to manage, and subject to large uncertainties (Zio, 2016).

CIS are subject to many types of hazards/threats of different nature, ranging from random mechanical/electrical/material failures and potential common cause failures (design flaws, aging, etc.) to natural hazards (earthquakes/tsunamis/floods, landslides, extreme weather situations, etc.), and soft- and hardware failures as well as human errors at different points in time and different levels (design/manufacturing, operation to political-strategic) to intentional malevolent attacks. As CIS are increasingly interconnected globally, anything and everything could be exposed to large-scale cyberattacks/cyberrisks.

CIS can either cause systemic risks, be put at risk, or both as the California electricity crisis of 2000 and 2001, in which the state had a demand–supply gap caused by market manipulations and suffered from multiple large-scale blackouts and related economic and political fall-outs, demonstrates (US-FERC, 2008).

Most of today's (cyber-) physical-engineered CIS systems share the main properties of systemic risks that have been outlined in the second section. They require multinational governance structures as a means to cope with complexity and complex behaviors of those systems, respectively, that are completely different from the past and for which our basic knowledge and suitable analytical methods are still limited. The evolution of systemic risks that may threaten CIS has been shaped by the following components: (1) competitive markets and globalization replaced monopolistic and small-scale structures, (2) digitalization and other innovative technologies offered substantial benefits and new services, (3) new paradigms and global needs, for example, due to climate change, and (4) unprecedented disasters like "Fukushima"-prompted changes. The phase-out of nuclear energy as a major element of the "Energiewende" in Germany may serve as a prominent example.

7. SYSTEMIC RISK FROM A DIGITAL TRANSFORMATION PERSPECTIVE

Technological developments are causing major societal evolutions. This also holds true for the digital transition. Digital technologies and services are linked to complex, uncertain, and ambiguous impacts and consequences of their development, application, and use, and cause multiple ripples effects throughout many crucial systems of society. Potential threats that can be characterized as systemic risks include risks of failure, cybercrime, cybersecurity, misuse of data, protection of privacy, inequitable access to digital services, and many others (overview in Lupton, 2015).

The shift from an analogue to a digital mode of representing and processing data fundamentally changed all domains of life (Scholz & Steiner, 2015). There are three pillars of the digital world: (1) global networking that allows the connectivity of all people and machines, (2) the seemingly unlimited storage of data, and (3) tremendous computing capacities (for artificial/machine intelligence and natural language-based interactions with machines). Yet, there is uncertainty with respect to unexpected and often unintended side effects, potential failures, and breakdowns (Johansson, Hassel, & Zio, 2013). Given all the complexity and uncertainty in this dynamic field, it is astonishing that some regularities can be observed over a long period of time. For example, Moore's prediction of an exponential increase in storage capacity has been valid for the last 50 years (Courtland, 2015).

Digital innovations have been planned for beneficial purposes. Yet, ambiguities regarding technological impacts and risks are ubiquitous. There are, in particular, unintended, often higher-ordered, asynchronously appearing side effects accompanying the diffusion of digital technology. These side effects may affect highly esteemed values of stakeholder groups or subsystems of a country. The German Advisory Council on Global Change (WBGU) stated: "If we continue with digitalization the way we did so far, digitalization becomes a fire accelerator of ecological and social crises of our planet" (WBGU, 2019). If digitalization fosters automatization and economic efficiency without a significant change in consumption patterns, environmental degradation will dramatically increase. Social crises may result from the option of economic and political surveillance societies (Zuboff, 2019). In this context, the maintenance of privacy or the right to know (including the right to receive unfalsified information as a prerequisite of democratic capability) can be seen as a sensitive objective that a society wishes to preserve (Peled & Rabin, 2010). But professions and industries are also vulnerable to disruptive innovations (Frey & Osborne, 2013). Thus, a major challenge is to increase society's reflexive capacity with respect to digital risks, which are systemic by nature even if they manifest at smaller scales. This includes the anticipation of threat scenarios that endanger important accomplishments and values of stakeholders in society. Due to complex, multicausal, interaction-based negative events and multiple ripple effects, there are limits for risk assessment by quantitative modeling and prediction. Risk analysis needs to include qualitative and often hybrid, semiquantitative modeling as suggested by the method of "Strengths, Vulnerability, and Intervention Analysis related to Digital Threats" (SVIDT) (Scholz, 2017; Scholz, Czichos, Parycek, & Lampoltshammer, 2019).

The functionality of the web-based services is permanently threatened by technical failures as well as human actions, in particular cybercrime. These services are particularly vulnerable as they allow multiple entry points from the outside world and multiple pathways for risk scenarios with typical domino effects (Jonsson, Johansson, & Johansson, 2008). Measures that protect continuous web-based services require precautionary measures on topology structure, anticipatory modeling, and simulation of complex interactive effects and adaptive forms of experimentation in decoupled systems (Sterbenz et al., 2013).

With the help of decision theoretic approaches, experts' judgments can be used to provide assessments of the scenarios' impacts on key performance indicators. Both risk analysts and risk managers can identify what interventions are possible to reduce prospective losses and construct consistent intervention scenarios. Models based on expert judgments might assess how the losses can be reduced and also what bundle of interventions makes a system resilient, that is, increases the capacity to avoid or compensate impacts from negative events and to keep a system's functionality (Linkov et al., 2014).

8. SYSTEMIC RISKS FROM A BEHAVIORAL SCIENCE PERSPECTIVE

The perspectives of the behavioral sciences on risk broaden the scope of expressing risks beyond the familiar components (severity and probability of harm) and expand the horizon of risk outcomes by referring to "individually perceived," "socially constructed," and/or "socially mediated" realities (Lemyre, 2018). Naturally, they include (the perception of) actual damage, but are more focused on the evaluation of the risk context, the nonphysical impacts, and the associations between the risk and social or cultural artifacts.

The basic concept behind this perspective is the assumption that human behavior is generally driven by risk perception, not facts or what is understood as facts by risk analysts and experts. As stated by Paul Slovic, pioneer for identifying explanatory factors in risk perception, "risk does not exist independent of our minds and culture" (Slovic, 1992). Mental models and other psychological mechanisms that individuals use to judge risks (such as cognitive heuristics and risk images) are internalized through social and cultural learning and constantly moderated (reinforced, modified, amplified, or attenuated) by media reports, peer influences, and other communication processes (Zinn & Taylor-Gooby, 2006). Perceptions may differ depending on the type of risk, the risk context, the personality of the individual, and the social context. Various factors, such as knowledge, experience, values, attitudes, and emotions, influence the thinking and judgment of individuals about the seriousness and acceptability of risks. Perceptions also play a major role for motivating individuals to take action in order to avoid, mitigate, adapt to, or even ignore risks. There are also typical risk judgment biases (Renn & Rohrmann, 2000; van der Linden, Maibach, & Leiserowitz, 2015) or drivers of risk perception (Syberg, Hansen, Christensen, & Khan, 2018) that often lead to behavior that does not correspond with the technical results of risk assessments. Understanding and anticipating these psychological, social, and cultural mechanisms are necessary preconditions for understanding human responses to risk challenges but also for designing effective measures for risk management, since perceptional patterns or biases may enhance the negative outcomes of a risk, determine the effectiveness of management measures, or even maybe the cause of the risk itself (Zinn & Taylor-Gooby, 2006).

Findings from the behavioral sciences play an even more significant role when it comes to understanding and mitigating systemic risks. Systemic risks are experienced or even generated within the social system where social interactions can enforce or reduce the gravity of negative outcomes. Perceptions and behavioral responses can be amplifiers as well as attenuators for systemic risks (Breakwell, 2014). A range of factors, such as cognitive, affective, social, and cultural aspects, all determine the public perception of and responses to risks. Furthermore, these factors often interact with each other in complex ways (van der Linden, 2017). Thus, society faces multiple complexities. On the one hand, risks as such are complex, uncertain, and ambiguous. On the other hand, perceptions of these complex risks constitute complex response patterns in themselves. Systemic risks, such as climate change, are often understated when it comes to personal risk perception ("it won't affect me"), since they are often intangible and cannot be experienced first-hand. Furthermore, risk perception is attenuated by many individuals as climate change remains an abstract concept, which may manifest in the long run, but requires major behavioral changes even before negative impacts become tangible to most people (Renn, 2011). Thus, risk management and mitigating strategies must take into account the barriers to public perception of systemic risks.

The psychological and social processing of risk also has major implications for societal risk management. Management of systemic risks is much broader defined than management of conventional risks management and includes the following tasks (Klinke & Renn, 2019):

- Widening the scope of targets for using risk assessment methodologies beyond potential damages to human life and the environment, including financial risks, risks to social cohesion or political stability, effects on personal well-being, and interaction with social lifestyles;
- Addressing risk at a more aggregate and integrated level, such as studying synergistic effects of several risk agents or constructing an aggregate risk profile for including the nonlinear crosscutting impacts that often accompany systemic risks;
- Studying the variations among different cultures, socio/economic systems, and political regulatory styles and getting a more adequate picture of the ranges of sensibilities with respect to lifestyle factors, social institutions, political structures, and cultural patterns;
- Integrating risk assessments into a comprehensive problem-solving management practice encompassing economic, financial, and social impacts so that management decisions can be adapted to the threats and opportunities given by the dynamic evolution of systemic risks;
- Developing technologies that are more forgiving and that tolerate a large range of human error and provide sufficient time for initiating counteractions.

The following section demonstrates how these new management tasks can be integrated into a larger risk governance concept for systemic risk.

9. IMPLICATIONS FOR GOVERNANCE

The insights from the various disciplines and perspectives shine a light on systemic risks, particularly the perspective of complex systems theory. Similar patterns emerge that govern complex structures and dynamics in different domains of risk analysis. The insights from complexity studies demonstrate that we are able to build mental methods of a semiquantitative exploration of possible future settings when combining scenario construction with judgment and decision-making methods. This requires that we first recognize the complex and dynamic structure of systemic risks and, second, design early warning systems based on weak signals as well as intervention scenarios based on coherent strategies to adapt to and absorb variations, disturbances, disruptions, and surprises (Steen & Aven, 2011).

One of the conceptual challenges for systemic risks is hence to understand the commonalities of complex cause–effect relationships in both risk generation and risk-governing systems and discern them from idiosyncratic behavioral patterns that may only be peripherally correlated to the seriousness of the risk at hand.

Obviously, the insights from the natural and engineering sciences can only be transferred to more general systems, including socioeconomics, by the price of some abstraction. However, there are general traits that can be applied to systemic risks for society (Cairney, 2012). Even in human society, it remains generally valid that the emergence of collective order associated with systemic risks is due to the dynamics of elementary agents under nonlinear interactions and circular causality (Lucas et al., 2018).

Since the emergence of macroscopic structures happens as an effect of selecting and collective ordering of elementary processes, any systematic analysis starts with identifying these overarching characteristics of complex systems and adds empirical knowledge to improve the understanding of systems behavior as well as of each risk situation and context. Both inputs, first the insights from the theoretical perspective on the structure and evolution of complex systems, and, second, the insights from the empirical perspective on the identification, characterization, and measurement of these relevant variables and relationships, need to be taken into account for the design of an appropriate approach for governance of systemic risks. Once the system is defined, the analysis starts with an identification of the agents, as a starting point to cope with mechanisms of complex systems interactions and the nonlinearity of functional and causal relationships. This complex system–environment interaction necessitates a comprehensive, integrative approach, which relates to both top-down and bottom-up modeling. What are the lessons learnt for a vision of risk governance that takes all these perspectives into account?

First, and most importantly, the decisions of risk governance and the measures taken in order to influence, control, or regulate risk need to be recurrent, adaptive, and synchronized (Klinke & Renn, 2012; Linkov et al., 2014). The dynamic and complex nature of systemic risk cannot be handled by static-reductionist methods and step-by-step assessments. The primary focus is on developing an adaptive, continuously learning style of governance based on observations of early warning indicators that can be identified by using insights from the combination of empirical analysis and complexity modeling. This can be accomplished by establishing global institutions that systematically investigate the environment for weak signals that are potentially related to major threats. During the recent Corona pandemic, such a watchdog role was already in place in the shape of the WHO or the Center for Disease Control in Denver, Colorado. Immense time constraints required the cooperation of all agents already in the emerging phase of the virus outbreak (Collins, 2020; Kormann, 2020). While in the systems of physics and chemistry such early signals can be found from a mathematical stability analysis, they have to be scrutinized empirically when systemic risks from technology, human behavior, or social actions are addressed. Signals that precede the approximation of a system toward a tipping point tend to be nondimensional in natural systems and based on ratios between expanding and contracting variables in social systems. Similar patterns have also been found in social systems. Examples are the ratio of local uprisings to police interventions in the forefront of revolutions (Schroeter, Jovanovic, & Renn, 2014), the size of the economy to the amount of private debt in the onset of a financial crisis (Minsky, 2008), or the ratio of conflict-related news to official appeasements before the outbreak of war (Chadefaux, 2014). These signals help to identify candidates for early warning systems. Their validity has to be tested through in-depth empirical analysis.

Second, as evolutionary science demonstrated, it is not required to revolutionize routines or procedures of assessing and managing risks but to redefine the existing routines to become more attentive to surprise, unusual developments, or unexplainable events (Steen & Aven, 2011). While complexity research in the natural and social sciences emphasizes the unpredictable and often surprising agglomeration of events that are continuously creating political reality, evolutionary theory acknowledges that there are temporally stable, reliable, and settled procedures and components on which successful governance can flourish. Such aspects of persistence are part of the governance framework, but they need to be reprogrammed to adopt and incorporate adaptive and learning mechanisms that arise due to ongoing interactions and institutional advancements of how a dynamic society deals with its affairs and challenges (Sanderson, 2009). Hence, routines of risk identification, assessment, evaluation, and management are still important to follow when dealing with systemic risks, but they cannot be performed by a single agency within a defined domain or silo. Routines need to take into account the cascading as well as transgressive nature of systemic risks in order to analyze and control the ripple effects that expand beyond the domain of origin (IRGC, 2015, 2018).

Third, governing systemic risks requires special steps within the familiar sequence of risk identification, assessment, evaluation, and management. The IRGC report on systemic risk governance (2018) lists seven of these steps that are crucial for coping with this new challenge:

- Step 1: Explore the system in which the risk management organization or agency operates; define the boundaries of the systems that are and might be affected and identify the agents that are part of the risk network in a dynamic environment.
- Step 2: Develop scenarios, considering ongoing and potential future transitions.
- Step 3: Determine goals and the level of tolerability for risk and uncertainty.
- Step 4: Codevelop management strategies to deal with each scenario and the systemic risks that affect or may affect the various systems that are at risk.
- Step 5: Address unanticipated barriers and sudden critical shifts that may come up during the process.
- Step 6: Decide, test, and implement strategies.
- Step 7: Monitor, learn from, review, and adapt.

These seven steps can be used as a checklist for organizations and agencies that are mandated to deal with systemic risks. In order to perform these seven steps in a professional and effective manner, it is crucial that the private management organizations or public agencies operate as independent, involved, informed, and informative agents (Woods, 2006). They need to conduct their risk management without being constrained by economic or political interests, stay involved with the people they serve, are well informed about the complex interactions between risk agent and risk-absorbing systems, and be transparent about what they do and inform the wider public about their activities.

Fourth, since systemic risks are caused or modified by multiple actors, it is crucial that these actors take part in the risk assessments (using their specific experiential knowledge) and in particular the governance of risk reduction policies. The complex relationships between requirements for risk reduction (e.g., to limit climate change) and a political regulatory system, which needs to allow for an entire universe of tradeoffs and conflicting values, constitute difficult and often unresolvable problems for systemic risk governance. In this situation, including the many actors in defining the problem space and exploring the solution space has been proven to be a reliable and valid method to cope with complex and contested policy options (US-National Research Council, 2008). There are numerous methods and formats to engage the affected population and other parties in the risk evaluation and management process (Renn & Schweizer, 2009). Inclusive governance provides the structures and processes for an early and meaningful involvement of all stakeholders and, in particular, civil society. Inclusive governance is based on the assumption that affected and interested parties have something to contribute to the governance process and that mutual communication and exchange of ideas, assessments, and evaluations improve the final decisions, rather than impede the decision-making process or compromise the quality of scientific input and the legitimacy of legal requirements (Brink & Warnsler, 2017). It involves a wider array of actors, that is, political decisionmakers, scientists, economic players, and civil society actors. Transdisciplinary processes, in which representatives of key stakeholder groups and a multidisciplinary team of scientists are deliberating about wicked problems (Gibbons & Nowotny, 2001; Scholz & Steiner, 2015), have the potential to integrate analytical scholarly knowledge and experienced, reflective practitioners' contextual knowledge in order to provide effective as well as socially just risk reduction policies (Binder, Absenger-Helmli, & Schilling, 2015; Scholz & Steiner, 2015).

Such an inclusive approach to governance reflects the insights from complexity research. Having many stakeholders involved provides a much more effective guarantee to pay attention to a multitude of early warning signals and to detect irregularities that may be outside of the screen that official risk observers use (Florin, 2013). Furthermore, assigning responsibility, power, and accountability to representatives of the affected publics helps to focus on the complex, often counterintuitive threat scenarios that otherwise may be attenuated in public discourse or simply ignored, for example, when collective measures against climate change or reduction of biodiversity are debated (Laws & Rein, 2003).

Inclusive governance requires several basic features for being effective and is in line with many guidelines for good governance (Schweizer & Renn, 2015).

- A good level of transparency from the point of view of third parties, in documenting how specific inputs relate to the decision on one or more management measures.
- Freedom from constraints in the way participants may express themselves.
- A high degree of reflection on the different conditions and perspectives bearing on the threat in question.
- An effective level of communication between participants concerning the different factual and value issues involved.
- A clear understanding of who is in the end responsible and accountable for decisions.

Last but not least, an effective governance strategy for dealing with systemic risks is alert to the high sensitivity and suddenness of tipping points (Lenton et al., 2008). The elementary selection processes on the micro-level are ultimately responsible for a panarchy of interacting levels and environments. The universally observable phenomenon of a slow approach to an instability regime is frequently followed by a sudden phase transition with systemic risks in widely differing domains. Typical examples are the sudden tipping phenomena of ecosystems or social upheavals after a long period of enduring stress. As a matter of precaution, responsible governance honors the necessity to observe a system bearing the chance of serious systemic risks by a time series analysis in order to discover dangerous developments well before a sudden tipping of irreversible consequence may occur.

10. CONCLUSIONS

The analysis and governance of systemic risks require new approaches and policies. This is due to the fact that systemic risks are not easily isolated but rather are able to cascade through an entire system by elementary processes that are not easily understood let alone controlled. Systemic risks pose significant threats to society because they can destroy not only the system of origin but even propagate beyond its boundaries (ripple effects) (Kambhu, Krishnan, & Weidman, 2007).

This article aimed to illustrate the significance of several attempts in the natural, engineering, management, computer, and social sciences to contribute to a better understanding of complex risk situations and to design more effective strategies for systemic risk governance. Current societies are challenged by a number of pressing systemic risks. Some arise from global environmental change, in particular climate change, others from social inequality, from breakdown of technical and organizational infrastructures, including financial systems, from local environmental damage and threat of biological diversity. Recent developments include new political transitions toward postdemocratic regimes (Crouch, 2004) and the emergence of postfactual tendencies that underestimate the value of plurality (Keyes, 2004).

To this day, risk analysts lack an adequate understanding of the structure and dynamics of systemic risks and related data, methods, and tools. The stochastic and nonlinear nature of these risks impedes the routine application of conventional risk assessment methods based on the probability function of adverse effects. The focus of systemic risks lies on the combination of revealed patterns of complex dynamic systems and insights from empirical studies of how these patterns manifest themselves in the risk domains under investigation. When facing higher vulnerabilities and risks, such as in climate change, societal actors and decisionmakers are confronted with making tradeoffs between the right amounts of mitigation versus adaptation.

In an attempt to develop a theory of systemic risks with possible elements of governance strategies, it is rewarding to realize that systemic risks in any domain show analogies to complex physical, cyberengineered, chemical, and biological systems. Understanding systemic risks and providing good governance advice relies on a combination of realism and constructivism that integrates novel modeling tools from complexity sciences with empirical data from observations, experiments, or simulations and evidence-based insights about social and cultural response patterns revealed by quantitative (mainly surveys) or qualitative (mainly participatory appraisals) investigations. Systemic risks are not easily characterized by single numerical estimations but can best be assessed by using multiple indicators and including several dynamic gradients that can be aggregated into diverse but coherent scenarios. Lastly, governance of systemic risks requires interdisciplinary and cross-sectoral cooperation, a close monitoring system, and the engagement of scientists, regulators, and stakeholders to be effective as well as socially acceptable.

For this purpose of identifying, analyzing, and governing systemic risks, our article addressed the four major systemic risk characteristics: complexity, uncertainty, ambiguity, and the propensity for ripple effects beyond the system of origin (Florin, 2018). Whereas the governance of conventional, that is, simple, well-understood risks is better served by relying on the physical understanding of triggers and likely consequences, highly complex, uncertain, and ambiguous problems, furthermore, demand the integration of mental responses and social interactions for both understanding and managing these risks (Kloprogge & Van Der Sluijs, 2006). Thus, we propose, first, that management organizations develop a risk governance approach that expects to deal with surprises and unforeseen stressors and takes into account that risk will spread from one domain to the next. The article develops some step-by step procedures for dealing with these two major challenges. Second, we propose an inclusive model of systemic risk governance that attributes an important function to public and stakeholder participation as well as risk communication in the risk governance process. Inclusive governance requires an effective, fair, and efficient participation procedure. The concerns of stakeholders and/or the public should be integrated in the risk assessment and management process. Furthermore, stakeholder and public participation should become an established part of risk management.

In democratic societies, risk governance requires more than reducing intolerable risks effectively. It also needs to satisfy the need for democratic legitimization, justification to those who are affected, assurance of due process, and reference to societal values, such as social justice and sustainability (Rosa et al., 2014). The complex relationships between requirements for risk reduction, for example, to mitigate climate change, and a political regulatory system which needs to allow for an entire universe of tradeoffs and conflicting values, constitute difficult and often unresolvable problems for systemic risk governance. The ultimate goal is to implement a governance regime that constitutes an adaptive, coping, and participatory response to systemic risks.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support by the Berlin-Brandenburg Academy of Sciences and Humanities, Germany. The publication is the outcome of the Academy's interdisciplinary initiative "Systemic Risks as Prototypes of Dynamic Structure Generation" chaired by Klaus Lucas and Ortwin Renn. The initiative conducted several workshops from 2017 to 2019. We are thankful to the workshop participants and the anonymous reviewers of *Risk Analysis* who have provided valuable feedback on earlier versions of the publication. In addition, the authors are grateful for the support of the Institute for Advanced Sustainability Studies in Potsdam, Germany.

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