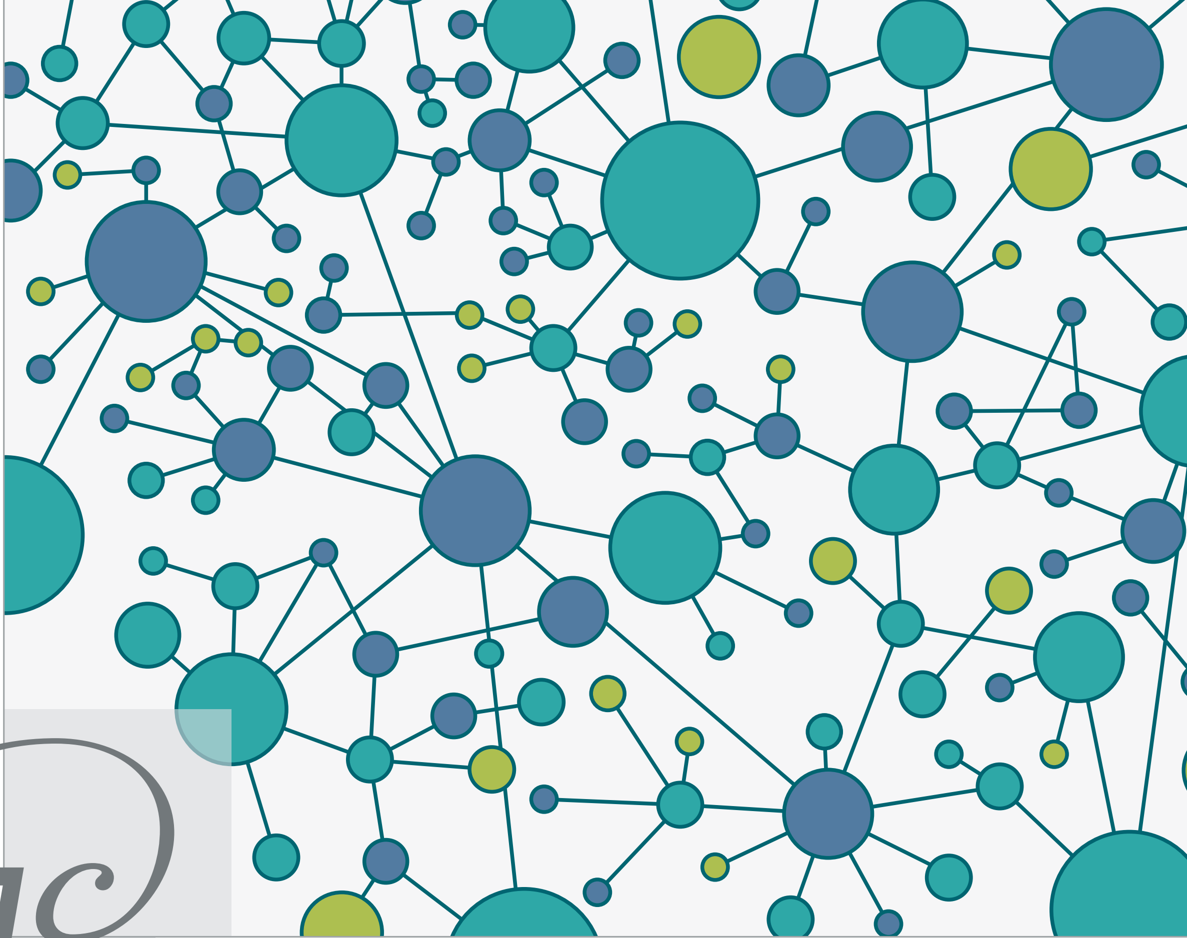

IRGC GUIDELINES FOR THE GOVERNANCE OF SYSTEMIC RISKS

In systems and organisations
In the context of transitions

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

international risk governance center

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PREFACE

Interconnectivity between systems is one of the structuring and determining features of our modern world, which is becoming ever more complex and dynamic. Many systems are growing larger. Socio-ecological systems are moving ever closer to biophysical boundaries, thresholds and tipping points. Socio-technical systems are being exposed to disruption of various causes. Dealing with risks associated with so-called *complex adaptive systems* is a concern for many organisations. Complex adaptive systems contain interacting feedback loops and are subject to external shocks and internal stresses that may destabilise or disrupt their functioning.

External shocks to interconnected systems, or unsustainable stresses, may cause uncontrolled feedback and cascading effects, extreme events, and unwanted side effects. Real-world examples of such unanticipated impacts are myriad, such as the disastrous economic and social consequences due to the collapse of the Aral Sea or large fisheries worldwide. Given these looming threats, organisations need to think about how they can avoid, mitigate or prevent the manifestation of systemic risks, which may affect their normal functioning. If such risks cannot be prevented, organisations must either adapt or transform to cope with them. Otherwise, they may have no other choice but to be exposed to unexpected destructive consequences, operate in crisis mode and integrate loss and damage, as in the case of unavoidable negative consequences of climate change (UNEP, 2016).

This document proceeds from the working hypothesis that **systemic risks are risks that evolve because of the inherently dynamic nature of complex adaptive systems**. In particular, due to nonlinear interactions among system components, these risks often appear as ‘surprises’. Its purpose is thus to help organisations deal with systemic risks that develop in complex adaptive systems, which characterise the environment in which most organisations operate.

IRGC intends neither to build a theory of systemic risks nor to focus on particular systemic risks, but rather seeks to provide practical guidelines that organisations can adapt to their particular needs and objectives. This is in contrast to other literature on systemic risks that focuses on understanding them. The scope of this IRGC project is on systemic risks in socio-technical and socio-ecological systems, i.e., these guidelines do not address purely financial risks. They are aimed at risk and policy analysts and other professionals in business and the public sector, who work to improve capabilities to identify, understand and manage risks in complex systems (OECD, 2017), which implies coping with instability and unpredictable or low-probability events.

IRGC’s project on systemic risks governance stems from previous IRGC work on risk governance, emerging risks, slow-developing catastrophic risks and resilience:

- The **IRGC Risk Governance Framework** describes the fundamental principles and concepts for governing risks marked by complexity, uncertainty and ambiguity. It is the cornerstone of IRGC's, following work and publications. In that sense, the guidelines described in this report focus on specific aspects of systemic risks, thus complementing and adding to the main framework (IRGC, 2005; 2017).
- IRGC's work on **emerging risks**, defined as new risks or known risks that develop in new context conditions and are unfamiliar to their managers, is presented in several publications (IRGC, 2010; 2011; 2015).
- In 2011, IRGC convened a group of scientists and policymakers to discuss the topic of **slow-developing catastrophic risks** (SDCRs) that may ultimately lead to critical transitions or regime shifts. The workshop led to a concept note (IRGC, 2013), which broadly described the characteristics of SDCRs as well as some mathematical features of early-warning signals associated with regime shifts. The concept note prompted further interest in how to deal with SDCRs, and IRGC convened a second workshop on SDCR governance in 2013.
- **Resilience** in IRGC concepts is a strategy to deal with risks that have potentially large and unexpected negative outcomes and disruptions. IRGC invited selected authors to contribute to a resource guide on resilience, published in 2016, that provides insight to academics and practitioners alike (IRGC, 2016).

In March 2017, IRGC invited a group of experts to jointly discuss these concepts in the context of risks in complex adaptive systems and work towards producing guidelines that could help organisations deal with systemic risks. In October 2017, a second workshop discussed an earlier draft of the guidelines described in this document. The guidelines are thus the result of a collaborative process in which more than 40 experts in academia, policy and industry have participated.

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SUMMARY

Systemic risks are fundamentally different from conventional risks. Traditional risk management practices are not sufficient for dealing with them. This document addresses the question of how to deal with systemic risks in the context of system transitions, i.e., in situations that require adaptation to new context conditions or transformation of an organisation or ecosystem.

The guidelines have the following objectives:

- Provide guidance to organisations in their initiatives to understanding complex system dynamics and reflecting upon their position within these dynamics.
- Help actors in a system to (a) prevent the shift of the system within which the organisation operates to an undesirable regime, or (b) trigger and facilitate the transition of the respective system to a preferable regime, considering changes in underlying context conditions or proximity to a tipping point that may trigger a regime shift.

The guidelines comprise seven interlinked steps:

Step 1 Explore the system in which the organisation operates; define the boundaries of the system and the organisation's position 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 Co-develop management strategies to deal with each scenario and the systemic risks that affect or may affect the organisation, and to navigate the transition.
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.

There must be iteration between the phases, orchestrated by a process manager or 'navigator.' While these guidelines neither dictate what should be decided nor prescribe a normative 'best' objective, they do provide options that organisations can consider.

At all stages, communication, openness and transparency are key to ensuring smooth proceedings and collaboration; learning together and experimentation are essential for improving an organisation's capacity to deal with systemic risks. This can be organised by the process manager or 'navigator,' who has the additional tasks of organising some form of ownership for systemic risks within the organisation, and helping the organisation 'navigate' through transitions that mark changes in complex systems.

In the face of many unknowns, increasing the overall resilience of an organisation can be a way to prepare for and better deal with the shocks and stresses arising from systemic risks. In line with mainstream recommendations for resilience-building, IRGC proposes three main strategic approaches for operationalising the concept of systemic risks management:

- Support and strengthen the ability of a system to self-organise and self-control
- Undertake pro-active interventions based on prevention, mitigation, adaptation and transformation principles
- Prepare for disruptions, accidents and crises.

These strategic approaches can be combined or implemented successively if proximity to a regime shift seems to increase.

GUIDELINES FOR THE GOVERNANCE OF SYSTEMIC RISKS

1. INTRODUCTION

Economies, societies and ecosystems are dynamic, constantly evolving complex systems that contain a great number of interacting feedback loops. Some of these loops promote stability; others cause instability, leading to cascading events and potential runaway collapse. Planners usually try to ensure that the stabilising loops prevail, because they are more familiar and comfortable with routine strategies that aim to maintain existing situations. However, this may be a short-sighted approach, because there is always the possibility of a new situation arising where destabilising loops abruptly take over to produce percolation effects. The analysis presented in an IRGC report on 'slow-developing catastrophic risks' suggests that while such collapses are often foreseeable, they are largely inevitable because they are built into the nature of complex adaptive systems (IRGC, 2013; Centeno, Nag, Patterson, Shaver & Windawi, 2015). This aspect of complex adaptive systems and the risks that develop in those systems are key features that support IRGC's suggestions in these guidelines.

Interconnectivity within and between complex adaptive systems is one of the defining and determining features of our modern world. While interconnectivity can increase system efficiency and service delivery, it can reduce resilience to shocks if it does not include buffer capacity and if the connections between the nodes are too tight. Interconnectivity may expose the various layered (sub-)systems to risks of sudden external shocks and unsustainable stresses within the system (e.g., slow-moving and imperceptible changes that can ultimately drive the system beyond a tipping point), resulting in cascading changes in the system itself and other interconnected systems. From a broader economic welfare perspective, thinking in terms of resilience in contrast to efficiency implies fostering policies that reduce the duration and depth of shocks, enhance the capacity to recover quickly and reduce the severity of the impact on welfare (Connelly et al., 2017).

Complex adaptive systems are in constant flux, and transitions between regimes are natural processes. Traditional probabilistic risk-assessment methodologies, which are based on linear or well-established cause-and-effect-relationships, cannot be successfully applied to risks that arise in such systems and may even have counter-intuitive and unintended consequences. A better understanding of systemic risks and an appropriate approach for developing management options are thus essential for decision-makers to prepare their organisation for future challenges. Since a system can be hampered by factors that reside inside or outside of its functioning as a complex system, dealing with systemic risks requires a dual process of identifying both problems and their interactions. The OECD recommends that governments should seek to address global shocks and cascading failures, strengthen resilience and create capacity for improved agility in case something happens (OECD, 2011; 2014a; 2014b; Linkov et al., 2014).

1.1 Characterisation of systemic risks

Systemic risks are the "threat that individual failures, accidents, or disruptions present to a system through the process of contagion" (Centeno et al., 2015). The notion of systemic risk "refers to the risk or probability of breakdowns in an entire system, as opposed to the breakdown of individual parts or components" (Kaufman & Scott, 2003). While such events can also be triggered by a failure in one subcomponent, i.e., an individual breakdown, they are characterised by further cascading effects that affect the larger system. In the context of interconnected financial systems, for instance, Hendricks (2009) suggests that "a systemic risk is the risk of a phase transition from one equilibrium to another, much less optimal equilibrium, characterised by multiple self-reinforcing feedback mechanisms making it difficult to reverse."

Systems prone to systemic risks are highly interconnected and intertwined with one another. Such interconnection contributes to complex causal structures and dynamic evolutions, non-linear in their cause-effect relationships, often stochastic in their effect structure, and potentially global in their reach (in the sense that they are not confined within borders) (Renn, 2016, 2017b). Systemic risks overwhelmingly do not follow normal risk distributions but tend to be fat-tailed, and there is a high likelihood of catastrophic events once the risk materialises. They can trigger unexpected large-scale changes to a system or imply uncontrollable large-scale threats to it (Helbing, 2010)

Box 1: Complex adaptive systems

Complex adaptive systems (CAS) are systems of distributed interacting components, whose conditions can change in response to their environments and each other (see Figure 1).

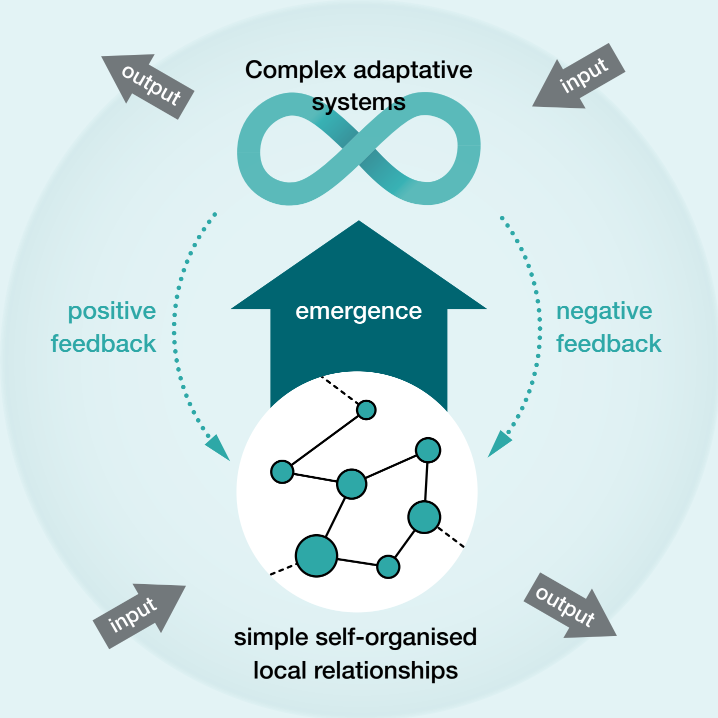

Figure 1: Complex adaptive system in a changing external environment

A common element of a CAS is that an understanding of the individual parts of a system, taken individually, does not offer a robust explanation of how the larger system functions or changes over time. Instead, a CAS includes a dynamic network of interactions, where feedback loops between systems and nested relationships between a larger system and a component sub-system can trigger system-wide disruptions or changes. Under some conditions, small interactions or disruptions to minute sub-systems can generate substantial systemic changes across a much larger web of interconnected infrastructures, or social and economic systems. The adaptive and multi-actor nature of a CAS makes it inherently difficult to model or analyse via simple linear cause and effect models (Cohen & Axelrod, 2000).

CAS typically show the following features (Nursimulu, 2015a; Helbing, 2010):

1. **Self-organisation and emergence** – The aggregation of the individual behaviours of system drivers or components produces an organised pattern at the macro level, where resulting macro behaviours cannot be ascribed to the added effects of individual components.
2. **Feedbacks** – Negative feedbacks have a dampening effect and maintain a system within a particular regime, whereas positive feedbacks amplify changes occurring in subsystems.
3. **Diversity and regime shifts** – CAS often have alternative stable states and can flip from one regime to another. Regime shifts can happen naturally owing to the internal dynamics of the system, but may also be triggered by external events that disrupt normal feedback mechanisms (Figure 2).
4. **Regime-shift cascades** – These can happen as a result of common drivers affecting different systems, whether directly or indirectly by affecting drivers in other systems.
5. **Anthropogenic influence** – Although regime shifts occur naturally in CAS without the influence of external agents, human actors and activities influence the state of the system, especially when they are primary components, and trigger regime shifts.

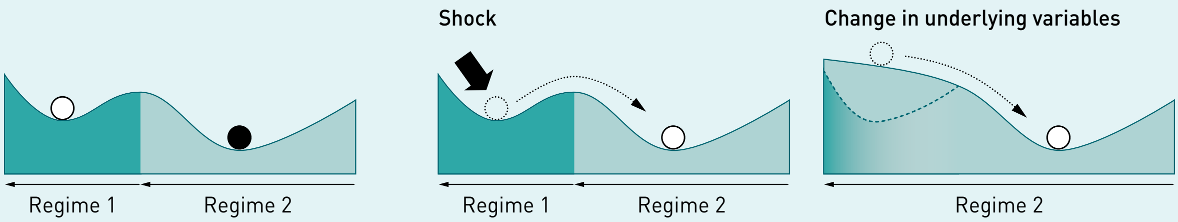

Figure 2: Ball-in-cup diagram to illustrate regime shifts (original design in Scheffer, M., 2009a. *Critical Transitions in Nature and Society*. New Jersey: Princeton University Press)

The leftmost plot shows two possible stable states, the white ball in regime one and the black ball in regime two. The middle plot indicates a regime shift due to an external shock. The rightmost plot indicates a regime shift due to a change in underlying variables / components.

and may cause ripple effects beyond the domain in which the risk originally appears (Renn, 2016, 2017b). Complex systemic risks are thus fundamentally different from conventional risks (see Box 2), and new tools and practices are needed to address them.

Systemic risks tend to be underestimated and do not attract the same level of attention as catastrophic events. One of the reasons for this is that complex structures defy human intuition, which assumes that causality is linked to proximity in time and space (for example, relatively small and even imperceptible system shocks can trigger substantial system change over an extended period). Another reason is that systemic risks are under a distributed responsibility: everyone is responsible for a part of the system but no one has the legitimacy to act on the entire system. However, complexity implies that far-fetched and distant changes can have major impacts on the system under scrutiny. Furthermore, humans tend to learn by trial and error, and facing non-linear systems with tipping points encourages us to repeat our errors because feedback remains positive for a long time until the tipping point is reached. But when the tipping point is passed, the error (which can induce a collapse) is so dramatic that learning from the crisis is either impossible or too costly (Renn, 2016, 2017b). Finally, systemic risks also touch upon the common pool problem. Within such a common pool problem, each actor wins individually in the short run if he or she takes the free rider position and lets others invest in risk reduction. There is no incentive to change one's behaviour. However, if we want systems that exhibit better properties to deal with risks, the incentives must be designed in such a way that they do not require changing human nature (Luyendijk, 2015).

The consequences of failing to appreciate and manage the characteristics of complex global systems and problems can be immense (Helbing, 2012).

Well-known examples are the 2008 global financial crisis, the collapse and desertification of the Aral Sea, or the 2011 Japanese earthquake and Fukushima nuclear accident. For lesser-known examples, in Southeast Asia, the destruction of mangrove forests for commercial shrimp farming is known to have caused water pollution and increased the vulnerability of coastal areas to cyclones and tsunamis. The result of this was seen in 2004 when these areas were devastated by the South Asian Tsunami, with significant loss of life and property. Areas where mangroves were not destroyed were less affected by such losses. This led to calculations about the actual contribution of commercial farming to the economy, in comparison to the loss of natural protection against tsunamis and cyclones and other damages. The cost-benefit analysis suggests that the cost of loss of biodiversity (negative social value) was larger than the economic benefits from shrimp farming (positive private value) (Giri et al., 2008).

Box 2: Comparison of conventional and systemic risks

Type of risk	Definition	Main features	Examples	Implications
Conventional risks	Known and well-defined risks	• Familiarity – recognisable patterns and management regimes that are relatively stable and have proven to be effective if implemented according to certain rules	• Bicycle theft • Salmonella infection • Car accidents • Obesity	Use standard risk management practices, e.g., regulation
Emerging risks*	New risks or known risks that become apparent in new context conditions (IRGC 2015)	• Uncertainty regarding causes, potential consequences, and probabilities of occurrence • Lack of familiarity with the risk	• New processes and products in the field of synthetic biology • Malaria spreading to higher latitudes	Focus on early detection and analysis of elements that trigger emerging risks. Prepare to revise decisions and adapt
Systemic risks	Threats that individual failures, accidents or disruptions present to a system through the process of contagion	• Highly interconnected risks with complex causal structures, non-linear cause-effect relationships • Lack of knowledge about interconnections in an interdependent and complex environment, prevention	• Desertification and collapse of the Aral Sea • 2008 global financial crisis • Pandemics • Cyber-security • Global climate change • Fish stocks depletion	Focus on adaptation and transformation of the organisation and the system

* Some emerging risks may manifest themselves in complex systems and thus require a systemic approach to their assessment and management. Some systemic risks may be first seen as emerging.

1.2 Examples of systemic risks

This section details a small number of notable examples in various sectors, including economics (the 2008 financial crisis), ecology (the collapse of the Aral Sea as well as steady depreciation of global fish stocks), society (the rise of a rideshare/personal transportation economy), and global megatrends (planetary boundaries). These examples show that systemic risks can have multiple causes and impacts, are difficult to delineate and are perceived differently by stakeholders. They can be resistant to policy response.

The 2008 financial crisis

In 2008, the United States experienced a major financial crisis that led to the most serious global economic recession since World War II. The crisis triggered a global economic meltdown in a 'financial contagion effect.' This international contagion effect was driven by the highly interconnected nature of the global financial system, which had all the characteristics of a complex dynamic system, including the potential for tipping points and system-wide cascading failures (Haldane & May, 2011). A collapsing, debt-fuelled bubble in residential real estate led to a rapid spread of credit problems across institutions and markets, which ultimately brought down major institutions and threatened the viability of global markets.

The complexity of the system, the perverse effect of certain regulations and practices, and the resulting cascading failures have been analysed thoroughly. They are famously illustrated by a reply from the British Academy in response to a question by the Queen of England as to why nobody had foreseen the financial crisis: "Everyone seemed to be doing their job properly on its merit. And according to standard measures of success, they were often doing it well. The failure was to see how collectively this added up to a series of interconnected imbalances. Individual risks may rightly have been viewed as small, but the risk to the system as a whole was vast" (Helbing, 2013; Centeno et al., 2015; Maila, 2010; Marshall, Goodman, Zowghi & da Rimini, 2015).

Takeaway
In interconnected systems such as the global financial systems, the risk of contagion is high. One needs to better align or coordinate regulations, incentives, responsibilities and practices.

The collapse of the Aral Sea

Located in Central Asia, the Aral Sea used to be one of the four largest lakes in the world. The Aral Sea had been steadily shrinking since the 1960s after the two main rivers that fed into it were diverted by irrigation projects for water-intensive cotton and wheat fields. By 2007, it had declined to 10% of its original size, and by 2014, the eastern basin of the Aral Sea had completely dried up. Former UN Secretary-General Ban Ki-moon called this development "one of the planet's worst environmental disasters" (UN, 2010). The main cause for why the once-large Aral Sea has slowly dried up is years of overuse in irrigation and land-reclamation projects, driven by political and economic ambitions. The reduction of the Sea triggered various ecological, economic, and sociological outcomes that affected environmental and economic sustainability.

Besides immediate ecological and socioeconomic shifts, further cascading consequences arose. As one example, the shrinking lake left behind a salt desert contaminated by toxic waste, pesticide residues and agricultural run-offs, resulting in poison dust storms and contaminated water that negatively impacts public health across the region (Nursimulu, 2015a).

Takeaway
Even after the cause of the risk was eliminated, the Aral Sea ecosystem was not able to go back to its original state because a threshold had been crossed and the shift was irreversible.

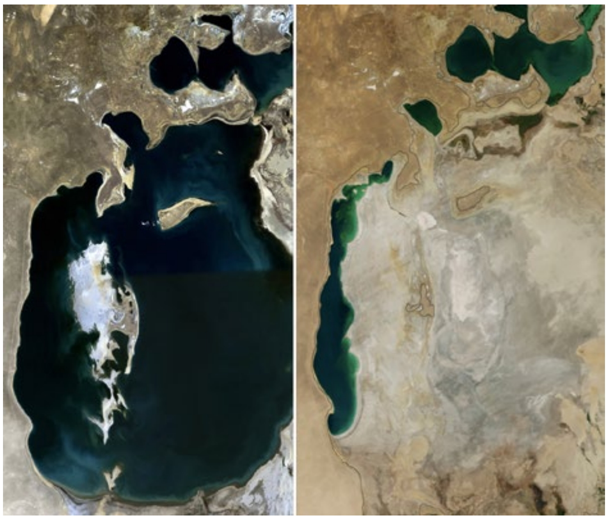

Figure 3: The Aral Sea in 1989 (left) and 2014 (right)
(Source: NASA. Collage by Producercunningham)

Fish stocks depletion / overfishing

Billions of people around the globe depend upon robust quantities of seafood for their diet. However, overfishing has contributed to situations where stocks of various fish and shellfish are at or below levels of replenishment. As much as 85% of the world's fisheries are thought to be overexploited, including complete depletion, near-depletion, or recovery from near-depletion (Worm et al., 2009).

Past examples include the collapse and closure of California Sardine fisheries in the early 1960s, the collapse of the Atlanto-Scandian Herring fisheries (Iceland, Norway, Russia) in the late 1960's, and the collapse and closure of the Northern cod fisheries (Newfoundland, Canada) in 1992 (Hauge, Cleeland & Wilson, 2009). Plausible future examples include the Bay of Bengal, where growing 'dead zones' signal an imminent collapse of fish populations without strong interventions to stem local overfishing (Ghosh & Lobo, 2017).

The consequences of overfishing are beyond the substantial drop in the stock of any individual fish species. Fish and shellfish ecosystems are both interconnected and fragile – a disruption via the collapse of one species can easily trigger a collapse in others as well. Further, the depletion of local fish stocks could prove disastrous for coastal communities that depend upon seafood as a staple of their diets, and major negative economic and social consequences often follow the collapse of fisheries. As such, national and international management of complex fish ecosystems is necessary to prevent ecosystem collapses (Hauge et al., 2009).

Takeaway
Currently, many fish stocks worldwide are nearing a tipping-point of depletion. There are obvious incentives for people to freeload and ignore the limits until it is too late. It is critically important to implement management strategies to avoid the crossing of tipping-points.

Development of new systemic risks in the personal transportation sector

Four fundamental innovations are currently revolutionising the automotive sector, car driving, and personal transportation. While such innovations may produce substantial improvements in economic development and service delivery to millions of people, they also represent broader threats that will affect both traditional automotive and taxi-based services:

- Automated driving (towards full automation) modifies drivers' behaviours, will probably reduce the number and severity of accidents and is expected to increase traffic fluidity and efficiency.
- The connectivity between cars and infrastructure further improves traffic fluidity and paves the way for fully autonomous private transport systems.
- Electric cars contribute to reducing air pollution and CO_2 emissions.
- The traditional community and business of taxi drivers are challenged by the advent of new services offered by companies such as Uber, and the ubiquity of transport services as a commodity.

The revolutionary developments in the transportation sector create a combination of disruptions that will have cascading consequences, causing systemic risks that in the coming future may affect a range of actors including traditional car servicing, parking operators, or taxi drivers. Many taxi companies did not anticipate or adjust to the revolution in the personal transportation sector and have lost a substantial proportion of their business already. Initially, such taxi companies have tried to resist at first, but likely have no other solution than to adapt their business by adopting similar technologies for direct online connectivity with clients, or transform their business models for more flexibility, in a society where connectivity and adaptability are key advantages. We might then see that traditional taxi drivers will rebound, adapt and transform their business model, by adopting the same innovations.

Takeaway
The automotive and transportation sectors are marked by complex interactions with several other systems. Changes in these sectors can be caused by and can cause disruptions in other interconnected systems.

Planetary boundaries and global megatrends

The world has witnessed unprecedented demographic and economic growth during the last two centuries, accompanied by massive urbanisation, globalisation of markets, accelerating technological development, and fundamental socio-economic and cultural transformations. These large-scale, long-term and high impact changes — often referred to as 'global megatrends' (EEA, 2015b; EEA, 2015a) — have led to substantial economic and human development, but have also resulted in excessive burdens on the global ecosystem, resource demands and adverse pressures on local ecosystems.

Researchers of global environmental change have identified nine critical processes that regulate the stability and resilience of the Earth system (Rockström et al., 2009; Steffen et al., 2015b). They argue that sustainable development can only be achieved within a safe operating space for humanity identified by the biophysical realities of critical natural thresholds. Transgressing these 'planetary boundaries' could lead to undesirable and irreversible changes in the environment, putting ecosystems and societal resilience at risk, and making the Earth a much less hospitable place (Steffen, Broadgate, Deutsch, Gaffney & Ludwig, 2015a).

Despite the uncertainty, there is evidence that both planetary and regional boundaries for some areas have already been transgressed, and systemic risks to human societies have or will soon materialise. The projected increased frequency of extreme climate-related events in Europe (EEA, 2017) and elsewhere (ECA Working Group, 2009) will have effects on human health, agricultural production, energy, transport and tourism.

Takeaway
The risk of sudden, non-linear and irreversible change in Earth system processes poses serious threats to humanity. Preserving resilience of socio-ecological systems at the regional and global scales will depend on transforming the societal systems driving environmental degradation.

1.3 Governance of systemic risks: navigating transitions

Risk governance includes the totality of actors, rules, conventions, processes and mechanisms concerned with how relevant risk information is collected, analysed and communicated, and how management decisions are taken (IRGC, 2005).

Operationalising the concept of systemic risks into principles and instruments for their governance is particularly challenging, as our current political and economic systems are not constructed to address such complex problems. The gradual evolution of many systemic risks entails a necessary look further into the future than regular planning timeframes usually allows (although the manifestation of these risks may result in immediate and catastrophic failure once a tipping point is crossed). Systemic risks also require a broader framing of the issue.

If prevention or avoidance is not possible or sufficient, a key question for policymakers is how to limit the build-up of systemic risks and contain the impacts of breakdowns or collapses, which may lead to crises when they do happen. This report suggests that, instead of planning or managing for stabilisation or persistence (Folke et al., 2010), organisations may be advised to collaborate differently and engage in steering or governing a transition to a new regime, which involves adaptation to new context conditions or transformation of the organisation or system (Geels, 2016).

The EEA (2016) defines transitions as "long-term, multi-dimensional and fundamental processes of change" which are based on "profound changes in dominant practices, policies and thinking." It is important to note that transitions that are designed to reduce known systemic risks can potentially also be the source of new systemic risks. For example, energy transitions will trigger the development of renewable and less carbon-intensive fuels, which can contribute to reduced climate change risk and energy sustainability (Nursimulu, 2015b). However, this may contribute to economic risks in traditional industries, which may cascade to economic risks in other interconnected sectors and societal risks.

The guidelines discussed in this report serve as a process by which top management and key decision-makers can better understand the systemic threats relevant to their organisation, and take action against such threats. However, the approach by which this action is possible and undertaken will vary widely based upon the political, institutional, and cultural elements of a given organisation and its willingness to address systemic risks and trigger change. For example, a complex Western democracy will likely have to engage into broad deliberation to develop substantial political capital to craft new policy against systemic threats. In contrast, leaders in an autocratic regime, or a private sector organisation with clear hierarchies and a small number of veto holders, may not have to work as hard to take action. Regardless of the type of organisation, the key is a willingness to explore one's exposure and vulnerability to systemic risk, and identify opportunities to take action should permission be acquired to do so. The guidelines below serve as a process to reach that conclusion.

After describing the guidelines (Section 2), this report provides additional insights, supporting evidence and further guidance from specific disciplines:

- Resilience (Section 3)
- Complexity theory, systems thinking and network science (Section 4)
- Foresight and early-warning systems (Section 5).

Illustrative approaches are presented in Sections 6, 7 and 8.

Box 3: Terminology – transition, adaptation, transformation and resilience

In these guidelines, some terms are used that may be defined differently across various application sectors and disciplines. This box provides clarity regarding how each key term will be used throughout each step of the guidelines – pulling insight from seminal scholarly works and the Oxford Dictionary.

Persistence involves absorbing on-going change or risk. It may also correspond to a non-vital degradation of the system as it absorbs such risk. Persistence can be thought of regarding the capacity of a system to exhibit low vulnerability to risk or provide a good level of resistance to risk. For example, persistent ecosystems can provide a steady supply of valued ecosystem services, but over the long term, this may require adaptation and possibly transformation at other scales.

Transition is the process or period of changing from one state or condition to another (Oxford Dictionary, n.d.). It is seen as a fluid change towards a new future, which is an improved version of what exists; it is a "gradual, continuous process of societal change, changing the character of society (or a complex part) structurally" (Rotmans, van Asselt, Geels, Verbong & Molendijk, 2000). A dynamic phase between two stable phases enables the system to shift from a first context to a new, stronger one. Crises are often needed to make such changes happen. In a condensed form, the EEA defines transitions as "long-term, multi-dimensional and fundamental processes of change, based on profound changes in dominant practices, policies, and thinking" (EEA, 2016).

Adaptation is the action or process of adapting or being adapted to something. It involves adjusting responses to changing external drivers and internal processes to remain in a necessary or a desired regime and on the current pathway. Adaptation is achieved through incremental change. It is seen as a slow process, which modifies the landscape only slightly.

Transformation is a thorough or dramatic change in form or appearance. It involves fundamentally changing the system dynamics, so there are new feedbacks to maintain the system in a new regime or along a new pathway (Renn, 2017a). It is a change towards a future that is fundamentally different from the existing paradigm (Roggema, 2012). In the case of the resilience of the global social-ecological system, transformability for sustainability is about shifting into new pathways of development (Folke, Biggs, Norström, Reyers & Rockström, 2016).

Resilience includes sustaining what we want to keep the same (i.e., persist). Adaptability can also be part of resilience because it represents the capacity to learn and adjust responses to changing drivers. The capacity to transform into something new and better may be beyond what conventional strategies for resilience can do. "The very dynamics between periods of abrupt and gradual change and the capacity to adapt and transform for persistence are at the core of the resilience of social-ecological systems" (Folke et al., 2010).

Ultimately, an organisation or system can engage in the process of change (transition) to adapt to change and, if needed, transform itself.

(Oxford Dictionary, n.d.; Rotmans, van Asselt, Geels, Verbong & Molendijk, 2000; Roggema, 2012; Folke et al., 2010)

2. GUIDELINES FOR DEALING WITH SYSTEMIC RISKS

2.1 Objectives

The guidelines proposed in this document are intended as a set of elements that policymakers and senior managers in public- and private-sector organisations are advised to consider when they work to address systemic risks. Because systemic risks evolve when systems are unstable, in transition to new regimes, the guidelines have the following objectives.

1. Guide organisations in understanding complex system dynamics and reflecting on their positions within them.
2. Help the actors in a system:
   - prevent the shift of the system to an undesirable regime as a result of internal stresses or external shocks.
   - trigger and facilitate the transition of the system to a preferable regime where the system and the elements that compose it are less susceptible to internal stresses or external shocks, considering changes in underlying context conditions or proximity to a tipping point that may trigger a regime shift.

For example, a desertification process in a region may be first observed by more frequent and longer periods of drought, but agricultural practices can adapt to new climate regimes to a certain extent. In the transportation industry, the advent of automated, connected and electric vehicles may trigger a regime shift and systemic change to a new type of transportation system. The transition will force actors in the system to adapt and transform. A change considered positive for certain actors can be disastrous for others. Transitions create winners and losers, and it is important to support losers in their efforts to recover from the transition, and adapt or transform.

The guidelines build on previous IRGC work and follow the overarching principles outlined in the IRGC risk governance framework (IRGC, 2005). However, they are more specific about those aspects of risks in CAS that cannot be dealt with using conventional mitigation. The proposed process is also aligned with IRGC's guidelines for the governance of emerging risks, which feature systemic risks as one type of emerging risks (IRGC, 2015). However, the present document focuses more on the systemic dimension and the extra knowledge it requires than upon the forward-looking (explorative) dimension that is covered in the guidelines for the governance of emerging risks. The suggested process is similar to traditional resilience assessment approaches but may differ in its aim: building capacity to adapt and transform, rather than bounce back after recovery (Quinlan, Berbés-Blázquez, Haider & Peterson, 2015).

Before being applied, the guidelines must be adapted to specific cases and contexts. Their successful implementation depends on strong leadership and the willingness to adapt or revise processes, focus on mid- and long-term issues, and accept and resolve trade-offs.

2.2 Process for the governance of systemic risks

IRGC's guidelines for the governance of systemic risks comprise seven interlinked steps (see Figure 4).

1. Explore the system, define its boundaries and dynamics
2. Develop scenarios considering possible ongoing and future transitions
3. Determine goals and the level of tolerability for risk and uncertainty
4. Co-develop management strategies dealing with each scenario
5. Address unanticipated barriers and sudden critical shifts
6. Decide, test and implement strategies
7. Monitor, learn from, review and adapt

Iteration between and within each step. The seven steps are listed here in the most likely sequence, but they can be ordered in different sequences depending on the application, existing knowledge and context. The whole sequence should be seen as a reflective exercise that includes all steps in a variety of orders and a system of iterations and feedback loops. The extent of iteration *within* each step depends on the circumstances and whether the various stakeholders agree on priorities and decisions to be taken.

The process is coordinated by a process manager or 'navigator'[1], who plays a crucial role in connecting the various stakeholders, ensuring the effective implementation of the process, and helping an organisation navigate through transitions. The process manager organises the iteration between steps and decides to adapt the process to organisational specificities, as unexpected events will most certainly come up. For example, the guidelines suggest that organisations should "explore their system" before setting their goals. In some cases, the organisation can set its own goals at the beginning of the process. However, it must be prepared to revise its goals. The navigator constantly monitors the changing conditions of his complex and uncertain environment. He navigates complexity and uncertainty.

The process includes a step to "address unanticipated barriers and sudden critical shifts", which is placed after the decision yet before the implementation of management strategies. The recommendation is that major known obstacles should be considered before deciding on a strategy, but also that attention should be given to preparing for unexpected barriers and lock-ins that will inevitably come up because of the dynamic nature of complex adaptive systems. When systems are in transition, strategies for the management of systemic risks will have to adapt to changing circumstances.

Processes for the governance of systemic risks must be open to various entry points, depending on where the organisation is, considering the timing and path of development of a given risk / threat. If the risk is in a phase of slow development, the organisation has time to organise long- and broad-term strategies to adapt or transform. However, if a risk is imminent and a regime shift is impending or ongoing, the process manager may decide to skip or modify their approach to Steps 1, 2 and 3.

Communication, openness and transparency are central to the process and key at all stages. The effective management of systemic risks requires a common fundamental understanding on the part of all relevant stakeholders that these are success factors for the governance of systemic risks. While this also holds for the management of

[1] A navigator is an individual responsible for guiding a vehicle to its destination. On a ship or aircraft it is the person on board responsible for its navigation. It is not the captain. The navigator's primary responsibility is to be aware of ship or aircraft position at all times. Responsibilities include planning the journey, advising the ship's captain or aircraft commander of estimated timing to destinations while en route, and ensuring hazards are avoided. The navigator is in charge of maintaining the aircraft's or ship's nautical charts, nautical publications, and navigational equipment, and generally has responsibility for meteorological equipment and communications. (Source: en.wikipedia.org/wiki/Navigator)

conventional risks, it is even more relevant for systemic risks that are notoriously hard to perceive due to difficulties in identifying causal relationships, psychological barriers and (often) long latency periods. The establishment of platforms or roundtables for sharing views and concerns, and providing information about systemic risks, is a prerequisite for creating awareness of an existing need for action and the necessary acceptance of the available management options.

The following sections provide detailed descriptions of each step, and respective objectives, required actions, expected outcomes, as well as key success factors.

Figure 4: Elements of IRGC's Systemic Risks Governance Guidelines.
The smaller figure provides an illustration that the sequence is flexible and can be arranged differently or adapted to better align with specific cases, and organise 'on-demand' interaction and iteration. The process may be non-linear and non-sequential, to provide support to managers in a variety of situations, such as when they face an impending systemic disruption or if they have time and resources to elaborate long-term strategies.

STEP 1 – EXPLORE THE SYSTEM, DEFINE ITS BOUNDARIES AND DYNAMICS

KEY OBJECTIVE: EXPLORE AND FRAME THE SYSTEM IN WHICH THE ORGANISATION OPERATES, AND DEFINE ITS POSITION WITHIN A DYNAMIC ENVIRONMENT

Step 1 involves scanning, observing and analysing the organisation's internal and external environment and boundaries, and developing an initial understanding of the system in which the organisation operates and develops. It also considers whether important transitions are ongoing

Required actions	• Environment scanning: Observe the environment for potential precursors of major changes and transitions that might affect the organisation (horizon scanning, early-warning) • Taking a 'systems thinking' approach • Interacting with others to understand possible ongoing transitions of the system or around it
Expected outcomes	• Characterisation of the environment/context regarding opportunities and risks, including an overview of the interconnections and networks between the organisation and external players • Definition of the boundaries of the system in scope for the organisation • Understanding the direction in which the system seems to be heading, indicating possible transitions • Understanding key external triggers of change
Key success factors	• Institutional capacity (skills, funding) for environment scanning • Diversity of information • Scientific soundness of data collection, analysis and prioritisation • Data reliability and consistency • Effective communication of early-warning findings to decision-makers • Willingness and ability to act upon early-warning/faint signals

Step 1 aims to explore, frame and define the boundaries of the system in which the organisation operates and develops. It involves:

- Scanning, observing, and analysing the internal and external environment.
- Developing an initial understanding of the system in which the organisation operates, including its boundaries.
- Considering whether important transitions are ongoing, which can provide information about ongoing dynamics.

Important actions include characterising the system and identifying potential precursors of major changes and transitions that might affect the organisation (horizon scanning, early-warning) and might represent systemic risks to the organisation. Communication and collaboration with others to understand interconnections and possible frictions as well as possible ongoing transitions of the system or around it are also key features.

System characterisation

A system is characterised by its organising principles and mission as well as the critical functions and services that it must deliver in normal operating mode. Firstly, it is essential to screen and analyse an organisation's internal boundaries to understand how a given system operates, acknowledging though that attempting to define boundaries should be seen as a heuristic to make analysis possible – not as an actual decidable fact. Understanding the internal environment and boundaries of a system helps to (a) identify the components or sub-systems that must operate efficiently for the larger system to survive, (b) better understand the areas where an intervention may be undertaken to strengthen a system's ability to absorb, recover from, and adapt to systemic risks over time (NAS, 2012), and (c) identify communication weaknesses in the system. Secondly, it is important to identify the external environment and boundaries of a system. This may allow to prescribe a normative value regarding how important such a system is to an individual, organisation, or society (i.e., how much benefit do we get from a given system when it is operating normally).

As soon as a system has been defined and the internal environment and boundaries analysed (i.e., the focal scale), it is important to identify and describe the interconnections with other systems (via external boundaries) and possible frictions. Boundaries are a necessary yet artificial construct to make sense of risks, but organisations need to realise what the impact of the very choice of boundaries is on systemic risks. Structurally, systemic risks are driven by the interconnected and nested nature of various infrastructural, social, economic, informational, and environmental systems (RSA-WWF, 2014). Large systems (say homeland security in the U.S.) are composed of sub-systems (e.g., disease control, prevention of terrorism and criminality, efficient transportation networks, protection against severe weather) that are often interconnected amongst themselves. As such, a disruption to one such system can have a cascading impact that negatively influences others (i.e., a failure of dams or levees against tropical storms can severely degrade transportation networks and public health facilities to meet demand in an emergency scenario). In social-ecological systems, transitions into and out of a crisis mode must involve analysing interactions between different risks, between risks and subsystems and between subsystems themselves (Haas, Ye, Shi & Jaeger, 2015; Scheffer, 2009). Step 1 is designed to allow organisations to explore their operational needs and the structure of their system, which in later steps will allow them to better deal with systemic threats.

The process in Step 1 of exploring the internal and external environments and boundaries requires one to acknowledge the role of human decision-making and analytical capabilities to understand systemic risks. The nature of systemic risks (often low probability but high consequence events) challenges human decision-making due to our reliance upon availability heuristics and proxy data, which often leads to subjective assessment. Though such decision-making allows humans to meet ongoing challenges of the current day, such decision processes are biased. They focus upon more recent risk events over those with older or more limited rates of occurrence. In other words, it is easy to place importance upon systemic risks that are visibly ongoing, yet such focus diminishes over time as new concerns arise (Gilovich, Griffin & Kahneman, 2002). As such, where Step 1 is designed to explore a system and understand its dynamics, it is important to be mindful of any potential biases and current perceptions of systemic risks that could cause one to overlook a critical system component.

The characterisation of the system in which 'systemic' risks materialise poses a different challenge than the characterisation of emerging risks. Rather than *imagining* future developments based on weak signals detected in the environment (the core challenge for emerging risk characterisation), systemic risks require one to invest in *knowledge* (supported by facts and evidence) and *models* as an initial task. It can also be helpful to analyse how organisations have faced previous stresses, as that information may suggest where future vulnerabilities may arise. In this regard, new knowledge management tools, modelling exercises, and data arrays provide unprecedented opportunities for anticipating future threats. Further, analysing contributing factors to risk emergence can be helpful in exploring changes in the system (see Section 5.1).

Environment scanning

Observing the environment for potential precursors of major changes and transitions that might affect the organisation is a task of the utmost importance for various ecological, social, and economic systems today. This includes scanning the horizon for weak signals that may indicate shifts in existing trends or situations and tracking factors known to contribute to the emergence of risks. In addition to weak signals, statistical early-warning signals (s-EWS)[2] can inform risk assessors and decision-makers about the proximity of a regime shift. These s-EWS can complement weak signals, by providing a quantifiable metric of the imminence of change. Questions remain, however, as to whether s-EWS are sufficiently early (advanced), robust, reliable and useful (see Section 5.2 for more details). While they cannot predict when a regime shift is going to happen (as they only 'kick in' once the shift begins to unfold), statistical EWS can be an integral part of a continuous and quantitative system monitoring process.

Communication and collaboration with others

Dialogue, interaction and collaboration with others are critical to helping an organisation understand its external boundaries and its dynamic environment. Organisations have incomplete information regarding the state of their external boundaries, making collaboration with organisations along one's boundary beneficial to gain a better understanding of how a larger network of systems operates. As an expected outcome of Step 1, such collaboration helps characterise a given organisation's environment more robustly and can help it acquire insight into early warning signals for systemic risks that the organisation may not have access to, or may not be aware of. Examples of such communication and collaboration can include international datasets for global megatrends (i.e., climate change), industry consortia (i.e., shared best practices for an industrial sector), or international agreements and research efforts (i.e., modelling and analysis of potential impacts of space weather), among others.

> Additional references and background material for Step 1 are provided in Section 4.2 about systems thinking, as well as in 5.2 about early-warning systems and statistical early-warning signals , and Section 8 about systems thinking for innovation in the public sector (OECD, 2017).

[2] Namely temporal s-EWS (e.g., critical slowing down and flickering), spatial s-EWS (e.g., spatial clustering), and signals based on power spectra (e.g., increased volatility in low frequency domains)

Expected outcome of Step 1

- Characterisation of the environment regarding opportunities and risks, including an overview of the interconnections and networks between the organisation and external players.
- Definition of the position of the system in a dynamic and complex context including boundaries of the system in scope.
- Understanding of the direction in which the system in scope seems to be heading.
- Understanding of key external triggers of change, such as regulation, which can work both ways.
- Development of communication and collaboration strategies for external boundaries and triggers for change – particularly in situations where it is difficult for an organisation to independently acquire information to explore and frame their external environment.

At this stage, organisations can move to Step 2 to develop scenarios and then define their goal.

Important recommendations for action

- It is essential to define and understand one's system, and relevant sub-systems, and their dynamics. Characterising and analysing internal and external system boundaries are important for identifying the internal and external critical factors of functioning.
- Scanning for possible systemic risks, and transitions that may trigger systemic changes, is a task of the utmost importance for various ecological, social, and economic systems today. It is critical for system sustainability and survival.
- Given the multifaceted nature of systemic risks, these two tasks cannot be performed well without collaborating with others. Identifying opportunities for collaboration and communication to explore external boundaries, and a given organisation's general operating environment, can help them better understand their exposure to other systems as well as acquire and understand data to help determine the direction where their organisation is heading.

STEP 2 – DEVELOP SCENARIOS

KEY OBJECTIVE: EXPLORE POSSIBLE FUTURE EVOLUTIONS OF THE SYSTEM AND ORGANISATION-RELEVANT RISKS, CONSIDERING POSSIBLE ONGOING AND FUTURE TRANSITIONS

Step 2 involves deepening the understanding of key elements and critical functions of the system and sub-systems under consideration, and reviewing the dynamics of possible future interactions within the interconnected risk landscape. Then Step 2 unpacks how organisations can evolve and develop, considering the potential systemic risks that may impact them

Required actions	• Using information from Step 1 on systemic exploration, seek to deepen the understanding of interconnections and forces that can trigger a change or possibly disrupt a regime, from either the inside or the outside • Identify and monitor critical system functions within such scenarios • Modelling (e.g., using agent-based models) • Develop scenarios of future developments ('alternative futures') • Include low-probability scenarios as a means to understand the scope and intensity of risk events that could endanger the entire operation of the organisation and its environment
Expected outcomes	• Improved understanding of key system characteristics and dynamics (driving forces and dynamics, thresholds, tipping points, early-warning signs of impending shifts, triggers for disruptions and change, windows of opportunity for interventions, etc.) • Explorative scenarios of possible developments of the system, or the organisation, or the systemic risks that may affect them, with the clear framing of the systemic risks to the organisation • Communication of the resulting understanding of how the system develops; making sense of the system for key actors within the organisation
Key success factors	• Taking a 'systems thinking' approach • Sufficient investments in data, research and tools • Relevance, credibility and legitimacy; plausibility of the scenarios • Creativity (thinking outside of the box)

Step 2 aims to explore possible future evolutions of the system and organisation-relevant systemic risks, considering ongoing and potential transitions. This step particularly concerns the development and analysis of multiple scenarios, which are efforts to understand possible futures. This step involves:

- Deepening the understanding of key elements and critical functions of the system and sub-systems under consideration.
- Reviewing the dynamics of possible future interactions within the interconnected risk landscape. This requires making sense of the interconnections and forces that can trigger a change or possibly disrupt a regime, from either the inside or the outside.
- Developing scenarios of how systemic risks could impact the organisation and scenarios of future developments (alternative futures). It is wise to include low probability scenarios as a means to understand the scope and intensity of risk events that could endanger the entire operation of the organisation and its environment.
- Modelling (e.g., using agent-based models, see Section 5.3).

It is important to note that scenario development in Step 2 is not geared towards quantifying via probabilistic risk assessment how likely a given threat may develop. Rather, this Step is intended to allow stakeholders to review how their system performs across a variety of situational conditions – allowing for a greater understanding of how the system's interconnections and interdependencies might trigger a cascading effect and threaten the ability of the system to function as expected. One example of such activity includes financial stress tests, which consist of a variety of scenarios to review how large banks would respond to various financial threats given the banks' current operating procedures, access to capital, and other concerns. In this way, scenarios allow for a richer understanding of how a system operates, and may suggest options to reduce its potential for cascading risk and/or improve its response to disruption of key sub-systems.

Scenario development

Step 2 is where organisations invest in exploration and simulation exercises to assess how they may develop and grow over time. Given various developmental scenarios, organisations then consider how their system, within a certain developmental path, can be impacted by systemic risks within the landscape, and what that means for the achievement of their goals. In the context of systemic risks, scenarios are not necessarily quantitative but are rather narratives that 'play' with different trigger-consequence relationships within the risk landscape. Scenarios must thus be forward-looking ('foresight') but also look to horizontally interconnected systems ('broadsight'), to develop alternative futures (Tourki, Keisler & Linkov, 2013).

Various sources of information should be considered for scenario development. Big data, data analytics and artificial intelligence, as well as network science, can help to make sense of interconnections. These allow the user to acquire a sense of the plausibility of various scenarios by utilising an evidence base and connection of (future) scenarios to events that have happened in the past or present.

Likewise, qualitative exploratory scenarios of plausible futures (narratives, or storylines) can be equally useful in exploring various scenarios 'in play' in a complex interconnected system, as well as in identifying goals for how one would like a system to operate under shock or stress. They can be a key feature of effective preparedness for future development of systemic risks (Nauser, 2015), especially if they aim to propose a vision of a desirable state of the system, accompanied by a backcasting approach to reach the vision. The question that is asked during the development of such scenarios is, "How could the system evolve?" This can enhance the ability to expand one's imagination beyond the limits of experience, which can be described by the concept of "disciplined imagination," developed to explain the process of theory construction in organisational studies (Weick, 1989; Cornelissen, 2006).

Understanding key characteristics of complex systems is important for anticipating events that may require policy interventions and identification of where those interventions should or could occur for maximum efficiency (OECD, 2011). The use of scenario-based reviews of system operations can identify weak points in a system's critical functions (in other words, areas that could trigger a negative cascading feedback loop that could cripple system functionality) and/or identify strategies for a system to transition to a more favourable state before, during, and after a shock takes place.

Additional references and background material for Step 2 are provided in Section 5 (Foresight, 'broadsight' and early-warning systems), along with additional background information on systems thinking and complexity in Section 4.

Expected outcome of Step 2

- Explorative scenarios of possible developments of the system, the risks and the organisation; framing of the systemic risks to the organisation.
- Communication of the resulting understanding of how the system develops: making sense of the system for key actors within the organisation.

At the end of Step 2, policymakers and other relevant decision-makers should be able to identify various pathways by which their organisation may develop and change, as well as how such developments may alter their exposure to systemic risks. Such understanding affords opportunities for improvement of systems that are likely to experience degradation or collapse due to a variety of shocks or stresses, and prepare for transitions if necessary.

Important recommendations for action

- Scenario development is one essential step to make sense of systemic risks.
- Scenario-based exercises can help stakeholders to prepare for transition.

STEP 3 – DETERMINE GOALS AND LEVEL OF TOLERABILITY FOR RISK AND UNCERTAINTY

KEY OBJECTIVE: SET GOALS FOR THE ORGANISATION, CONSIDERING POSSIBLE SCENARIOS AND ONGOING OR ANTICIPATED TRANSITIONS

Step 3 serves to develop the organisation's vision or goal regarding risks and opportunities, considering its level of tolerability for risk and uncertainty (or risk appetite)

Required actions	• The list of system components (Step 1) and scenarios (Step 2) is reviewed by the Board, which will make decisions about its strategy
Expected outcomes	• A list of the organisation's short-, mid-, and long-term objectives
Key success factors	• Leadership • Holistic view • Engagement with important internal stakeholders

The objective of Step 3 is to determine the goals that an organisation will seek to achieve as determined by its Board. An inherent consideration of such goals includes the organisation's appetite for risk, which determines the level of exposure to potential harms that the organisation is willing to operate under. Risk appetite is determined by various characteristics – such as cultural, institutional, and socio-economic factors – and can shift over time due to experience or exposure to risk (or lack thereof).

The goal-setting process should account for various time periods into the future, including near-term, intermediate-term, and long-term objectives. Such a separation of goals by time period can inform the immediate actions that an organisation will take in its operations (i.e., near-term economic goals), as well as its aspirations for where it would like to be and how it would like to improve over time (i.e., achieving sustainability and accountability in its operations) (National Research Council, 2014). This process can help identify opportunities to make long-term goals a reality, while also defining how exposure to systemic risks can influence an organisation's capability to meet such goals.

One exercise that is helpful for goal creation is to explore various scenarios, developed in Step 2, that reflect likely conditions under which an organisation may be required to operate. Scenarios inform decision-making about the capacity for adaptation, risk appetite, estimated time for reaction in case of crisis, and availability of reduction, mitigation and adaptation. Scenario-based exercises can be reviewed methodologically via agent-based models or game theoretic approaches, and can elucidate how choices made by an organisation can bring it closer to or further away from achieving its desired goals.

Key success factors for Step 3 centre upon the institutional need for visionary leadership to explore and establish organisational goals, as well as a broad frame of mind to explore how such goals are impacted by various events.

Additional references and background material for Step 3 are provided in Section 5 (Foresight, 'broadsight' and early-warning systems) along with considerations about global environmental systemic risks in Section 6 and risk governance for climate adaptation in Section 7.

Expected outcome of Step 3

- A clear vision and goal for the organisation, including, if possible, how it aims to navigate transitions.
- An understanding of organisational objectives in the short, intermediate, and long-term.

At this stage, the organisation will be able to develop a management strategy that accounts for tolerability for risk and uncertainty.

Important recommendations for action

- Setting goals includes not only short- to mid-term business or economic goals, but also more normative goals such as improving sustainability, increasing accountability and responsibility, building competitive advantage, distributing wealth in a better way, or achieving more inclusive economic growth.

STEP 4 – CO-DEVELOP MANAGEMENT STRATEGIES

KEY OBJECTIVE: DEVELOP MANAGEMENT STRATEGIES TO DEAL WITH SYSTEMIC RISKS THAT AFFECT OR MAY AFFECT THE ORGANISATION

Step 4 serves to co-develop – with other actors in the system – strategies for addressing systemic risks in a proactive, effective, cost-efficient and adaptive manner. This often requires 'navigating transitions'

Required actions	• Engage and collaborate with other actors in the system to co-develop solutions with them • Set objectives for each intervention (keep status quo, adapt to incremental changes, or transform the organisation or the system)
Expected outcomes	• A list of management strategies to address the scenarios developed in Step 2, including anticipatory (proactive) and adaptive (reactive) mechanisms to improve a system's capacity to absorb and recover from shocks and stresses, and adapt to new context conditions or transform itself if needed • A selection of specific measures to build resilience to uncertain and unknown shocks and stresses
Key success factors	• Consistency with organisational values and culture • Flexibility for adaptation and adjustment in the face of new evidence • Creation of an institutional space for innovation and trial and error • Engagement with all internal and external stakeholders

Step 4 aims to develop management strategies to deal with systemic risks that affect or may affect the organisation. It involves:

- developing strategies for addressing systemic risks in a proactive, effective, cost-efficient, and adaptive manner.
- a willingness and capacity to flexibly 'navigate' transitions.

The creation and implementation of management strategies to adequately govern systemic risks requires considering exposure and vulnerability, engaging and collaborating with other actors to co-develop solutions with them, and setting goals for each intervention (keep status quo, go back to prior regime, adapt to incremental changes, or transform the organisation or the system). Where systemic risks are multifaceted, complex and have uncertain outcomes, strategies must address the need to:

(1) **Reduce system exposure and vulnerability to various shocks and stresses.**
Should such a shock or stress occur, a reduction in system exposure to the consequences of such a shock would make it less severely affected, and fewer resources would be needed to achieve full system recovery. Furthermore, promoting redundancy in a system's network structure, such as with the case of backup systems running in parallel, can mitigate damages caused by system outages. Further strategies here include optimisation of network complexity and the creation of firewalls or security breaks, which facilitate quick decomposition or de-compartmentalisation into disconnected or weakly connected subnetworks before a failure cascade has percolated through the whole system or large parts of it.

(2) **Collaborate with others at the periphery of the system.**
Whereas systemic risks are inherently driven by a web of complex interaction effects between various sectors, a disruption in one area (i.e., severe weather) can have percolation effects that disrupt others (i.e., public health or local markets, among many

others). Addressing such systemic risks may require collaboration between public and private actors to overcome common obstacles (see Box 4). In doing so, the focus should be on systems building and overcoming behavioural, institutional, and human obstacles to collaboration, rather than strictly problem-solving. The management of interconnected risks requires the development of new decision-making frameworks and institutional capacity, and new types of regulatory arrangements between the public and the private sectors (see Box 5 for more discussion and examples).
Multi-stakeholder partnerships will inherently require some elements of value-chain analysis to transparently assess the role of each participant in the creation and use of a product or service. This could serve to provide incentives to those actors who contribute to reducing systemic risks by adding diversity, modularity or other components of resilience, in such a way that the supply chain can be more adaptive and able to re-organise if needed.
For example, ongoing initiatives to encourage transitions to circular economies will require collaboration between actors (see Box 5). Multi-stakeholder management teams should consider the role of individuals/consumers in the marketplace in order to understand larger-scale consumption trends and information asymmetries with the general public. Understanding public opinion, and working with the public to generate shared knowledge, can serve as a crucial step towards developing sustainable management solutions (Palma-Oliveira, Trump, Wood & Linkov, 2018).

(3) **Prepare proactive measures to adapt or transform the system should a fundamental change occur.** Organisations with the ability to prepare for and anticipate potential future shocks are better able to position themselves to prevent or mitigate the damage caused by systemic risks. Proactive measures pre-emptively address exposure to systemic risks, or the consequences of systemic risks, and can be a more effective and cost-efficient format to institute organisational response to such risks well before tipping points are reached (see 'Main strategic approaches to governing systemic risks' below).

(4) **Consider planned adaptive governance,** an approach in which stakeholders decide together to design arrangements that will learn from experience and update over time. Such approaches foster an environment where operating procedures or organisational assumptions may be adjusted in the face of new or compelling information (see Box 6).

(5) **Prepare for when a window of opportunity opens**, which will make possible the actual decision and implementation of strategies to adapt or transform a system or an organisation (see Box 7).

Main strategic approaches to governing systemic risks

In line with mainstream recommendations for resilience building, and in acknowledgement of the governance needs noted above, IRGC proposes three main strategic approaches for dealing with systemic risks.

(1) **Supporting and strengthening the ability of a system to self-organise and self-control.** The first strategy is motivated by a preference to develop organic solutions to address systemic risks, provided certain conditions of social acceptance are met. Helbing (2010) recommends supporting and strengthening the self-organisation and self-control of a system, i.e., working with it rather than against it and using the immanent tendency of complex systems to self-organise and thereby create a stable, ordered state. This is an extension from biological systems that engage in 'self-healing' in order to overcome disruptions to biological processes. Self-healing is a critical component of system resilience, whereby such systems are able to better recover from and adapt to threats and disruptions from various sources. Critical considerations here include scale and time, whereby certain types of systems are more amenable to self-organisation and threat response than others, and certain critical functions within a system are more sensitive to threats and better able to adjust to them in a quick and efficient

manner. Self-healing is also discussed in the context of non-organic systems such as machine learning, where neural networks learn and adapt based upon environmental conditions to better structure information and provide more robust analysis of data. Self-organisation and self-control are derived from a system's capacity to respond to stimuli, and use lessons learned to adjust system operations accordingly. However, not all systems are capable of self-organisation, or of utilising principles of self-organisation in a manner that would allow them to optimally address threat and disruption without the serious risk of system losses and collapse. Furthermore, while this can help prevent brittleness and excessive complexity, it may be that a self-organised system resulting from a spontaneous change in the system is not what managers want to have, given their goals. In that case, more proactive strategies may be necessary.

(2) Pro-active intervention strategies: Prevention, mitigation, adaptation and transformation.

The second strategy promotes active intervention to prevent or change the system and/or its potential for cascading failure. This includes four different forms of proactive interventions: (a) a prevention-based approach, (b) using mitigation as far as possible, (c) an adaptation-based approach, and (d) a transformation-based approach. Each of these approaches must work within the political, economic, and institutional realities for the system within which they are implemented, and each has their own strengths and weaknesses that must be considered for the management of systemic risks.

- **Prevention** is concerned with averting or at least reducing the likelihood of regime shifts. This includes altering critical thresholds or increasing the system's capacity to absorb changes. Interventions include fostering long-term visions, proactive intervention on slow variables, exploring new development pathways, and diversifying options for societal response. An example is building flood defences to reduce vulnerability to sea level rise. However, such strategies can sometimes also make a system more vulnerable; for instance, when higher dykes give a feeling of security, which results in increased building activity in flood-prone areas, ultimately leading to higher losses in the case of dyke failure.
- **Mitigation** may be a worthwhile approach when the causality link between cause and impact are easy to identify and not affected by too much interaction with other risk systems. For example, some direct causes of climate change or loss of biodiversity can be addressed by mitigation strategies such as public regulation. While mitigation strategies should definitely be part of the portfolio of risk management tools, they are however rarely suitable to deal with the complex systemic risks that are the focal point of this document.
- **Adaptation** consists of measures for preserving societal and ecosystem functions in new regimes. It is the optimal strategic response if prevention is not possible or its costs are too high, or if pre- and post-tipping regimes are similar over relevant timescales. It can take the form of adaptation to gradual changes, to abrupt changes, and to second-order effects such as an increased frequency of extreme events. An example is adapting agricultural practices to changing climate conditions. It could be the organisation that adapts to new system conditions, or the system that is adapted to other systems with which it is connected.
- **Transformation** is based on the logic that there is a window of opportunity to catalyse a positive regime shift and let the system evolve on newly improved trajectories. It typically involves initiating changes at lower scales while maintaining the resilience of the system at higher scales as the transformation proceeds, until the feedbacks in the new stability domain are sufficiently established. An example is the energy transition in Germany or the transformation to a circular economy (CEPS, 2017). Successful transformations require technological and social innovation, and leadership and adaptive management (Geels, 2002). Innovations outside the dominant regime, such as new technologies, new social practices or new business models, can be catalysts for systemic change. Hallmarks of governance for transformation also include inclusiveness, adaptiveness and distributed deliberation (Klinke, 2017).

(3) **Prepare for disruptions, accidents and crises.**
The third strategy balances the objectives of the first two by actively preparing for future threat scenarios without necessarily proactively intervening within various interconnected systems. This strategy builds the capacity of various stakeholders to help their system address and overcome future shocks and stresses. It includes the creation of scenario-based plans for emergency and recovery. For example, the severity of extreme weather events can result from climate-related systemic risks and can trigger cascading systemic risks, such as in the case of Hurricane Katrina (New Orleans, 2005), Harvey (Texas, August 2017), and Irma (Florida, September 2017). The disaster that followed Hurricane Katrina prompted the design and implementation of effective strategies to prepare for disruptions of critical infrastructure services. Those strategies were developed and fully effective when Harvey and Irma hit the coasts.

These strategies can be combined or implemented successively if proximity to a regime shift seems to increase.

Additional references and background material for Step 4 are provided in Section 3 (Resilience) and Section 4.5 (Leverage points for intervention within a system).

Expected outcome of Step 4

- A list of management strategies to address the scenarios developed in Step 2 and the goals determined in Step 3.
- A selection of specific measures to build resilience to absorb and recover from shocks, but also adapt to fundamental change and transform the organisation and system if desired.
- The creation of an institutional space for innovation and trial and error.

At this stage, the organisation is ready to decide on a strategy, but must also prepare for unanticipated obstacles.

Important recommendations for action

- To develop management strategies for systemic risks, it is essential to understand where a system's windows of opportunity may arise and identify the leverage points to drive systemic transitions to a more desirable state, as well as to identify factors, drivers, and other indicators that unveil when such windows of opportunity and leverage points may be in play.
- To address systemic risks that evolve in the context of transitions, resilience must promote adaptation or transformation of the system.
- It is useful to test different strategies by using simulations and virtual experiments. If major problems occur in the simulations or if new systemic risks evolve, the strategies can be corrected before they manifest themselves in real life.
- It is necessary to consider the effects of regulations and rules, and to inform public decision-makers about needed reforms of the regulatory system, perhaps in contrast to actions to alter organisational culture and values.

Box 4: Common obstacles to collaboration in the development of management strategies – Groupthink and silos

A critical concern in information-sharing for strategy design is the potential for lock-ins such as silos and groupthink to neglect signals and formally acknowledge that a critical disruption is upcoming (which should trigger immediate action), or to diminish the potential for the transparent sharing of information. The tendency to 'silo,' or cause expertise to form in small and self-contained groups that do not communicate well with one another, is well documented in various scientific endeavours. The September 11 terrorist attacks are a prime example of this, where differing intelligence agencies each had pieces of information on terrorist operations that, if combined, may have been able to thwart some or all of the hijacking attempts. Likewise, groupthink reinforces a 'yes-man' tendency where members of a group assume that some collective idea is the correct one, and little is done to question the veracity of that given course of action in favour of a differing approach. Overcoming groupthink requires a participatory approach to decision-making in a way that accounts for a broad diversity of opinions, experiences, and perspectives.

Box 5: Examples of public-private / supply-chain collaboration for systemic risk management and resilience

Dealing with systemic risks requires boosting collaboration among actors. The governance of inter-connected risks requires the development of new decision-making frameworks and institutional capacity, and new types of regulatory arrangements between the public and the private sectors. Incentives could be provided to those actors who contribute to reducing systemic risks by adding diversity, modularity or other components of resilience, in such a way that those value chains can be more adaptive and able to re-organise if needed. Such approaches can include adapted measures from previous communication and reporting infrastructure, or new collaborative arrangements altogether.

For an example of **adapting existing measures**, the US Center for Disease Control (CDC) in Atlanta, is required to coordinate with dozens of partners to better prepare for potential future pandemics. Epidemiologic testing and protocol is well established and precautionary in nature, yet is required to adapt to novelties or complexities posed to a given disease. Due to the global nature of such epidemiologic work, the CDC is required to work with multiple partners in the public and private sectors in a manner that coordinates a normalised process of acquiring, analysing, and reporting disease information in a timely manner.

For an example of **new collaborative arrangements**, ozone depletion due to the use of chlorofluorocarbons (CFCs) required an international arrangement to reduce the commercial use of CFCs. This international agreement via the Montreal Protocol of 1987 fostered a phase-out plan for the use of CFCs in various contexts (inclusive of input from industry developers) and suggested regulatory mechanisms that could be adopted by individual governments. This case serves as an example of how public-private collaboration can address systemic risks before harmful system transitions can occur through the use of early-warning signals.

As an example of **on-going transformations**, consider the case of the transition to a circular economy as a strategy to mitigate systemic risks related to over-consumption of certain natural resource. Alliances (or other forms of high-level collaboration across the value chain) must be formed to engage in fundamental business transformation. This is necessary to overcome the barriers to circular economy and causes of systemic risks such as:

- Under-pricing of commodities, since this generates overconsumption of materials and natural resources
- Lack of deliberate planning for circular economies in product design and development
- Complicated logistics management, due to little collaboration among producers, suppliers and consumers
- Absence of robust markets for used or recycled products.

In general, success factors for effective collaboration include (Bresch, Berghuijs & Kupers, 2014):

- Alignment of interests, or shared goals. Each actor must understand their and others' roles, expectations and constraints in the value chain
- Understanding and alignment of incentive systems
- Sharing of risks and opportunities, sharing of resources and infrastructure
- Using crises as triggers for change.

Box 6: Planned Adaptive Governance

Regardless of the chosen strategy, planned adaptive approaches generated through multi-stakeholder collaboration are likely essential to govern systems against systemic threats. Planned adaptive governance, and its application to regulation in 'planned adaptive regulation,' is an approach in which stakeholders decide together to design arrangements that will learn from experience and update over time. In complex systems and in the face of systemic risks, the evidence is uncertain or changing. The knowledge used to underpin a rule or a governing arrangement, whether public or private, binding or non-binding, will change over time. Overall, efforts to institute planned adaptive governance require stakeholders to use 'windows of opportunity' within which they can prepare their system to avoid disruption, or even transition their system to a more desirable state that is less exposed to systemic risks in the future.

Planned adaptive governance is difficult to implement because it creates additional uncertainty for stakeholders, especially those that need to make long-term decisions, such as regulated industries that make long-term investments, or legislators that cannot frequently revise the laws that structure technical regulations. It is still rare to see a purposeful combination of:

- Planning for future review and revision of governance arrangements
- Monitoring of performance and impact of existing arrangements
- Funding of targeted research organised in a way that is credibly overseen for quality and relevance and that explicitly feeds into the reassessment of the evidence base.

However, planned adaptive governance is a policy tool that is too infrequently considered. It is appropriate for risk issues whose comprehensive assessment is evolving because of changes in the technologies or in context conditions. It is already applied in the environmental and medicine sector, which are both prone to systemic risks. It has been used for the regulation of criteria pollutants in the atmosphere (in the US National Ambient Air Quality Standards and the European Air Quality Standards), in the US Lautenberg Chemical Safety Act of June 2016, in flood management in the Netherlands, and in adaptive licensing of new drugs by the European Medicines Agency.

Box 7: Windows of opportunity to intervene in a system in transition

When risks in complex systems build up slowly, they are often foreseeable, but nonetheless rarely avoidable. IRGC has described such risks as slow-developing catastrophic risks (IRGC, 2013) and argues that their slow-developing feature implicates the existence of windows of opportunity for intervention measures.

Windows of opportunity represent key moments or developments when signals of an impending regime shift become visible, and it will be possible to move from preparing the transformation of a system and navigating the transformation towards an improved organisational configuration. Acknowledging that a regime shift is inherently difficult to undertake and that many systems are structured to favour the status quo, windows of opportunity are often triggered by actions or events that ease the potential for a system to change its organisation or behaviour in various ways. In a normatively positive sense, transformations occur when a window of opportunity is used to initiate a change within a system or organisation that propels it onto an improved trajectory.

Windows of opportunity for transformation typically involve initiating changes at lower scales, possibly through niche innovations (Raven, Van den Bosch & Weterings, 2010), while maintaining the resilience of the system at higher scales as the transformation proceeds until the feedbacks in the new stability domain are sufficiently established (see also Section 6.2).

The time window or management timeline for effective outcomes also determines how much advance warning is needed and whether it is possible to rely on them. The time window depends on at least three factors: regime shift drivers, managerial inertia, and system inertia and variability (Contamin & Ellison, 2009; Nursimulu, 2015a).

1. Regime-shift drivers

- The type of driver matters: Averting regime shifts driven by slow drivers requires much earlier detection and intervention than those driven by fast drivers.
- Fishery collapse, for example, can happen because of fast drivers, like over-fishing, or slow drivers, like shoreline development. Timely policy decisions to reduce harvesting can have a rapid impact and can avert potential regime shift in less than a decade, but policy decisions to restore shorelines need about four decades to be effective in avoiding a regime shift.

2. Managerial inertia

- Managerial inertia in the system refers to the speed at which intervention can be initiated.
- Delayed intervention can arise due to factors such as lack of political will, difficulty to get buy-in from relevant actors or sectors, scientific uncertainty, or a lack of 'solutions.'

3. System inertia variability

- The intrinsic variability of complex adaptive systems influences the power of regime shift indicators, i.e., the extent to which the indicator can detect an impending regime shift with reasonable certainty and with sufficient lead time for effective intervention.
- System variability also blurs the predictability of system behaviour and the impact of interventions.
- For effective intervention, it is critical to identify key management entry points, i.e., drivers and feedbacks that can leverage change in the system, based on its specific interaction patterns.

STEP 5 – ADDRESS UNANTICIPATED BARRIERS AND SUDDEN CRITICAL SHIFTS

KEY OBJECTIVE: IDENTIFY AND PRO-ACTIVELY ADDRESS UNANTICIPATED OBSTACLES, WHICH MAY COME UP DURING THE SYSTEMIC RISK GOVERNANCE PROCESS AND WHICH MAY REQUIRE SPECIFIC INTERVENTIONS

Uncertain and cascading consequences often imply that not everything has been identified and addressed beforehand. Step 5 addresses any unanticipated barriers to achieving the goals of an organisation and the effective management of systemic risks. Unexpected and sudden shocks may also prevent the effective deployment of transition strategies, especially when they involve critical disruptions that may trigger regime shifts or crises, and require urgent intervention. Step 5 is, therefore, a possible entry point in the process towards the governance of systemic risks

Required actions	• Watch out for barriers and lock-ins that may purposely ignore or hide information asymmetries, regulatory capture, or improper or biased incentives that earlier steps in the process may have overlooked • Remove barriers and lock-ins, develop counter-measures • Engage all relevant stakeholders in the resolution of unanticipated problems
Expected outcomes	• Unanticipated obstacles do not cause major disturbances to achieve the long-term goal
Key success factors	• Engaging/involving stakeholders in management actions to create legitimacy to act in whatever circumstances • Incentivise key actors • Develop organisational capabilities to ensure that management measures can be successfully implemented, even under severe constraints • Transparency, agility, openness to innovation

The aim of Step 5 is to identify and pro-actively address unanticipated obstacles to strategies for the effective governance of systemic risks, which may come up during the process and may require specific interventions. Uncertainty and systemic cascading consequences often imply that not everything has been identified and addressed beforehand. For example, a long-term strategy for transformation may have been decided in Step 4, but an external shock disrupts its implementation. This can signal a need to adjust to new contextual facts and phenomena that were not previously accounted for, and to take steps to address, overcome, or even avoid disruption on route to strategy implementation. Step 5 thus addresses two concrete needs:

- Overcome any *unanticipated barriers* to achieving the goals of an organisation and the effective management of systemic risks
- Prepare for *unexpected and sudden shocks*, which may also prevent the effective deployment of transition strategies, especially when they involve *critical disruptions* that may trigger regime shifts or crises and require urgent intervention.

Agility, early-warning, sense-making and the development of robust crisis management frameworks are key to help those in charge of crisis decision-making deal with the complexity, uncertainty and ambiguity that caracterise catastrophic events nowadays (OECD, 2015).

Required actions involve constantly watching out for typical barriers and lock-ins that may purposely ignore or hide information asymmetries, regulatory capture, improper or biased incentives that earlier steps in the process may have overlooked; removing constraints, developing counter-measures; actively engaging all relevant stakeholders in the resolution of unanticipated problems; and flexibility and agility.

Unanticipated barriers to implementing the strategy co-developed in Step 4

Step 5's primary objective is to identify and proactively address unanticipated obstacles (i.e., 'barriers and constraints') that may arise within strategies for an organisation to govern systemic risks – whereby such obstacles can negatively influence the implementation and adaptation of such strategies in Steps 6 and 7. These barriers and constraints might include, among others, the decision-making structure of an organisation, its social culture, or limited availability of relevant information to make informed decisions. One such recurring barrier includes neglected information asymmetry. Stakeholders from differing areas (government, industry, academia, NGOs), countries, and disciplinary sectors each may possess different bodies of information as well as differing opinions and beliefs regarding how a system should optimally function under stress. Sharing such information across stakeholders in a transparent manner is key to building a shared understanding of the systemic risks facing the various systems in question.

In this step, we consider '*remaining*' barriers, especially those that are outside of the control of the organisation, and that may come in the way of constraints to the effective development of the management strategy. This also includes being aware that strategies of other organisations, or simply change, may bring new constraints, especially if strategies deployed in other connected systems are not taken into account. Ultimately, such preparation will help ensure that various barriers do not generate major disturbances to an organisation's governance strategy for systemic risks.

An entry point in the process towards the governance of systemic risks

Additionally, Step 5 also serves as an entry point in the process where, should an organisation be faced with a sudden or immediate shock, the process manager may decide or have to skip Steps 1–4, and enter with Step 5. This is due to the general immediacy of the problem facing the organisation, where there is no time to conduct exploration and scenario development under Steps 1–3, and urgency dictates the need for the organisation to deal with sudden shifts in their system's capacity, operations, or contextual information. Information from this sudden shock inherently requires decision-makers to rethink their strategy to accommodate new contextual realities, and adjust their organisation's operations in a manner that accounts for new information that may possibly be in conflict with previously held ideas or operational motivations.

Expected outcome of Step 5

- Unexpected obstacles to implement a relevant strategy are or can be overcome.

At this stage, the organisation should be ready to implement a strategy to address systemic risks that affect or may affect it, and navigate transition successfully.

Important recommendations for action

- Barriers and obstacles are recurring threats within a comprehensive risk governance and implementation process, and should be actively sought out ahead of time through monitoring of signals or drivers.
- Governing systemic risks requires deliberative exercises to identify and overcome such barriers and obstacles before they strengthen.
- Even with the most sophisticated analysis of future developments, surprises may happen.
- Increased proximity to a regime shift, when it becomes visible, must trigger a rapid revision of an established strategy to face disruptions, catastrophes or crises. In urgent situations where the sudden materialisation of a systemic risk is imminent or ongoing, organisations may use Step 5 as an entry point into the governance process, and temporarily bypass Steps 1-3.

STEP 6 – DECIDE, TEST AND IMPLEMENT STRATEGIES

KEY OBJECTIVE: IMPLEMENT AN APPROPRIATE STRATEGIC RESPONSE

Step 6 deals with deciding, testing and implementing the most appropriate strategy to manage systemic risks to an organisation

Required actions	• In view of the obstacles and capabilities, evaluate and compare the options developed in Steps 4 and 5 and decide which ones to implement • Test and experiment, if possible • If an unexpected event is occurring, revise the strategy and adopt a crisis preparedness and management approach • Allocate resources to match operational capabilities with strategy • Clearly define roles, responsibilities and incentives according to the strategic options adopted • Support strategy implementation by ensuring adequate authority and leadership and enabling the creation of appropriate risk cultures
Expected outcomes	• Final decision as to which management option will be implemented • Translation of the strategic objectives into individual and collective objectives at the various levels of the organisation • Implementation of the decisions made
Key success factors	• Clear and transparent criteria for taking decisions • Appropriate evidence and / or scenarios • Inclusion of all relevant stakeholders • Accountability / clarity about roles and responsibilities

Steps 6 aims to implement the most appropriate strategy to manage systemic risks to an organisation. It includes decision-making, testing and experimentation (if possible and necessary), and implementation.

The options developed in Step 4 will be evaluated and compared, considering obstacles and capabilities. Then one or several options will be decided and implemented. If an unexpected event occurs the strategy may have to be revised and crisis preparedness and management may have to be implemented (OECD, 2015). Appropriate resource allocation will be needed to match operational capabilities with strategy, as well as clear definition of roles, responsibilities and incentives. Finally, adequate authority and leadership will support strategy implementation and enable the creation of an appropriate risk culture.

Decision

The governance of systemic risks is challenged by the complexity, uncertainty, and potential ambiguity of the knowledge about systemic risks (Lowell, 2016). In situations of uncertainty, lack of knowledge, or distributed responsibilities, the challenge is to both collect sufficient evidence to base decisions on that scientific evidence, and to frame the conditions of shared and comprehensive distribution of knowledge (Merad, Dechy & Marcel, 2014). Where previous Steps were designed to explore a system's internal and external boundaries, identify signals of potential threats, and craft strategies to address those threats, Step 6 requires an organisation to decide upon, test, and implement the most appropriate identified strategy to manage the organisation's systemic risks.

Decisions about systemic risks require the ability of the decision or policy to perform well in the context of various identified possible futures. It is one of the qualities decision-makers look for when choosing among different options. Therefore, decision-makers will aim for robust decisions that can remain good enough under a range of possible outcomes. Robust decisions are those that either maintain enough flexibility for adaptation in the future or offer good performances for more than one of the future scenarios.

Due to lingering uncertainty and ambiguity regarding an organisation's exposure to systemic risks, there may be different interpretations of the same knowledge, which may create conflicting views about the best decision. In this case, decision-makers will engage in dialogue and social learning with the public (where appropriate), to share the decision with others. A critical objective of such interactions is to articulate underlying assumptions for all policy options/decisions, and ultimately generate shared knowledge that is understood by all stakeholders to prevent confusion or disharmony in management. In any case, decision-making about systemic risks is always challenging for policymakers as well as senior management in private companies.

Experimentation

Experimentation is likely a key component for the success of broader management strategies for systemic risks. Given the high degree of uncertainty and complexity facing interconnected systems in a spatially dispersed environment, testing potential management strategies on a smaller scale and within a more controlled environment can offer valuable experience and insight regarding how such a strategy might perform on a larger scale. It is helpful to note that many political frameworks inherently allow for smaller-scale testing of policy options, such as with state-based regulatory experimentation in the United States. For example, various states such as Massachusetts and Tennessee experimented with state-based health care exchanges in the years prior to the passage of the Affordable Care Act (which had some lessons learned from these cases built into the law) (Ten Napel, Cohn & Martinez-Vidal, 2009). If errors in implementation are extremely costly or irreversible, it may be prudent to develop simulation or virtual spaces to test the decisions.

Implementation

Effective implementation of strategies for prevention, adaptation or transformation will require creating supportive conditions for the organisational, technical and cultural shifts that are necessary to lead and support the transition (Nursimulu, 2015a). Resilience is often regarded as the optimum strategy for dealing with systemic risks due to its inherent systems-focus on generating improved system recovery in the aftermath of a disruptive shock, although other tools and frameworks abound. Ultimately, successful implementation requires organisations to clearly define roles, responsibilities, and incentives for action by various players within their organisation. This ensures adequate leadership and authority that is relevant to a given organisational culture.

Expected outcome of Step 6

- Final decision as to which management option will be implemented.
- Translation of the strategic objectives into individual and collective objectives at the various levels of the organisation.
- Implementation of the decisions made.

At this stage, a strategy and specific interventions are implemented. The final step will be to monitor performance and review decisions if needed.

Important recommendations for action

- Strategy selection requires deliberative thought, testing, and experimentation to help further its success.
- Particularly, experimentation allows one to 'bound' uncertainty in a manner where it is possible to understand the range of outcomes that a certain management strategy may have. Experiments should be designed in controlled circumstances, yet mimic natural activity and behaviour as much as possible. This can be through modelling exercises or live experimentation in small organisations.
- Robust strategies must be chosen since it enables organisations to navigate a range of possible futures, ensuring adherence to the chosen strategy (prevention, adaptation or transformation).
- Successful strategy implementation requires clearly defined roles, responsibilities and incentives, as well as a shared understanding of goals.

STEP 7 – MONITOR, LEARN FROM STRATEGY IMPLEMENTATION, REVIEW AND ADAPT

KEY OBJECTIVE: REVIEW AND, IF NEEDED, ADAPT THE STRATEGY TO CHANGING RISK PATTERNS OR CIRCUMSTANCES

Step 7 involves monitoring how the system evolves and the risks unfold, reviewing the relevance and performance of the decisions taken and, if needed, adapting the strategy and modifying the course of action

Required actions	• Ex-ante decision to review • Deploy monitoring capabilities • Establish periodic reviews of strategic decisions, which integrate feedback from monitoring and new knowledge • Adapt where necessary
Expected outcomes	• Increased capacity to anticipate and execute adaptation to a more favourable organisational state • By implementing a closed loop between monitoring, learning and decision-making, the final outcome is an increased overall resilience of the organisation, with the ability to adapt and transform in a dynamic environment
Key success factors	• Involvement of all internal stakeholders • Open and transparent discussions • Regular updates of strategic decisions based on new information • Flexibility for adaptation and adjustment in the face of new evidence

Step 7 aims to review and, if needed, adapt the strategy to changing risk patterns or circumstances. It involves:

- **regular monitoring** of how the system evolves and how the risks unfold
- **reviewing** the relevance and performance of the decisions taken
- if needed, **adapting** the strategy and modifying the course of action.

Step 7 builds from previous organisational efforts in Step 4 to co-develop management strategies to address systemic risks to a given organisation, and applies this information to, if necessary, adapt the organisation to changing risk circumstances. The process should follow best practice recommendations for planned adaptive governance (see Box 6), i.e., it should be based on a closed loop between monitoring, learning and decision-making, including by taking ex-ante decision to revise the strategy if needed, deploying capabilities to monitor how the system develops and continue research to improve knowledge, integrating feedback from monitoring and new knowledge into the periodic reviews of strategic decisions, and adapting where necessary.

Even accounting for the unique contextual characteristics of a given organisation, adaptability is needed to iteratively address various threats to interconnected systems *as well as* the capacity for a disruption to one system to trigger outages in others. This allows organisations to determine what is working well, and what might need to be improved based on various performance metrics. Such an evaluation can then indicate areas within an organisation that should be improved to overcome limitations and improve operations. For example, adaptive governance may be driven by a legislative decision to monitor risks and review existing regulatory frameworks in the light of evolving landscape and risks. In that case, any regulatory instruments (hard law) must include clauses for regular revisions of risk assessment and management. Alternatively, adaptive governance may also be driven by voluntary arrangements among major affected stakeholders, and include instruments such as codes of conduct (soft law) that may be modified as needed to meet emerging challenges posed by systemic risks.

Step 7 inherently includes the idea of learning from what has been implemented (even if it fails) and acquiring new knowledge. Adaptation is an iterative process that organisations operating in CAS should commit to, partly to avoid the creation of new lock-ins. As such, planned adaptive governance requires mechanistic approaches that allow multi-stakeholder groups to on-board lessons learned at various stages of the creation, implementation, and revision of their management strategies for systemic risks – thereby incorporating more robust data sources and experimental knowledge of system behaviours over time. This allows for continual improvement towards gradual and constructive transitions rather than sudden, unexpected, unwanted, or otherwise harmful disruptions.

Expected outcome of Step 7

- Increased capacity to anticipate and execute adaptation to a more favourable organisational state. From such improved adaptive capacity, increased overall resilience of the organisation.

Important recommendations for action

- Regular monitoring and evaluation must take place to determine (a) what is working well, (b) what is working sub-optimally, and (c) what data or lessons have been acquired to better frame and structure the system or management strategy.
- Mechanistically, planned adaptive governance allows various decision-makers to integrate new information over time, and gradually improve their management strategy.

2.3 The role of the process manager or 'navigator'

Developing and deploying a systematic process for the governance of systemic risks that supports strategic decision-making requires that a dedicated person in the organisation coordinates various kinds of technical expertise, challenges existing organisational routines, and facilitates the balancing of possible conflicting individual stakeholder objectives within and external to the organisation.

The core tasks of the process manager are the following:

- Facilitating interaction among participants for collaboration, networking, learning and experimentation
- Bringing new knowledge to the organisation, and familiarising with multi-disciplinary work
- Validating and legitimising the technical methods and approaches used during the process, in view of pursuing the organisation's objective
- Ensuring that scientific concepts are translated into understandable concepts for effective risk management and policy
- Working to break silos of whatever form (disciplines, sectors, stakeholder groups).
- Monitoring performances to demonstrate their relevance for the organisation (the internal process will be scrutinised for its capacity to provide effective and relevant outputs and benefits for the organisation)
- Organising capacity-building of all staff and promoting behaviours and attitudes adapted to the challenges of systemic risks
- Communicating internally and externally and engaging with system-relevant stakeholders outside the organisation, and working to create a common language about systemic risks
- Reporting and reviewing.

If the organisation deliberately engages in a transition, a 'navigator' may be needed to facilitate the transition process, and be responsible for the implementation of the management strategy. The main difference between management and navigation is that the former applies defined processes, guidelines or strategies in practice, while the latter helps develop new capacities within the organisation. In that case, important functions to process navigation include:

- Providing clarity about roles and responsibilities in relation to risk
- Organising the ownership of systemic risks in the organisation, which defines responsibility, accountability and reward
- Communicating about leadership
- Working to develop trust in the people in charge
- Leveraging expertise in calling relevant external expertise, and ensuring that its contribution is usable by the organisation
- Overall enhancing collaboration.

> Navigation in unknown waters
>
> *"The science and art of navigation is holistic. The navigator must process an endless flow of data, intuitions and insights derived from observation and the dynamic rhythms and interactions of wind, waves, clouds, stars, sun, moon, the flight of birds, a bed of kelp, the glow of phosphorescence on a shallow reef – in short, the constantly changing world of weather and the sea."*
>
> *Wade Davis 2009*

Process management and navigation can come in all shapes and formats. Inherently, the responsibility is to build shared knowledge and consensus across a wide body of stakeholders (government, industry, academia, NGOs, the general public) in a process that is both thorough and deliberative. It is important to note that depending on the organisation, the process manager and process navigator may be the same person or different people. For large organisations, it may be necessary to separate the roles to ensure that the needs of both process management and transition navigation are met. For small organisations with limited resources, one person in both roles may suffice.

While each transition process must respect political, social, and institutional contexts, the success depends upon the capacity of the navigator to build a creative coalition that actively engages in the process by defining the boundaries and dynamics of the system, fostering opportunities for multi-actor scenario development, identifying groupthink and lock-ins that may act as obstacles, enabling experimentation if possible, generating ideas for specific management actions, and reforming the organisation or the system in a manner that is constructive for the various stakeholders involved.

Despite the benefits of appointing process navigators or managers, certain considerations must temper expectations of the capacity to reform or improve a system against systemic threats. Notably, such individuals do not have leadership to decide how to balance their organisation's short- and long-term goals, as well as various behavioural and organisational tendencies that may lead an organisation to underinvest in preparing to deal with future systemic threats (or, more cynically, assume that such problems will occur only after current organisational leaders have already left their roles). These tasks remain with 'captains' or leaders.

Box 8: Use of a process manager and process navigator in political campaigns and public office in the United States

Political campaigns for national office are complex affairs with substantial implications in policy domains such as defence, finance, public health, infrastructure, and many others. In the United States, newly elected politicians often rely upon transition teams, serving as process navigators, to help build up the capacity for the politician's team to address all relevant policy arenas. This navigation occurs well before the politician even takes office. Once in office, politicians and their policy teams are guided by process managers to ensure continued capacity to address a shifting universe of policy objectives, as well as frequent changes in staffing over the tenure of the politician.

Both *navigation and management* are different yet equally critical roles that influence the success of a politician to develop and implement a given policy agenda. Especially at the US Presidential level, transition teams ensure that national priorities are met despite a transition in power from one administration to the next.

2.4 Concluding remarks

Systemic failures and extreme events are consequences of our highly interconnected systems. Collapses, regime shifts or other 'catastrophes' of various sizes are part of complex adaptive systems. They can sometimes be foreseen, but avoidance is difficult unless the entire system is steered into a transition to another regime. Organisations need to develop a better, more holistic understanding of the systems in which they operate, to adequately deal with the corresponding risks.

Approaches for dealing with conventional risks are not sufficient for dealing with systemic risks because they are often too reductionist and limited in scope to account for complex system interactions and challenges. As such, managing systemic risks requires a more comprehensive approach to hazard and impact identification, risk assessment and risk management (Renn, 2016, 2017b). The options for managing complex systems in a targeted manner (e.g., with mitigation) are limited, and interventions can have unexpected and uncontrollable consequences (Nauser, 2015), which may appear stochastic and chaotic.

Instead, organisations should seek to cooperate with others to identify options that can be effective in reducing systemic risks. The objective of such work is to prepare one's system for a wide universe of threats in order to increase the capability of the system to recover from shocks, adapt or transform. Where identified as harmful or unnecessarily disruptive, cascade failures should ideally be stopped right at the beginning when the damage is still small, and the problem may not even be perceived as threatening (Helbing, 2013). This requires (1) appropriate monitoring measures to detect failures immediately, and (2) sufficient understanding of the system and its interconnections to know what to do to stop the cascade. As both prerequisites are difficult to achieve in practice, several authors recommend precautionary measures such as modularity or functional diversity to reduce network vulnerability to cascade spreading effects.

It is essential that policymakers, regulators and institutions become more familiar with the concept and better at identifying the build-up of systemic risks, which includes developing early-warning indicators that provide sufficient advanced warning to take cost-effective actions. However, even the best early-warning system will never be able to identify all pending catastrophic events in advance, and public and private leaders are faced with the challenge of preparing their respective organisations to be able to respond to unexpected events.

Developing resilient social and economic structures that are able to respond and rapidly adapt to sudden change is the best and often only way to cope with risks in complex systems. More efforts should be directed towards understanding how such structures work (Helbing, 2015). Adaptive governance strategies to deal with the consequences of tipping points and risk of undesirable regime shifts in a given system can be sustained by resilience-building strategies. However, building resilience does not come free, and there are trade-offs and conflicts of interest to consider.

While rigorous scientific investigations and sound academic debate are necessary prerequisites for improving our understanding of risks in complex systems, they alone are not sufficient. Findings must be translated into actionable recommendations for decision makers and managers in order to make a difference in practical terms.

These guidelines intend to provide a basis to help organisations get a first grip on the challenges and threats posed by systemic risks in the context of transitions. The recommendations given here need to be broken down and translated to the individual context of each organisation. What works for one might not work for the other, and broad and impartial exploration is required to come up with a promising strategy for addressing systemic risks.

CONCEPTS UNDERLYING THE DEVELOPMENT OF THE GUIDELINES

The IRGC guidelines for the governance of systemic risks describe key steps and associated methodologies for the exploration of complex adaptive systems and the identification and management of systemic risks. The guidelines suggest a flexible and adaptable process designed to address the need to govern systemic risks in the context of transitions requiring adaptation or transformation. They are interdisciplinary in nature and result from the contributions of many scholars and practitioners with theoretical or applied experience with systemic risks and their governance.

While the main underlying concepts remain those developed in the IRGC risk governance framework described in IRGC white paper number 1 (IRGC, 2005, 2017), and complemented by further IRGC work on emerging risks (IRGC, 2015, 2011, 2013), additional insights from specific disciplines are needed to address the specific aspects of:

- Resilience for recovering from shocks while transitioning to a new state that is better adapted when context conditions and even the system itself has changed (Section 3)
- Complexity theory, systems thinking and network science applied to resilience (Section 4)
- Foresight to look to the future, but also ‘broadsight’ to look at current trends at the border or outside of the main system in which an organisation operates, and also detection of early-warning signs of impending regime shifts that may trigger a system’s collapse or a significant regime shift (Section 5).

Alltogether these sections thus provide underlying rationale for Section 2, in the form of supporting evidence from specific disciplines and further guidance on specific tools.

3. RESILIENCE

3.1 A background on resilience

This section was developed with contributions from Igor Linkov, US Army Corps of Engineers.

Resilience is a growing field of interest relating to the effect that shocks and stresses have upon increasingly interconnected systems, such as with energy grids, cloud-based information systems, coastal ecosystems and infrastructure, and public health activities. The US National Academy of Sciences (NAS) defines disaster resilience (Figure 5) as "the ability to plan and prepare for, absorb, recover from, and adapt to adverse events" (NAS, 2012). The reference to recovery and adaptation in the NAS definition highlights a societal need to address highly uncertain and consequential risk events that are not easily addressed through traditional approaches of risk management (Trump et al., 2017). The Organization for Economic Development (OECD) uses a slightly different definition of resilience, which they define as "the ability of individuals, communities and states and their institutions to absorb and recover from shocks, whilst positively adapting and transforming their structures and means for living in the face of long-term changes and uncertainty," thus emphasising the possible need for engaging with transitions (OECD, 2014c). The German Academy of Sciences has adopted a definition where resilience refers to the capability of a system to maintain or quickly restore its functionality if faced with severe stress or disturbances (German Academies, 2016).

Decision-makers and policymakers have utilised the concept of resilience to evaluate the capability of various complex systems to maintain safety, security and flexibility, and recover from a range of potential adverse events. Further, resilience offers the capability to better review how systems may continually adjust to changing information, relationships, goals, threats, and other factors to adapt in the face of change – particularly those changes that could yield negative outcomes. Preparation for reducing the negative consequences of such events when they occur is thought to include enhancing the resilience of systems in desirable states, and include considerations of risk assessment as well as necessary resilience actions before, during, and after a hazardous event takes place. As such, resilience efforts inherently consider the passage of time and shifting capabilities and risks that may accrue due to changes in system performance and their capacity to absorb shocks (Hollnagel, Woods & Leveson, 2006). Resilience strategies have the potential to radically change how a nation prepares itself for the potential disruptions of key services such as its energy, water, transportation, healthcare, communication and financial services. When nations prepare for recovery from external shocks of a significant magnitude, resilience strategies must be considered (Linkov et al., 2014).

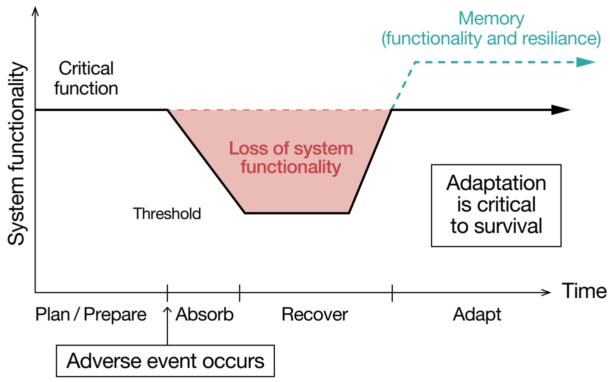

Figure 5: Illustrative representation of stages of resilience (adapted from "Committee on science, engineering and public policy", National Academy of Sciences (NAS), 2012).

This task is complicated by the limited amount of guidance regarding how resilience might be operationalised and formally reviewed. Such strategies are beginning to emerge in scholarly literature, including one example posited by Connelly et al. (2017). In that conceptualisation, features of resilience include (i) critical functions (services), (ii) thresholds, (iii) recovery through cross-scale (both space and time) interactions, (iv) memory and (v) adaptive management (Folke et al., 2010; Holling, 1986). The concept of *critical functionality* is important for prioritising protection or restoration of the front-line system in response to some shock or disturbance. *Thresholds* play a role in whether a system can absorb a shock or whether that shock will lead to cascading failure. *Recovery time* is essential for measuring system resilience after a disturbance where the threshold for system failure is not exceeded (Linkov, Trump & Keisler, 2018). Finally, the concept of *memory* describes the degree of self-organisation in the system, and *adaptive management* provides an approach for managing and learning about a system's resilience opportunities and limits in a safe-to-fail manner.

Traditional risk analysis and resilience analysis differ, yet overall they must be considered complementary approaches to dealing with risk. One way to assess how they are complementary and articulated is to consider risk assessment as a bottom-up approach starting from data, and resilience as a top-down approach starting with mission and decision-maker objectives, with the obvious need for integration (Linkov et al., 2014). The risk assessment process starts with a description of the context and the environment with data collection, and progresses through modelling and subsequent characterisation and visualisation of risks for management. Likewise, resilience begins by assessing values of stakeholders and critical functions. For this exercise, the use of decision aids can incorporate stakeholders' and decision-makers' preferences and other pertinent information to generate valid and legitimate metrics, models and conclusions that ultimately inform risk assessments and the different actors and stakeholders (Merad, Dechy & Marcel, 2014).

Resilience analysis may be based on risk assessment or include components of risk assessment such as exposure and dose-response relationships. But it always goes beyond risk assessment. Systems approaches for resilience include a greater degree of complexity of conceptualisation, as well as a disconnect from individual system components. Moreover, less severe and better-characterised hazards are more easily addressed by existing conventional methods (IRGC, 2005).

3.2 Lenses of resilience: a corporate perspective

While resilience is described in the literature as a concept and the property of a system with certain dynamic attributes, the formal operationalisation, assessment, and measurement of resilience is always difficult to determine before a sudden shock occurs. It is the behaviour of the system that demonstrates, after the shock, if the system was resilient. Bresch et al. (2014) have attempted to recognise from experience in a variety of companies which common factors enable the design of resilience solutions in the corporate sector. They begin by acknowledging that, since many kinds of stresses and disruptions may negatively affect companies, a systemic approach is needed to strive for resilience.

The company is a system, and resilient companies need to widen their horizon to embrace factors that they do not control (Kupers, 2014). Companies that build their *long-term adaptive* capacity are better prepared to absorb disruptions, acknowledge interconnectedness and proactively change to navigate transitions, adapt, and transform. The main goal of enterprise resilience is to improve the *adaptability* of a company. This goal differs from the goal of building robustness (or 'hardness'). Concretely, the authors recommend building three types of resilience:

- **Structural (or engineering) resilience** focuses on the systemic nature of a company, to improve business continuity with *redundancy*, *modularity* and *diversity*. The creation of buffering capacity that can absorb shocks is an important aspect, as is the decentralisation of important assets or processes and the creation or development of diversity. Structural resilience enables a system to endure greater stress and recover more quickly. It increases resistance to disruption, although this may be at the cost of efficiency. But it does not go further; it does not help a company to adapt to new underlying context conditions.
- **Integrative resilience** focuses on the complex interconnections of a company and its environment and mutual dependencies with others. It implies better understanding and having pro-active actions upon *interactions between different scales*, identifying important *thresholds* that can be tipping points before disruptions, and strengthening of trust and *social capital*. These features are typical of complex adaptive systems, which require systems thinking for their governance. This type of resilience improves the capacity of the company to change towards a complex adaptive system but here, again, it may be at the cost of efficiency (see Section 3.4). Also, if the changes are too big, the company has to undergo a transformation process, which the development of integrative resilience is not meant to facilitate.
- **Transformative resilience** requires systems to review changes over extended time horizons. This is necessary to enhance the capability of a company to transform itself if the fundamental conditions of its survival have changed. Such change can take many shapes, such as the need to reduce exposure to systemic risk via reduced interconnectivity and feedback loops with other systems, or the creation of redundancies and reserve capacities to quickly address such shocks as they arise. For more about transformative resilience, see Section 4.4.

3.3 Lenses of resilience: a social-ecological systems perspective

This section is based on a written contribution made by Allyson Quinlan, Resilience Alliance, at the October 2017 workshop.

Resilience thinking has emerged as a key concept for addressing many of today's most pressing challenges that stem from an increasingly interconnected and rapidly changing world. What began with the discovery that ecosystems have multiple alternative states and that a system's resilience determines how readily it will shift between them, has evolved to emphasise the role of complexity within social-ecological systems (Folke et al., 2016). A large network of interdisciplinary scholars, such as with the Resilience Alliance[3], has advanced our understanding of the dynamic nature of human-environment relationships as complex adaptive systems.

Over the past two decades, research exploring concepts such as thresholds, adaptive cycles of change and cross-scale interactions, has led to many insights for coping with rapid change and navigating the Anthropocene. Consistent with this perspective, resilience is the capacity of a system to absorb disturbance and reorganise, while keeping essentially the same function, structure, and system feedbacks (Folke et al., 2010; Walker, Holling, Carpenter & Kinzig, 2004). Furthermore, a resilient social-ecological system can learn and self-organise in dynamic environments (Folke et al., 2016).

Social-ecological systems emphasise how people depend upon, shape, and respond to the environment (Folke et al., 2016). How these types of complex adaptive systems behave, however, is rarely simple, linear or predictable. Whether it is a rural village, a rapidly growing city, coastal fishery or dryland ecosystem, these and other types of systems consist of people interacting with their environment across multiple levels in a variety of socio-economic, cultural and environmental contexts. A resilience approach embraces this complexity and accepts that there will always be some uncertainty.

Resilience principles

A set of seven policy-relevant and theoretically grounded principles for building resilience in social-ecological systems contributes to the practical application of resilience thinking and can be applied to a wide variety of different contexts (Biggs et al., 2012):

- Maintain diversity and redundancy
- Manage connectivity
- Manage slow variables and feedbacks
- Foster complex adaptive systems thinking
- Encourage learning
- Encourage participation
- Promote polycentric governance.

Resilience in practice

Applying a resilience lens in practice involves new ways of thinking about systems and also finding new ways to influence how a system develops and evolves. Resilience assessment aims to understand the capacity of the system to adapt or transform as needed, in response to both gradual and abrupt change (Folke et al., 2016). Originally conceived over a decade ago, resilience assessment is a structured learning process designed to engage a variety of stakeholders and deepen their understanding of a system's dynamics (Resilience Alliance, 2010). It involves describing how key social and ecological components interact, the role of historical legacies and how a system is influenced by what is happening at scales above and below. Particular attention is placed on external drivers and internal feedbacks, important cross-scale interactions, and potential thresholds or tipping points. Using a multi-method approach, the assessment helps build a shared understanding of how a system works and the processes that build, erode, or maintain its resilience over time (Quinlan et al.,2015).

Despite a structured approach, resilience assessment does not anticipate predictable outcomes. Rather, the process is one of on-going learning and adaptation. Designed to follow a general framework that encourages iteration and reflexivity, an assessment guide should not be mistaken for a blueprint. The behaviour of complex systems emerges from different groups of actors interacting and responding to new challenges and opportunities along the way. What successful outcomes share in common are novel insights that inform innovative strategies for managing social-ecological systems.

3.4 Trade-off between resilience and efficiency

Decentralising decisions, enabling self-organisation and social networking, and promoting diversity are examples of approaches that promote resilience development (OECD, 2014b; OECD, 2014a; OECD, 2011).

[3] The Resilience Alliance was established in 1999 and is supported by an international network of members from universities, government, and non-government agencies, and publishes the journal Ecology and Society.

On the other hand, organisations must be efficient. Efficiency implies the provision of satisfactory performance at a reasonable cost. For organisations to become more cost-efficient, they may reorganise work, realign priorities, and innovate their operating practices.

Increasing efficiency may be at odds with components of resilience such as redundancy and loose-coupling between elements of a network. But there are ways to resolve the trade-off, as exemplified by the way Walmart's supply chain logistics, organised to maximise efficiency, were resilient to disruptions caused by Hurricane Katrina (see Box 9 below). The trade-off between a system's resilience and efficiency is thoroughly discussed in literature, such as with flood risk management (Hegger, Driessen & Bakker, 2018), transportation networks (Ganin et al., 2017), or energy systems (Cholda & Jaglarz, 2015).

Box 9: Example of Walmart supply chain post-Hurricane Katrina

The response to Hurricane Katrina, which hit the Gulf of Mexico and the city of New Orleans in 2005, is as an example of organisational failure to anticipate and react to a major disruptive event. However, Hurricane Katrina also revealed some successful strategies based on improving resilience to cope with unforeseen events. Walmart stores were able to provide food and water to the most impacted areas of New Orleans much faster than the US Federal Emergency Management Authority (FEMA). In the three weeks following Katrina's landfall, Walmart shipped 2500 truckloads of merchandise and made additional drivers and trucks available for community members and organisations wishing to help (Horwitz, 2009).

The resilience of the logistics chain put in place by Walmart can be explained by the following factors:

- Flexibility – A dedicated business continuity unit, staffed by six to ten employees, was already routinely operating in 2005. In case of major events, the team was expandable to 60 people, including senior representatives from each of the company's functional areas.
- Reliance on various sources of information (diversity) – The company used its hurricane tracking software and had contracts with private forecasters to obtain reliable and updated information promptly.
- Decentralisation – Walmart's senior management gave district and store managers enough discretion to make decisions based on local information and immediate needs without requiring pre-approval. For example, a store manager who was no longer able to get in contact with his superiors decided to run a bulldozer through the ruined store to recover all products that had not been damaged by the water, and made them available for residents. Local decision-makers were praised by senior management for their initiatives after the crisis.
- Protocols and preparation – Protocols to deal with major disruptive events were already in place, allowing the organisation to adapt decision-making strategies based on the type and severity of threat experienced. For instance, the number of personnel who were part of the command centre was gradually augmented as the risk increased. Two days before landfall, 50 staff members had joined the team.
- Contingency planning – As uncertainties regarding the areas that would be heavily damaged became more tractable, the decision was made to move emergency supplies such as generators from the current warehouse location to "designated staging areas so that the stores would be able to open quickly" (Zimmerman & Bauerlein, 2005). Those staging areas were set up outside the areas most likely to be hit the worst, to facilitate quick response with minimal danger (Horwitz, 2009).

The benefit Walmart derived from this kind of preparation obviously goes beyond what could be quantified in monetary terms. It had a positive impact on local communities and greater society, which resulted in reputational benefits for Walmart (IRGC, 2015).

Box 10: Example from the food trade sector

The complexity and size of international trade in agricultural and food products enable the provision of food to the world population, despite large imbalances among countries that are net importers and countries that are net exporters. The food supply chain is heterogeneous, which is a component of resilience. However, a study supported by various sources indicates that only seven countries form the core of the network, providing more than 77% of international trading. Vulnerability is particularly high concerning the distribution of potential contaminants, because of the difficulty in tracing their origin. In case of large food poisoning outbreaks, such as the E-coli outbreak that hit Germany in 2011, it is very complex to identify the source of the contamination (Ercsey-Ravasz, Toroczkai, Lakner & Baranyi, 2012).

4. SYSTEMIC RISKS AND RESILIENCE THROUGH THE LENSES OF COMPLEXITY THEORY, SYSTEMS THINKING AND NETWORK SCIENCE

4.1 Complexity theory

Complexity theory is grounded in an attempt to explain how systems in various physical, social or virtual environments respond to stimuli and change over time. Within complexity theory, systems are constantly undergoing a state of change. This change is driven by a combination of (a) interaction with other external systems or change at the boundaries of a given system, and (b) feedback loops which operate due to interconnectivity within and between systems. In essence, complexity theory allows us to explain, beyond linear models, how a given system is challenged and affected by ongoing entropy and instability - conditions that result in the emergence of varying patterns and structures as the system evolves and organises itself into something new (Lowell, 2016).

Most complexity theory scholars would contend that because systems are in a constant state of change, attempting to remain unchanged over the long term becomes increasingly difficult due to the impossibility to control change *within and between* systems in question (Helbing, 2015). Complexity theorists emphasise the role of transitions in the process of managing systemic risks. Rather than resisting change, stakeholders should instead identify opportunities to adjust their system's parameters, operating principles, or input requirements in a way that is beneficial to all that depend upon it. In some cases, it may also be preferable to self-organise (Brock, Carpenter & Scheffer, 2008). However, based on ecological studies, many systems theories make a distinction between equilibrium conditions that are fairly stable and robust against changes, adaptive equilibria that allow changes within specific boundaries, and systems in transition or turbulence that have left a previous state of equilibrium and re-arrange themselves to form a new equilibrium (or remain in a chaotic phase).

A benefit of complexity theory is that it forces one to adopt a systems-view of how disruptions can percolate well beyond the point of origin of a given disruption. Examples include the failure of Lehman Brothers INC, which triggered a massive recession in the European Union, or the late 2006 food commodities and energy speculation that triggered a parabolic rise in fuel prices and contributed to mass-starvation in East Africa (Livingstone, 2012; Clapp, 2014; Haldane & May, 2011). For the former, the financial failure of Lehman Brothers due to their large stake in subprime and other lower-rated mortgage tranches triggered a 'contagion effect,' whereby firms directly connected with Lehman Brothers suffered substantial losses (Luyendijk, 2015). Furthermore, even those firms and companies indirectly connected to Lehman Brothers suffered from economic panic, a falling stock market, and a lack of liquid assets to cover losses as detailed in the United States Senate's Levin-Coburn Report (Levin & Coburn, 2011). For the latter, speculation in fuel and food prices caused sudden spikes in cost (wheat by 80%, maize by 90%, and rice by 320%) that placed 200 million global poor at risk of mass starvation – particularly in East Africa. Within complexity theory, a disruption to a system is not only a challenge for that given system, but can also have much larger implications over time.

Complexity theory inherently works well with resilience. It provides resilience analysts with a philosophical underpinning regarding (i) the ability of feedback loops and nested relationships between systems to generate cascading systemic consequences from a single shock, and (ii) the need to understand how individual sub-systems contribute to the larger operation of a system in ideal circumstances. Through such a systems-view that acknowledges the tenets of complexity theory, resilience analysts can identify interaction effects that could foster cascading failures across a larger system due to a shock or stress and identify leverage points, i.e., places in systems where small interventions can desirably influence the broader system (see Section 4.4.

4.2 Systems thinking

Given an understanding of complexity theory, Westley et al. (2002) argue that all activities and actors, ranging from individual humans to large and complex ecological biomes, are *both* participants in a larger web of systems as well as comprised of smaller sub-systems. Historically, these systems can be environmental (i.e., various ecological and climatological activities within a given biome), social (i.e., the interaction and cultural traditions of various people in a given location), economic (i.e., the exchange of goods and services, inclusive of the supply chains needed to produce and refine goods into products (Weetman, 2016)), and various others. This idea, known as 'systems thinking' helps consider the interconnectivity and feedback loops within and between systems, thereby allowing one to identify how disruptions to one system can have indirect yet significant consequences upon others (Fleischman et al., 2010).

Systems thinking is an inherent assumption within complexity theory (Ostrom & Janssen, 2004). Methodologically, systems thinking comprises two key exercises, including (a) an inwards review of the various operations and components *within* one's system to better understand how a given system functions normally, and (b) an outwards review of how one's system fits within a broader web of interactions with others, and thereby affects/is affected by such external systems (Pisano, 2012; Holling, 1986; Walker & Salt, 2012). The ultimate goal of a systems thinking approach is to determine where a system might be vulnerable to disruption based upon shocks within and without one's system – effectively applying principles of complexity theory to understand the conditions by which a system may encounter disruption that hinders its operations.

Collectively, systems thinking and complexity theory operationalise resilience as an approach where (a) we seek solutions to preserve beneficial systems against shock and bolster their recovery from disruption, or (b) we seek to transition a system in a manner that protects it from systemic risks and moves towards a more ideal or beneficial state (Anderies, Folke, Walker & Ostrom, 2013; Gunderson & Folke, 2011; Helbing, 2010; Renn, 2016, 2017b). Palma-Oliveira & Trump (2016) indicate that a system-centric approach alongside an understanding of complexity (i.e., the potential for cascading effects to trigger multi-system disturbance based upon system interconnectivity) is essential to move beyond using resilience as a metaphor for 'bouncing back.'

Instead, a systems and complexity-driven approach allows resilience analysts to understand the constant state of change and fluid interaction effects between systems and their relevant sub-systems. Fundamentally, systems thinking and complexity theory allow resilience scholars and analysts to address considerations of *panarchy*, where a system can not only move through different phases but where a change in one sub-system can have a cascading effect that alters all others (Gunderson, 2001; Holling, 2001). These interaction effects help determine where a system's brittleness may make it prone to failure and collapse, thereby indicating that certain interventions are needed at specific junctures within a system should it be deemed necessary to preserve it against future systemic threats (Palma-Oliveira & Trump, 2016).

4.3 Network science

Network science serves as one promising methodological option to illustrate, both qualitatively and quantitatively, the complex interconnectivity inherent within many systems. Defined by the National Research Council (2005) as "the study of network representations of physical, biological, and social phenomena leading to predictive models of these phenomena," network science seeks to visually and mathematically represent interconnected systems and their strength of attraction. In a network science approach, it is possible to visualise and model how a shock to a system percolates across the network to various connected nodes (other systems) over time. An advantage to such a network science approach is that it can be applied to various application areas (social, economic, infrastructural, etc.), and can account for the constantly changing nature of a system to absorb incoming disruptions and adapt to change. For example, Ganin et al. (2017) used network science to model transportation systems, where transportation systems experience traffic when a vehicle build-up or blockage to certain portions of the transportation grid cascades into broader traffic across the entire system. Network science is also being used to assess how and when collaborative governance can lead to better management of systemic risks. Bodin (2017), for instance, conducted a study on collaborative networks to identify which actors collaborate, and how the system in which they are embedded influences governance outcomes.

4.4 Intervening to trigger change in complex systems

Transformative resilience (see Section 3.2) requires several inputs to responsibly and thoroughly address systemic risks. These include (a) distributed governance, (b) foresight and anticipatory measures, and (c) innovation and experimentation. Collectively, these factors support strategies to anticipate and respond proactively to changes in the systems in which a company or an organisation is embedded with dynamic reorganisation, restructuration, and reinvention (Bresch et al., 2014).

Distributed governance is where management is undertaken from multiple centres of authority, with trust and effective communication between stakeholders and the capacity to develop and use measures of anticipating systemic risks (Bresch et al., 2014; Klinke, 2017; Palma-Oliveira et al., 2018). Mechanistically, such distributed governance can take multiple forms, yet usually integrates data reporting, analysis, and decision-making within a given sector across key stakeholders in government, industry, academia, and civil society. Such multi-stakeholder efforts require both a measure of coordination to align incentives across all players, as well as to empower the group to make changes to a system at risk of, currently experiencing, or in the aftermath of systemic risk (Klinke & Renn, 2012). A key motivation behind such an inclusive governance structure is the diversity of perspectives raised by the many different actors in a decision-making group to better address uncertainty (Polasky, Carpenter, Folke & Keeler, 2011). Such distributed governance is further benefitted by exercises of foresight and experimentation.

Foresight refers to the capacity of individuals and organisations to engage with uncertainty and anticipate the potential outcomes and the future state of the system (discussed further in Section 5). Such uncertainty can arise through an incomplete knowledge of systemic structure and behaviour, as well as through the wide and uncertain universe of threats that may disrupt a system at any given moment in time. By their nature, systemic risks include a multitude of connected parts that could trigger cascading failures upon disruption from a variety of threats – making it impossible to accurately predict the characteristics or consequences that disruption may have upon one's system (Berkes, 2007). Foresight is an effort undertaken by various stakeholders to both understand emerging trends regarding systemic behaviour and potential for disruption, as well as futuristic threats that may arise to disrupt a system in the years to come (Wilkinson & Kupers, 2013). For example, the US Center for Disease Control (CDC) regularly conducts foresight exercises to identify limited yet emerging viruses to determine likely future outbreaks and prioritise treatments and vaccines (CDC, 2013). Likewise, the Future of Life Institute explores futuristic systemic risks posed by artificial intelligence and seeks to identify strategies to pre-emptively reduce economic, social, and environmental harms that the technology may incur (Hawking, Russell, Tegmark & Wilczek, 2014). Such foresight exercises can comprise quantitative modelling efforts to more qualitative 'thought pieces,' whereby individuals and organisations try to get a better sense of how a system may be challenged in the future, and how it might be shaped and transitioned into a more favourable state to avoid negative consequences.

A critical element of robust foresight includes **innovation and experimentation** (Bresch et al., 2014). Innovation involves efforts to identify new strategies of system formation and operation, while experimentation reviews the efficacy of such innovative proposals through modelling or small-scale implementation. On the one hand, modelling exercises provide the ability to simulate how a system behaves under stress, and how transitions to a system can allow it to perform more optimally in response to such systemic risks in the future. Among many others, such exercises may include Monte Carlo simulations (Mooney, 1997) and network science. On the other hand, experimentation allows stakeholders to test how a system operates in real-world conditions, albeit under a controlled or smaller scale than would be derived in large interconnected networks. For example, policy experimentation within the US federal system allows federal governments to monitor the strengths and weaknesses of policies implemented within individual states – such as with pre-Affordable Care Act healthcare exchanges in Massachusetts or more rigorous environmental protection in New York and Michigan (Bednar, 2011). The strong benefit of experimentation includes the opportunity to analytically review system performance under stress of systemic threats, whereby those policy proposals that perform well are given evidence to support their implementation upon a larger, national scale.

4.5 Leverage points for intervention within a system

After understanding the importance of how systemic risks manifest and transitions in complex and ever-changing interconnected systems, as well as how such transitions may come about, a further point of consideration includes how to intervene in a system's given operations (Haas et al., 2015). Donella Meadows (1999) described these moments as 'leverage points,' which are areas within a system where changes in its organisational structure or activity are particularly effective at generating favourable organisational transitions. Leverage points serve as opportunities where changes to one part of a system can percolate across other connected nodes – inherently using the interconnectivity of a system to generate positive cascading changes to resolve an inherent weakness in the structure or operations of a system.

Meadows argues that such interventions can be implemented in 12 ways (in ascending order of effectiveness based upon her perception of each windows' respective capacity to induce widespread system transition to a different state):

Meadows cautions that this list can change based upon the context of a given system, whereby the order of these leverage points may change. Further, she argues that the further down the list one attempts to use as an intervention point, the greater systemic resistance is likely to arise, and more effort is needed to induce a change in the system. For example, a system's parameters for operation are relatively simple to change – mechanisms are readily available to impose a tax that disincentivises a certain behaviour. Likewise, it is quite difficult to alter the core mission statement and goals of a longstanding system due to the cultural norms and traditions that have preserved and reinforced it up until that point. However, the development of 'windows of opportunity,' which usually open following crises or in the event of disruptive innovations, can present rare chances to utilise more resistant system elements (i.e., paradigms, goals, or root structure of the system).

12. The power to transcend paradigms
11. The mindset or paradigm out of which the system arises (its goals, structure, rules, delays, parameters)
10. The goals of the system
9. The power to add, change, evolve, or self-organise system structure
8. The rules of the system (such as incentives, punishments, constraints)
7. The structure of information flows (who does and does not have access to information)
6. The gain around driving positive feedback loops
5. The strength of negative feedback loops, relative to the impacts they are trying to correct against
4. The lengths of delays, relative to the rate of system change
3. The structure of material stocks and flows (such as transport networks, population age structures)
2. The sizes of buffers and other stabilising stocks, relative to their flows
1. Constants, parameters, numbers (such as subsidies, taxes, standards)

5. FORESIGHT, 'BROADSIGHT' AND EARLY-WARNING SYSTEMS

In order to deal with high levels of uncertainty and explore possible future developments of complex systems, it is necessary to go beyond conventional forecasting approaches that rely mainly on past data to predict the future (Anderson, 1997), or that elicit and calibrate expert judgments in the event of data paucity. Foresight and 'broadsight' are needed to ensure advanced risk identification (and help elucidate opportunities for intervention, and identify leverage points and windows of opportunity as discussed in Section 4.5). While *foresight* is the construction of informed representations of possible futures, including the identification of future risks and opportunities, through a dialogue process among different stakeholders and combination of various types of knowledge to support decision-making, IRGC uses the term '*broadsight*' to extend the scope of the analysis beyond the boundaries of the organisation or system under consideration to ensure broad-based risk assessment by incorporating global megatrends and interdependencies between systems. A range of options is available for successful foresight and broadsight analysis. These include horizon scanning and scenario development, which may be selectively or jointly pursued in line with the objective, the time horizon under consideration, and system scale (Healey & Hodgkinson, 2008).

Horizon scanning

The first approach that many organisations pursue, in one way or another, is 'horizon scanning.' Horizon scanning is primarily about detecting, collecting, and interpreting weak signals that may indicate shifts in existing trends or situations. It is defined as a systematic process of strategic learning about organisations' circumstances (Spies, 1991) with the aim of identifying new developments that can challenge past assumptions or provide a new perspective on future threats and opportunities (Gordon & Glenn, 1994). Horizon scanning activities can be fully exploratory or issue centred (Amanatidou et al., 2012). Horizon scanning is used by enterprises and recommended by organisations such as the OECD. It can be defined as a technique for detecting early signs of potentially important developments, which requires a systematic examination of potential threats and opportunities. To be effective, horizon scanning must explore new, emerging and possible issues as well as persistent challenges and trends. The process must be open to creative thinking and able to detect signals at the margins of conventional thinking that may challenge current assumptions.

Horizon scanning is particularly suited for identifying elements of systemic risks for two key reasons. First, horizon scanning combines information on emerging trends in social, economic, political, technological and environmental domains, where such multidisciplinary insights are required to identify systemic risks. Second, horizon scanning takes a long-term perspective, which can reduce the chances of oversight when risks are emerging or slow moving. Horizon scanning may lead to information overload. As the set of threats and opportunities identified can exceed the organisation's capacity for further analysis, a filtering process is required. The filtering exercise can be performed according to qualitative and quantitative criteria such as exposure and vulnerability of the organisation, possible impact and consequences for the organisation's business, core values or system, the estimated likelihood of a threat to materialise, and available lead-time before the threat or opportunity could become a reality (IRGC, 2015).

Scenario development

To effectively identify and address systemic risks, scenarios about alternative futures for complex systems can be constructed to evoke queries and conversations regarding the future state of a system, as well as interlinked systems (van Notten, 2006). It is recommended to choose scenario approaches that help deal with the uncertain development of systemic risks and possibility of regime shifts. This requirement renders obsolete those forecast-based scenarios that extrapolate past trends into the future and at most account for some policy parameters, making them only relevant for short-term decision-making. Although scientific methods for scenario development exist, they are often limited when it comes to dealing with risks that arise in complex systems and that are highly uncertain and often unpredictable (Cornelissen, 2006; Tourki, Keisler & Linkov, 2013; Weick, 1989).

Wilkinson, Kupers and Mangalagiu (2013) propose the use of plausibility-based scenarios for complex systems. Plausibility-based scenarios expand the scope of exploratory scenarios by emphasising the need to engage heterogeneous agents iteratively. Science-fiction prototyping also helps in this regard (Merrie, Keys, Metian & Österblom, 2017). For more information on successful scenario development for systemic risks, see Section 3.4.

Since horizon scanning and scenario development are not specific to systemic risks, the following tools can be useful for improving the odds of anticipating risks that arise in complex and highly uncertain environments:

- Identifying the drivers of new or emerging risks, which causes risks to emerge, be amplified or be attenuated (see 'Contributing factors to risk emergence', Section 5.1).
- Complementing weak-signals from horizon scanning techniques with statistical early-signals (see 'Usefulness of early-warning systems' in Section 5.2).
- Developing and using quantitative modelling techniques for systemic risk assessment and informing decision-making (see 'Developing and using quantitative modelling techniques', Section 5.3).
- Engaging in participatory scenario development and visioning (see 'Scenario development for systemic risks', Section 5.4).

5.1. Contributing factors to risk emergence

IRGC's work on emerging risks, whether individual or systemic, has emphasised the role of 'contributing factors to risk emergence.' Horizon scanning for early identification of potential risks or imbalances in systems is complemented by tracking the existence of contributing factors to risk emergence as described by IRGC (2010) (see Box 11). Understanding these factors enables more accurate understanding of the changes to the system in which an organisation operates.

At the management level, it may be possible to take action based on the factors that are controllable. However, any action may have cascading consequences in the system and other connected systems, and it is important to integrate feedback from one's own and others' actions into anticipated outcomes. See also Option 1 for managing emerging risks in IRGC's guidelines for emerging risk governance (IRGC, 2015, p. 29).

5.2 Usefulness of early-warning systems

The question that interests most people involved in the assessment and management of systemic risks is whether it is possible to act on early-warning signals to deal with systemic risks. The answer to this question also depends significantly upon the nature and robustness of the early-warning signals, and the strategy chosen to combat systemic risks, particularly whether to (a) support and strengthen the ability of the system to self-organise and self-control, (b) undertake pro-active intervention in the form of prevention, mitigation, adaptation and transformation (c) prepare for disruptions, accidents and crises (absorb and recover from shocks) (see Section 2.2, Step 4). Some of these strategic choices may be specific to organisations given the system scope they are interested in, thereby influencing the type of early warning systems (EWS) they put in place.

EWS are likely to be tailored to industry and civil society. One example includes the use of social media monitoring systems, where companies can acquire real-time feedback regarding product opportunities, risks, and other information pertinent to their business operations. For example, Greenpeace campaigned on social media against the use of palm oil in 2016-2017 within Nestlé's Kit Kat bars. Nestlé quickly formed a social media monitoring service via their 'digital acceleration teams' (Nestlé's EWS) that acquired information of a social response to Greenpeace's campaign and sent signals to Nestlé management regarding ongoing trends of the protest. Though the effort is still underway, Nestlé used available information to transition its supply chain operations away from palm oil, which contributed to deforestation (Fitzgerald, 2013). Further, Nestlé has used their digital acceleration teams to review social media feedback on their general operations of 2,000 total brands, allowing Nestlé to transition operations and even advertising on a given brand based upon real-time consumer feedback (Fitzgerald, 2013).

Large public and private organisations routinely use EWS tools to provide a warning for impending undesirable regime shifts. Public agencies make use of early warning systems to predict near-future ecological hazards, such as floods, tornados, blizzards, and other severe weather events (Carsell, Pingel & Ford, 2004). These systems provide signals to decision-makers regarding the institutional steps that need to be taken to (a) protect a system against shock, or (b) transition various components of the system in a manner where it mitigates, avoids or prevents the shock from occurring (Scheffer et al., 2009). For certain events like floods, mudslides, or avalanches, EWS can signal near-future concerns that can be partially or entirely addressed through infrastructural, social, and

Box 11: IRGC contributing factors to risk emergence

Factor 1: Scientific unknowns
Scientific unknowns, whether tractable or intractable, contribute to risks being unanticipated, unnoticed and over- or underestimated.

Factor 2: Loss of safety margins
The level of connectivity in many of today's social and technical systems is greater than in the past, and the interconnections are increasing. The pace at which these systems operate is becoming faster, and many of them are operating under high levels of stress. This can lead to tight coupling of components within systems and a loss of safety margins.

Factor 3: Positive feedback
Systems exhibiting positive feedback react by amplifying a change or perturbation that affects them. Positive feedback tends to be destabilising and can thus amplify the likelihood or consequences of an emerging risk (ER).

Factor 4: Varying susceptibilities to risks
The consequences of an ER may be different from one population to another. Geography, genetics, experience and wealth are just some of the possible contextual differences that create varying susceptibilities to risks.

Factor 5: Conflicts of interest, values and science
Public debates about ERs seldom show a clear separation between science, values and interests at play. This results in conflicts, which create fertile ground for risks to emerge or amplify.

Factor 6: Social dynamics
Social change can lead to social harm. In other circumstances, it can attenuate potential harm. It is therefore important for risk managers to identify, analyse and understand changing social dynamics.

Factor 7: Technological Advances
Risk may emerge when technological change is not accompanied by appropriate prior scientific investigations or post-release surveillance of the resulting health, economic, ecological and societal impacts. Risks are further exacerbated when economic, policy or regulatory frameworks are insufficient. Technological innovation may be unduly delayed if such frameworks are overly stringent.

Factor 8: Temporal complications
A risk may emerge or be amplified if its time course makes detection difficult or if the time course does not align with the time horizons of concern to analysts, managers and policymakers.

Factor 9: Communication
Risks may be complicated or amplified by untimely, incomplete, misleading or absent communication. Effective communication that is open and frank can help to build trust. In many cases, such communication can attenuate or lead to better anticipation and management of emerging risk (ER).

Factor 10: Information asymmetries
Information asymmetries occur when some stakeholders hold back key information about a risk that is not available to others. These asymmetries may be created intentionally or accidentally. In some cases, the maintenance of asymmetries can reduce risks, but in other cases, it can be the source of risk or amplify a risk by creating mistrust and fostering non-cooperative behaviour.

Factor 11: Perverse incentives
Perverse incentives are those that induce counterproductive or undesirable behaviour which leads to negative, unintended consequences. Such incentives may lead to the emergence of risks, either by fostering overly risk-prone behaviours or by discouraging risk prevention efforts.

Factor 12: Malicious motives and acts
Malicious motives give rise to ERs and therefore, practitioners need to consider intentional as well as unintentional causes of risks. Malicious motives and acts are not new, but in a globalised world with highly interconnected infrastructures, their effects can have a much broader impact.

Source: IRGC 2010

environmental system transition. Likewise, EWS for hurricanes can provide governments and the public with valuable time to prepare to absorb the upcoming shocks of storms that could completely disrupt various social, economic, and infrastructural systems (Adger, Hughes, Folke, Carpenter & Rockström, 2005).

However, it is often difficult to determine which signals contain important information regarding impending systemic risks or threats. Interpreting such signals against other background noise can amplify or dampen the signal's indication of impending systemic threat, leading an organisation to chase red herrings or ignore key pieces of evidence regarding such threats in the near future. Though it is difficult to pre-emptively address this challenge, the triangulation of signals (in other words, identifying signals with similar messages or meanings) can help verify, confirm, or deny potential concerns.

Another limitation is that a critical point of emphasis behind the efficacy of EWS to help prevent undesirable regime shift is a willingness of policymakers and relevant stakeholders to take active steps to transition their system in a more sustainable and favourable manner. For example, Cape Town, South Africa was described in January 2018 as the first major international city to run out of water (Murphy, 2018). Despite years of warnings that such an event could happen, and months of observable data regarding the reduction in freshwater supply leading up to the crisis, few formal actions were taken to transition Cape Town's water use systems onto a more sustainable trajectory. More alarming are the water consumption trends of locals, which have not substantially reduced in response to the crisis (Murphy, 2018). The Cape Town Mayor's Office acknowledged this lack of voluntary transition in a January 2018 statement, arguing that "It is quite unbelievable that a majority of people do not seem to care and are sending all of us headlong towards Day Zero [when Cape Town has run out of water]". This ongoing case is a clear example of a lack of willingness to transition a system into a more favourable state despite the availability of multiple signals that call for such a transition before the crisis becomes unavoidable and even more damaging.

Such EWS limitations are amplified for systemic risks that are believed to be far remote in the future. A popular example of this includes the effects of climate change, which are typically slow-moving (making it difficult for many to observe environmental changes from one year to the next), with many destructive and possibly catastrophic system shocks suggested to arise decades from now (Stenseth et al., 2002). This presents two key problems, including (a) psychosocial responses that encourage procrastination as well as a belief that future generations will solve the problem, and (b) that signals from current EWS may be incorrect or misinterpreted due to various proposed confounding factors that challenge causality of an EWS signal as predicting future climate troubles (Dunlap, 2013). As such, even with dozens of repeated signals regarding the need to transition a system to be more sustainable to future climate change, various psychosocial, political, cultural, and economic factors can cause governments and publics to dismiss warnings posed by climate change EWS.

Statistical Early-Warning Signals

This section is based on A. Nursimulu (2015a).

As seen in Section 2.2 (Step 1), statistical early warning signals (s-EWS) can indicate the proximity to a regime shift.

1. **Temporal statistical early-warning signals (e.g., critical slowing down –CSD)**
   - Temporal s-EWS are based on the premise that systems recover more slowly from small perturbations in the vicinity of tipping points. Mathematically, this translates in an increase in autocorrelation, meaning that the system looks increasingly like its recent part, and an increased variance.
   - Other statistics, which have been observed in a wide range of systems (e.g., global finance, rangelands, fish populations and epileptic seizures), are skewness and flickering.

2. **Spatial statistical early-warning signals (e.g., spatial clustering)**
   - Spatial s-EWS include increasing spatial variance and skewness, which have been shown to provide forewarning of regime shifts in spatial systems.
   - Other spatial indicators include the patchiness or cluster structure of different spatial regions as well as the spatial correlation between different regions, which are determined by specific characteristics of the system being investigated (e.g., vegetation patchiness in the case of desertification in arid ecosystems).

3. **Signals based on power spectral density (e.g., increased volatility in low frequency domains)**
   - Power spectrum analysis separates the amount of variation in a time series into different frequencies; increasing variation at low frequencies relative to high frequencies is seen as an indication that a system is approaching or close to a transition.

The use of several indicators may help improve environment scanning and allow an organisation to acquire a better understanding of the nature and likelihood of proximate regime shifts.

Do s-EWS provide sufficient advanced warning to avert undesirable regime shifts?

Critical slowing downs (CSDs) are usually used to determine the proximity to regime shifts in many instances as well as to investigate time series data after regime shifts. However, they are often too tardy to allow the action to avert a regime shift because large changes in the regime shift indicators often only occur once a regime shift is underway and unstoppable. In other instances, system feedbacks are such that lags in the system or the momentum of change are so great that the system is already committed to a regime shift.

Spatial variance can at times provide better signals than *temporal variance*. But the signal may not be early enough. In the case of lake eutrophication, for example, the process is usually already underway when an increase in spatial variance is observed (Donangelo, Fort, Dakos, Scheffer & van Nes, 2010).

How robust or reliable are s-EWS?

Although useful in determining proximity to regime shifts (in the retrospective analysis), CSDs are neither universal nor specific to tipping points. On the one hand, many systems, because of the nonlinear nature of interactions and system variability, will not show typical leading indicators of regime shifts (Hastings & Wysham, 2010; Boerlijst, Oudman & de Roos, 2013). On the other hand, slowing down happens in situations where a system becomes increasingly sensitive to external perturbations independently of whether the system is approaching a catastrophic or non-catastrophic change (Kéfi, Dakos, Scheffer, van Nes & Rietkerk, 2013). It has also been shown that CSD indicators can fail to detect known regime shifts, for example in the case of desertification where more context-specific indicators such as grass cover, i.e., spatial s-EWS, are more appropriate (Bestelmeyer, Duniway, James, Burkett & Havstad, 2013). Early-warning detection by CSDs can also be sensitive to the choice of metric as observed by Lindegren et al. (2012) in the case of shifts in marine ecosystems.

s-EWS may result in false positives and negatives. The impact of action and inaction in the event of false positives and negatives, respectively, can exacerbate harmful outcomes to a system. Specifically, a false positive may lead to policy interventions that alter the system dynamics precipitating a regime shift where none would have taken place, while a false negative may create an illusion of control. It is therefore important to characterise the error rates of s-EWS, e.g., through using model-based indicators or indicators based on an intermediate generalised modelling approach (Lade & Gross, 2012; Boettinger & Hastings, 2012) (see Section 5.3).

How to improve the usefulness of s-EWSs?

To improve detection, it may be appropriate to use different indicators in conjunction (Guttal & Jayaprakash, 2009; Lenton, 2011). More work is often needed to find generic combinations of indicators, possibly combined with system knowledge, to detect approaching transitions (Kéfi et al., 2013; Gsell et al., 2016).

Recent research findings indicate that s-EWSs based on power spectrum can provide sufficient advanced warning for averting regime shifts. These indicators should be further explored in diverse systems, especially in light of emerging research on early signals of regime shifts in multidimensional systems where the interactions are described using varied network structures (Dakos & Bascompte, 2014; Suweis & D’Odorico, 2014).

5.3 Developing and using quantitative modelling techniques

Quantitative models of systemic risks are needed, since systems are driven by physical laws, and their behaviours can only be understood through rigorous modelling. Modelling outcomes are often used in the process of developing qualitative scenarios or are otherwise used to verify the consistency of qualitative scenarios and complement qualitative scenarios to inform decision-making. Modelling techniques are continuously being developed to understand the functioning of complex dynamic systems. Models vary in the extent to which they rely on historical data, capture structural relationships and processes, as well as their ability to assess the implications of policy interventions. They can be used in conjunction with s-EWS to determine proximity to regime shifts and the timing of interventions. We list below some models relevant to understanding specific aspects of systemic risks.

Semi-empirical models are physically plausible models of reduced complexity that exploit statistical relationships between the state of the system of interest and the driver, such as the relationship between sea level rise and temperature increase.

These models have the advantage that they can be parameterised to explain past relationships and can be designed to include fast and slow dynamics. One key limitation is that they may be inadequate for explaining future dynamics. Feedback mechanisms inherent in complex systems are one reason why past statistical relationships may no longer hold in the future. This limitation motivates structural or process-based models as in dynamic systems models.

Dynamical systems models are models based on sets of structural equations that describe the behaviours of interacting parts in complex systems. Dynamic systems models have the advantage of being able to depict temporal dynamics and system structure and vice versa. They can be used for simulating the outcomes of alternative policy interventions (such as which incentive-based mechanism works best for ecosystem management) and also to highlight unintended consequences of policies (such as the introduction of pollution taxes that leads to dislocation of key industries for the local economy).

Feedback loops, which are central to systemic risks, are often omitted from many dynamic systems models due to lack of knowledge (Hendricks, 2009). However, it is possible to overcome this "failure of omission" by improving our understanding of complex adaptive systems through experimentation and monitoring the occurrence of significant changes. Feedback loops can be added on this basis. The cause of a change and feedback mechanisms underlying the change must be established and then fed into the model. The dynamic act of monitoring and modelling enables continuous model augmentation and refinement, including the introduction of policy as balancing (negative) feedback loops. Such interventionism should, however, be implemented with caution to avoid the problem of *fixing the fix* (i.e., unintended consequences of policy intervention), which can arise when dealing with *meta-levels of model uncertainty*, often accompanied by data uncertainty.

Reduced-form models developed for complex systems with tipping thresholds are typically generic models of slow-fast dynamics. They have the advantage of being adaptable to different scales and are widely used in the scientific community, because although they are mathematical simple, they can exhibit complicated dynamics (May, 1976). They have been proven to be useful for developing model-based early-warning signals in socio-ecological systems and epidemiology, and are also being explored in economic and financial systems to the same end (Arora, Little & McSharry, 2013; Kaufman & Scott, 2003).

Agent-based or multi-agent models are simulation models of a system populated by artificial agents, be they individuals, organisations, groups or biological species. The models capture heterogeneity by endowing each agent with different attributes, whether behavioural or physical or both. Networks within which agents interact adaptively to each other and in light of aggregate outcomes are designed. This process of interaction and adaptation gives rise to emergent behaviour. One key advantage of agent-based modelling is that they can inform the agent traits and interaction patterns that yield sustainable system dynamics under different constraints. Agent-based models enable us to predict impacts of policies where conventional modelling approaches based on optimising representative agents do not afford to do so (Farmer & Foley, 2009).

Multi-criteria decision aiding approaches and methodologies aim at explicating, exploring and assessing decision-makers, actors and stakeholders view, preferences, expectations and arguments when dealing with complex systems and using a sound, valid and legitimate formal procedure to support expertise and decision-making. The methodology aims at dealing with both qualitative and quantitative information and weight of evidence considering inherent cognitive, social, cultural and procedural biases (Nickerson, 1998; Tversky & Kahneman, 1992; Gilovich, Griffin & Kahneman, 2002). These approaches can be used for both participative, deliberative and distributed decision processes and risk management (Merad, Dechy & Marcel, 2014).

Network analysis aims, in part, to identify network configurations that are particularly stable, where the network represents different features (e.g., agents, infrastructure, and resource) of a complex system. These features are represented by different nodes in the network and the linkages between nodes are characterised by specific laws of dynamics. The way the nodes are connected contribute to different network structures. Network analysis is particularly useful when data is limited and model structure uncertain. Network analysis can be used to identify drivers, interactions among them, and also the possibilities of cascading failure across a larger system. For instance, concerning marine regime shifts, Rocha et al. (2015) found that drivers related to food production, climate change and coastal-development most commonly and jointly caused regime shifts. Network analysis can also be used to assess intervention policies. When used for analysing disease spread, for instance, network analysis can identify nodes, which when disconnected, can reduce the rate of spreading. These network-based models can be enhanced based on an understanding of the functional connectivity between different nodes. Brockman and

Helbing (2013) for instance show that network analysis for contagion phenomena can be improved by using context-dependent effective distances between geographical nodes rather than the commonly used geographic distances. In the case of air-traffic-mediated pandemic outbreaks, effective distances include considerations such as the origin of the new disease and the flow of passengers – if it is large, the effective distance is small and vice-versa.

It is significant that no single model in isolation can integrate all features of complex adaptive systems, such that different models often must be used in conjunction. One promising approach is **modular modelling**, whereby different subsystems are modelled separately using the most appropriate technique, and then integrated using specialised routines. Modular modelling has the advantage of allowing the integration of different expertise and facilitating collaborative modelling, where models are developed independently (using different assumptions and approaches) and outcomes crosschecked against each other. Moreover, the process is cyclic: specialist scientists check model predictions against new data and use new data as fresh inputs to update their models, thereby improving the odds of generating robust and up-to-date insights about systemic risk development and update management responses. Also, collaborative modelling leads to model diversity, making it possible to assess many different scenarios.

To conclude, it is worth mentioning the important project work conducted by the International Institute for Applied Systems Analysis (IIASA), on 'Systemic Risks and Network Dynamics'. The project develops prognostic tools for assessing the likelihood and extent of cascading collapses under uncertainty and methods for reducing systemic risk through network design and control. For example, with regard to the resilience of national economies to natural hazards, it developed an agent-based model approach to assess indirect losses across sectors and over time in several dimensions (IIASA, 2018).

5.4 Scenario development for systemic risks

Scenario development for systemic risks is important both to identify the risks and to choose the appropriate resilience strategy (Merrie et al., 2017), but its use in this context is not commonplace. In addition to the fact that it can be a demanding process, wrongly done (e.g., when analysts work in silos, focus on traditional and linear cause and effect relationships), scenario development may fail to have the intended results of stimulating proactive governance of systemic risks. The main steps for scenario development have been outlined in the appendix to the IRGC Emerging Risk Guidelines report (IRGC, 2015). Herein, we highlight principles that are emerging to ensure that scenarios are effective for decision-making in the context of systemic risk, namely:

- **Stronger connection between analyst/researcher-driven and participatory processes**
  Hard evidence—based on facts and scientific models—is often the first input to scenario development. In some cases, as with scenario development by the Intergovernmental Panel on Climate Change (IPCC), researchers or analysts 'own' the scenario development process. Their objective is to provide rigorous descriptions of how the future could play out in the form of reports and narratives. An alternative to researcher-driven scenario development is that of participatory development, which emphasises the engagement of multiple stakeholders. Participatory scenario development recognises the fact that effective identification and management of systemic risks requires the integration of information from diverse temporal and spatial scales for all relevant systems, i.e., social, economic, technological, political and environmental. Making sense of trends and megatrends that arise within each of these systems and how they may influence other systems through interconnection requires different expertise – experts in risk, experts in systems, and key decision-makers (OECD, 2014c). Participant-generated scenarios can then be quantified using simulation and the appropriate modelling framework. Developing quantitative scenarios in this way requires close collaboration with researchers throughout the entire scenario development process.

- **Focusing on non-linearities and interactions**
  Another important aspect of scenario development for systemic risks is the incorporation of non-linear change and co-evolutionary dynamics in interconnected systems. And, to the extent relevant, incorporating megatrends in the analysis may additionally help develop more realistic futures that reveal the presence or emergence of systemic risks (Merrie et al., 2017); see also Section 3.3 on resilience assessment). When exploring the impacts of interlinkages or interactions between systems or factors, a clear distinction should be made between strong, weak and emerging links as these will determine whether the system is vulnerable to shifts and help to identify strategies to weaken specific links. Indeed, the existence of interlinkages is a necessary but insufficient condition to trigger risk cascade. On the other hand, a sub-system may seem to be very stable but highly vulnerable to risk in another sub-system to which it is tightly linked.

- **Developing multiple narratives**
  Multiple narratives are needed since they enable heterogeneous agents to evaluate their preparedness to navigate these plausible futures; they inform resource allocation for prevention, adaptation and transformation (Renn, 2017a). Moreover, developed in a participatory manner, these narratives help create a shared vision, averting resistance to change. In line with the imperative of focusing on non-linearities and interactions, it is important that these narratives highlight the possible interactions in addition to possible 'futures.'

- **Visioning and backcasting**
  Participatory scenario development will uncover a large number of possible ways in which systemic risks may develop. Each stakeholder or stakeholder group will need to clarify how the unfolding of such risks can impact its organisation, and identify which drivers and feedback loops it may influence, typically, with the overarching goal of ensuring business continuity (Fusion, 2014). It is quite likely that the appropriate solutions may not come from any one stakeholder or sector only, especially when system transformation is needed. Only if such an understanding is shared can a collaborative solution that disrupts the status quo be found. The solution will involve defining preferable futures through visioning. Once the vision is shaped, it is possible to explore different means for achieving the vision, whether it is a circular economy (Bocken, Olivetti, Cullen, Potting & Lifset, 2017; CEPS, 2017), a low-carbon society, sustainable fishing, or sustainable economic growth (Lacy & Rutqvist, 2015; Working Group FinanCE, 2016). The visioning process coupled with the development of adaptive strategies for transformation is commonly known as backcasting. Fostering shared or collaborative sense-making throughout the entire process can improve the effectiveness of scenario development for systemic risks (McBride, Lambert, Theoharides, Field & Thompson, 2017).

- **Iterative processes**
  Each phase of the systemic risk identification, evaluation and management process—horizon scanning, scenario development, visioning and backcasting—should be done iteratively using mixed methods, i.e., using both qualitative and quantitative approaches as well as cycling between exploratory and normative perspectives (Star et al., 2016). The iterative process also applies to a continuous system monitoring that allows assumptions and scenarios to be verified and updated.

GENERIC ILLUSTRATIVE APPROACHES

For illustration purposes, this section includes some examples of:

- Fostering sustainability transitions to reduce globally distributed environmental systemic risks (Section 6)
- How to integrate systemic risks and local context in climate-change adaptation: the economics of climate adaptation (ECA) (Section 7)

Further, the OECD approach to public sector innovation provides some illustration of how systems thinking can be used by governments to foster transitions (Section 8)

6. FOSTERING SUSTAINABILITY TRANSITIONS TO REDUCE GLOBAL ENVIRONMENTAL SYSTEMIC RISKS

This section is based on a written contribution made by Mike Asquith and Vincent Viaud, European Environment Agency. It describes on-going research developments in Europe around sustainability transitions and their implications for governance.

6.1 The rise of systemic environmental risks

Many of today's environmental challenges, such as climate change, biodiversity loss, ecosystem degradation and combined exposure to chemicals, are characterised by complexity. They have multiple causes and feature many interdependencies and feedbacks between their underlying drivers and associated impacts across time and spatial scales. They are also 'wicked problems' that are difficult to delineate, define clearly or agree on, as they pervade differing parts of the environment and society and are perceived in diverse ways by stakeholders (Radcliffe & Klein, 2002). Overall, such environmental challenges are resistant to policy response (National Research Council, 2014; EEA, 2018). This contrasts with more specific environmental issues, such as water quality and nutrient loading, urban wastewater, and waste management, which have been addressed successfully in Europe and elsewhere during recent decades. New approaches and perspectives are therefore needed to address these systemic challenges and identify associated risks (EEA, 2015a).

Adopting a more systemic, global and long-term perspective highlights fundamental concerns about the impact of global consumption and production on the natural systems that ultimately sustain human development. The world has witnessed unprecedented demographic and economic growth during the last two centuries, accompanied by massive urbanisation, globalisation of markets, accelerating technological development, and fundamental socio-economic and cultural transformations. These large-scale, long-term and high impact changes — often referred to as 'global megatrends' (EEA, 2015b) — have led to substantial economic and human development, but have also resulted in excessive burdens on the global ecosystem, resource demands and adverse pressures on local ecosystems. The 'great acceleration' in human socio-economic activity worldwide and its associated environmental impacts have been so great that scientists say that we have entered a new geological era, 'the Anthropocene.' In such an environment, humans have become the most influential factor impacting the Earth system (Steffen et al., 2015a).

If these global megatrends persist in coming decades, with the growing global middle class continuing to adopt resource-intensive Western lifestyles, it is relevant to ask about the limits of tolerable environmental pressure on the Earth's life support systems (UNEP, 2016; U.N., 2015). Scientists say that human pressures on the Earth system have reached a scale that risks precipitating catastrophic global changes (U.N., 2010).

Global environmental change researchers have identified nine critical processes that regulate the stability and resilience of the Earth system (Rockström et al., 2009; Steffen et al., 2015b). They argue that sustainable development is only achieved within a safe operating space for humanity identified by the biophysical realities of critical natural thresholds. Transgressing these 'planetary boundaries' could lead to undesirable and irreversible changes in the environment, putting at risk ecosystem and societal resilience, and making the Earth a much less hospitable place. Despite the uncertainty, there is evidence that both planetary and regional boundaries for some areas have already been transgressed, and systemic risks to human societies have materialised or will soon materialise. These include effects on human health, agricultural production, energy and transport, and tourism from the projected increased frequency of extreme climate-related events in Europe (EEA, 2017) and elsewhere.

Today, environmental governance increasingly focuses on understanding how societies can transform their systems of production and consumption in ways that avoid human-induced global systemic risks and ensure sustainable development for all, including social and business development (Centeno et al., 2015; Nauser, 2015; Yosie, 2017).

6.2 Governance for sustainability transitions

Sustainability science increasingly emphasises that global environmental systemic risks necessitate transitions or transformations – 'long-term, multi-dimensional processes of change [based on] profound changes in dominant practices, policies and thinking' (EEA, 2015b). To some extent, this trend reflects insights from ecology and complex systems theory, which maintain that the resilience of systems at the macro scale depends in part on transformability at smaller scales (Folke et al., 2010). Accordingly, preserving the stability and functioning of the global ecosystem requires that societies find ways to transform the production-consumption systems that drive environmental degradation (Helbing, 2013).

Socio-technical transitions research addresses precisely this issue, seeking to explain the characteristics and dynamics of the systems that meet core societal needs, such as energy, mobility, food and shelter. Such systems are understood to be complex and multi-functional, linking to diverse interests across society, including investments, jobs, skills, rules, habits and values. The interdependence of these elements means that there are often strong economic, social and political lock-ins to the dominant system, which prevent the emergence of new technologies and practices that could catalyse transformation. As a result, change in these systems normally takes the form of incremental efficiency improvements, rather than the radical reconfiguration needed to achieve sustainability (Helbing, 2012).

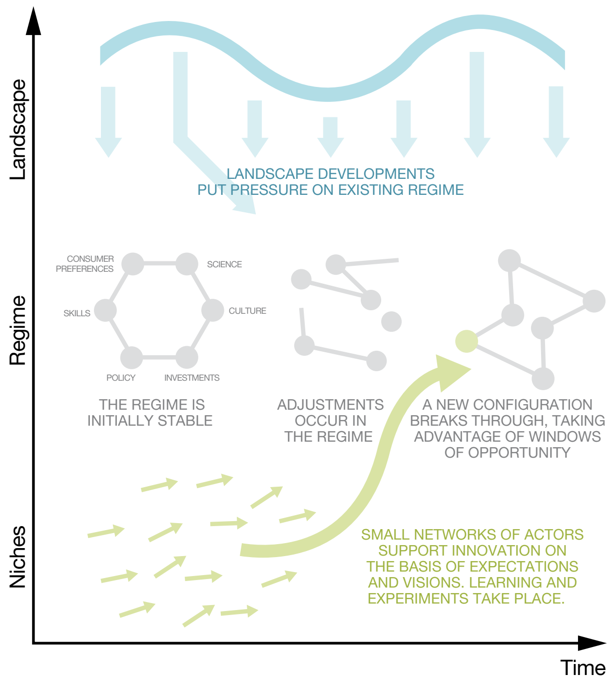

Figure 6: The multi-level perspective on sustainability transitions (adapted from Sustainability transitions: Now for the long term by EEA, 2016).

Within socio-technical transitions research, the 'multi-level perspective' (see Figure 6) is a popular framework for understanding systemic change (Geels, 2002). According to this perspective, the transformation of the established system or 'regime' requires two things. The first is 'niches' — protected spaces below the regime level where new technologies or practices can develop without direct exposure to the normal market or social and institutional pressures (Raven et al., 2010). These spaces include innovation labs within large companies or publicly funded research initiatives.

In addition to niches, the study of past transitions indicates that they depend on forces that can disrupt the established regime, creating windows of opportunity for innovations to establish themselves. Such forces come from the exogenous 'landscape' level and include slowly evolving megatrends such as demographic change and associated demand for resources, as well as more sudden shocks such as a nuclear disaster (Raven et al., 2010).

From a governance perspective, these insights into the dynamics of systemic change have some significant implications. They suggest, for example, that governments can contribute to transitions by creating niches and supporting upscaling using tools such as innovation and industrial policy. Similarly, they can facilitate reconfiguration of the dominant regime by putting pressure on incumbents (e.g., via regulation or fiscal policy) and helping compensate losers (e.g., via welfare policy or retraining) (Geels, 2016; Merad, Dechy & Marcel, 2014).

It is evident, however, that governments cannot simply plan and control transition processes. Systemic change engages diverse actors across society and involves the co-evolution of a considerable number of different social, technical, institutional and cultural elements. Transitions are therefore highly complex and uncertain processes, leading to unpredictable outcomes and creating new types of risks even as they respond to systemic environmental problems. The society-wide character of transitions implies that part of the state's role is to create enabling frameworks for more distributed, emergent forms of governance via markets and networks, and to help steer these processes by engaging social actors in articulating shared visions and goals. Governments can also help to mitigate and respond to the emerging risks inherent in technological and social change, for example by using horizon scanning methods, the precautionary principle, and iterative, adaptive processes of experimenting and learning.

7. INTEGRATING LOCAL CONTEXT AND SYSTEMS THINKING: AN ILLUSTRATION

The author of this section is David N. Bresch, ETH Zurich / MeteoSwiss.

This section describes and illustrates the Economics of Climate Adaptation (ECA) methodology (Bresch, 2017) for dealing with the complex and interconnected system around the economy of climate change adaptation. The approach is part of new evolutionary concepts of systems dynamics, which allow one to identify and review the behaviour of complex systems over time using feedback loops and other relevant information. Applying the logic of systems dynamics, ECA establishes an economic framework to integrate risk and reward perspectives. Starting from a comprehensive mapping of hazards and exposed assets, using state-of-the-art probabilistic risk modelling techniques, it integrates different economic development and climate impact scenarios to assess risk and combines them with a cost-benefit approach to prioritise a comprehensive portfolio of measures to address risk. The method fully acknowledges the complexity and uncertainty of weather and climate-related risks. It makes the case that an economic approach to climate change makes economic sense in local settings.

7.1. Incorporating weather vulnerability assessment into weather and climate resilience plans: the Economics of Climate Adaptation (ECA)

Improving the resilience of our societies in the face of volatile weather and climate change is an urgent priority today and will increase in importance in the decades to come. The climate of the past is by no means a sufficient basis for future decisions. Never in history has society known so much about the processes that shape its future and obtained a wealth of forward-looking weather and climate information – yet pre-emptive (and precautionary) action is not as widespread as is it could be. While measures exist to adapt to an ever-changing environment, decision makers on all levels – from multinational organisations (such as the Green Climate Fund, GCF, cf. Bresch et al., 2017), sovereigns, sub-sovereigns, cities and companies down to the local community – need the facts to identify the most cost-effective instruments. They need to know the potential weather and climate-related damages over the coming decades in order to identify measures to mitigate these risks – and to decide whether the benefits will outweigh the costs.

The Economics of Climate Adaptation (ECA) methodology – developed by the ECA Group since 2009 (ECA Group, 2009; Bresch, 2014; Bresch, 2016) – provides decision-makers with a fact base to answer these questions systematically. It enables them to understand and quantify the impact of weather and climate change and to identify actions to minimise that impact at the lowest cost. The application of a worldwide, consistent, yet locally specific methodology to strengthen climate resilience, therefore, allows integrating adaptation with economic development and sustainable growth.

The ECA methodology establishes an economic framework to fully integrate risk and reward perspectives of different stakeholders (Souvignet, Wieneke, Müller & Bresch, 2016). Starting from a comprehensive mapping of hazards and exposed assets, using state-of-the-art probabilistic risk modelling techniques (Monte Carlo simulations building on ensembles and weather generators), it integrates different economic development and climate impact scenarios combined with a cost-benefit approach (discounting capital and operational expenditures over time, compared to discounted averted damages) to assess a comprehensive portfolio of adaptation measures (Bresch, 2017).

Adaptation measures include, for example, building defences, improved spatial planning, ecosystem-based approaches, building regulations and risk transfer (insurance) against some of the more extreme weather events (RSA-WWF, 2014). Case studies in more than 20 different regions around the globe, ranging from Maharashtra in India to the US Gulf Coast, covering most key hazards (storm, surge, flood, drought) and a wide range of economic and even informal sectors, involving many hundreds of stakeholders in total, showed that a significant portion (up to 65%) of expected damage from climate change can be averted using cost-effective adaptation measures – a strong case for preventive action. Since many regions especially sensitive to natural hazards occasionally lack precise and long historical records of pertinent data, the ECA methodology provides a tool to overcome many of these limitations by making extensive use of probabilistic risk assessment and scenario techniques. This holistic approach avoids issues such as maladaptation due to too narrow a focus on incremental risk, and it explicitly deals with uncertainty by applying probabilistic modelling to cover the whole range of possible events, outcomes and climate impact scenarios to account for different, equally plausible consistent future states of the whole system of interest (while considering system boundaries). Such an approach accounts for concomitant changes in several climate variables and allows one to deal with their interactions.

In the ECA context, economics is understood as the art of resource allocation, using the concept of risk (and reward) as a means to incentivise the internalisation of known externalities – or, simply put, to make the most and best use of existing knowledge of any pertinent system in order to improve its long-term performance and balance stakeholders' needs and perspectives today and tomorrow. The goals of achieving economic growth and reducing climate risk are by no means in conflict. We do not have to choose between them. In fact, sustained growth cannot be achieved unless we address the risks associated with climate change. To realise growth opportunities, governments and businesses must therefore actively manage weather, climate and other environmental risks and incorporate them into their economic and development strategies, as well as in their investment decisions.

So far, ECA studies have been carried out for:

- The City of New York (a focus on urban infrastructure resilience such as storm surge),
- The City of Hull, UK (a focus on risk from multiple hazards such as wind, inland flood, storm surge),
- The City of Miami and the region of South Florida, USA (a focus on risk from hurricanes),
- The North and North East China and Maharashtra, India regions (a focus on drought risk to agriculture),
- Mopti region, Mali (a focus on risk to agriculture from climate zone shift),
- Georgetown, Guyana (a focus on risk from flash floods),
- Samoa (a focus on risks caused by sea level rise such as storm surge and groundwater salination),
- Tanzania (a focus on health and power risks caused by drought),
- The Caribbean (several multi-hazard and sector studies in Anguilla, Antigua and Barbuda, Cayman Islands, Bermuda, Barbados, Jamaica, St. Lucia, and Dominica),
- Energy sector study along the US Gulf Coast (Alabama, Louisiana, Mississippi, Texas),
- Flood risk in an urban context in Barisal, Bangladesh.
- Landslides in San Salvador, El Salvador.

7.2 Illustration: the case of Samoa

Samoa is a group of islands in the South Pacific Ocean. Sea level rise represents a very significant systemic risk.

Assessing the risk

Total climate risk comprises today's risk and the future risk associated with economic growth and climate change. Making use of high-resolution exposure information fed into probabilistic risk assessment models for storm surge risk, the study analysed the risk of sea level rise to Samoa today (yellow, USD 25 million) and by 2030 (red, USD 77 million). Both economic development (USD 22 million, orange) and climate change (USD 30 million, high impact scenario, bright red) are key drivers of risk by 2030. Samoa faces a substantial increase of risk in less than two decades, resulting in a total climate risk of USD 77 billion. The green arrow indicates the portion of risk that can be cost-efficiently averted, based on a rigorous analysis of a basket of adaptation measures, as explained in the next step.

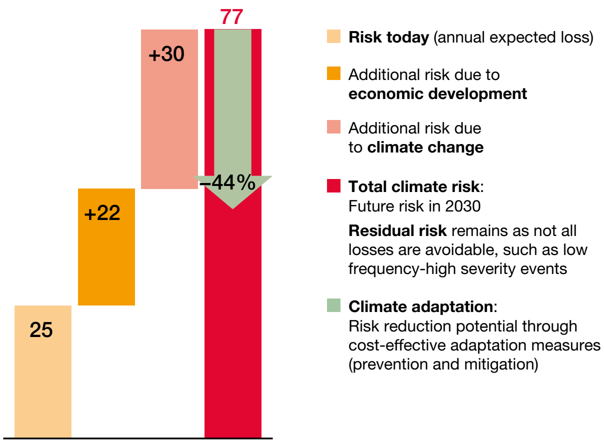

Figure 7: ECA Samoa – Risk of sea level rise to small island state

Addressing the risk

A comprehensive set of possible adaptation measures has been identified in dialogue with local stakeholders and based on further consultations. Such measures include, for example, building defences (dikes and seawalls), improved spatial planning (including the relocation of buildings), ecosystem-based approaches (e.g., reefs, mangroves), building regulations (e.g., floodproofing), behavioral initiatives such as awareness campaigns, and emergency planning and response measures (e.g., sandbags, mobile barriers). Using probabilistic risk assessment models, the damage aversion potential (horizontal axis) of each adaptation measure has been analysed (rectangle, green/orange), as well as its benefit/cost ratio (vertical axis). Note that for this particular case, about 40% of the damage under even a high climate change impact scenario can be cost-efficiently averted. But there remains a residual potential loss, which is addressed in the next step.

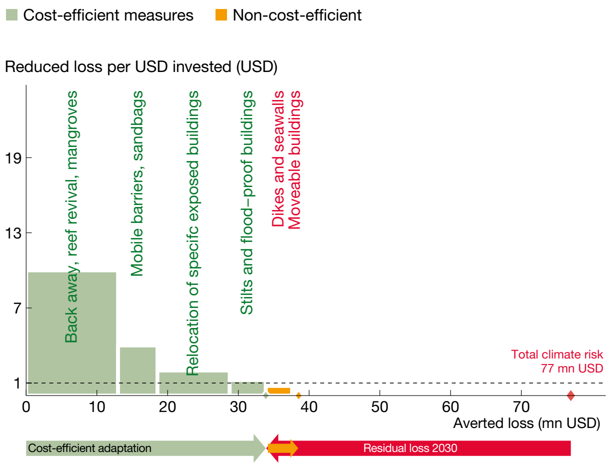

Figure 8: ECA Samoa – Reduced damage per USD invested

Covering residual risk

Consider a 250-year storm surge event, which will result in damage of more than 30% of local GDP. Even with cost-efficient adaptation in place (green arrow, summarising the effect of the measures described above) and budget tolerance (an assumed maximum bearable loss of 5% of GDP), there remains a significant residual risk to be covered (orange arrow). Risk transfer provides additional protection for low frequency, high severity events at a lower cost than further non-cost-efficient measures (orange arrow and bar). Note that the cost for risk transfer is lowered by the fact that cost-efficient adaptation measures reduce a substantial amount of risk (green arrow, here measured regarding GDP). Further non-cost-efficient measures (grey) would be both less effective (only reducing 49% of residual risk) and bear a much higher cost (USD 23 million compared to only USD 7 million for risk transfer).

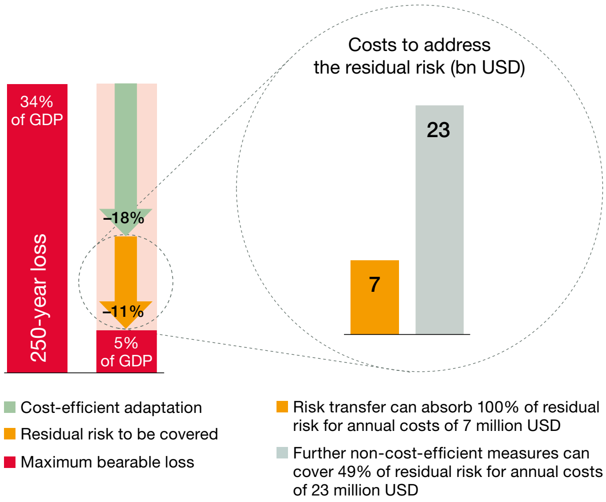

Figure 9: ECA Samoa – 250-Year storm impact

Risk prevention and risk transfer are mutually reinforcing. While insurance is a useful component in a given adaptation portfolio, keeping prices in check by minimising residual risks through prevention measures is key.

This case study illustrates the importance of a sound methodology to allow for integration of a broad set of stakeholder views and perspectives, not least expressed in their suggestions for possible adaptation measures. The ECA methodology establishes an economic framework for integrating risk and reward perspectives of different stakeholders. To strengthen resilience, the end-user or demand-side perspective matters. Therefore, the team that delivered the above case study did engage with end-users to seek a shared understanding of their vulnerability, or, more specifically, their climate sensitivity. In the present case, the study informed stakeholders about the fact that much more can be done to manage weather and climate risk, as it helped to correct the widespread belief that not much could be done against a 250-year storm surge event.

The study makes the strong point that, to realise growth opportunities, both the public and the private sector must actively manage the weather, climate, and other systemic environmental risks and incorporate them in development strategies, as well as in investment decisions, with the aim to foster societal resilience against these risks (Yosie, 2015).

8. SYSTEMS THINKING FOR INNOVATION IN THE PUBLIC SECTOR

In 2017 the OECD Observatory of Public Sector Innovation (an initiative of the OECD's Public Governance and Territorial Development Directorate) published considerations and suggestions about how the public sector could adopt a systems approach to address ‘wicked’ problems (OECD, 2017).

Systems thinking in the public sector is not widely used. Traditionally, public policy makers address problems through discrete interventions that are layered on top of each other, with the risk that such interventions may shift problems from one part of the system to another or address symptoms while ignoring causes. Faced with complexity and uncertainty that underlie complex systems, traditional analytical tools and problem-solving methods are largely ineffective and can even have perverse consequences.

The OECD report is based on case studies and applies the generic approaches outlined in previous sections on systems thinking, systems dynamics, complexity theory, and organisational resilience to address problems of systemic risks. It examines how the systemic change was triggered and managed by public sector interventions in the areas of preventing domestic violence (Iceland), protecting children (the Netherlands), regulating the sharing economy (Canada) and designing a policy to set a framework for conducting experiments in government (Finland).

Integrated interventions, stakeholder engagement, reverse process engineering and the role of "independent brokers" outside of government are techniques that the report analyses for stimulating progress towards more systems thinking in government in order to better address systemic risks. Success factors include:

- Moving away from traditional linear procedures, strategic planning and the notion of reform as an isolated intervention.
- Building capacity to elaborate future scenarios, based on a vision for a desired future outcome.
- Defining the principles according to which the desirable future system should operate.
- Designing a set of interventions to start the change from the existing system to the future system (transformation process).
- Ensuring that leadership can mobilise a broad range of actors that will form a critical mass willing to act, to focus on achieving a common good rather than on narrow institutional interests.
- Meaningful measurements and feedback mechanisms for constant adjustment throughout the policy cycle, so that the usual gap between policy design and implementation is reduced.
- Proper timing of change: people need time to live through, experience and appropriate change.

Systems approaches can help navigate difficult transitions from unsustainable systems to more desirable systems by allowing new practices to be rolled out while core processes are still running. These approaches are relevant both to stimulate innovation and to foster systemic resilience. But more work is needed to understand how to embed systems approaches in public policy.

GLOSSARY

Adaptation: the action or process of adapting or being adapted to something. It involves adjusting responses to changing external drivers and internal processes in order to remain in the desired regime and on the current pathway. Adaptation is achieved through incremental change. It is seen as a slow process, which modifies the landscape only slightly.

Agent-based modelling: a class of computational models for simulating the actions and interactions of autonomous agents to assess their effects on the system as a whole.

Ambiguity: divergent or contested perspectives on the justification, severity or wider meanings associated with a given threat.

Boundary: the periphery of a system, including non-core sub-systems.

Cascading effects: multiple self-reinforcing feedback mechanisms whereby a shock to one system triggers consequences in various connected subsystems.

Complex adaptive system: systems of distributed interacting components, whose conditions can change in response to their environments and to each other.

Complexity: difficulties in identifying and quantifying causal links between a multitude of potential causal agents and specific observed effects.

Critical slowing down: the theory that in cases where a system is close to a critical tipping point the recovery rate should decrease.

Data analytics: the process of inspecting, cleansing, transforming, and modelling data with the goal of discovering useful information.

Early-warning signals: markers, either data-based or context-based that indicate a possible impending transition towards an unfavourable state.

Efficiency: the capacity of a system to perform intended functions in optimal time and with a minimal resource cost.

Emerging risks new risks or known risks that become apparent in new conditions (IRGC 2015).

Feedback loop: when outputs of a system are routed back as inputs as part of a chain of cause-and-effect that forms a circuit or loop.

Horizon scanning: an organised formal process of gathering, analysing and disseminating value-added information to support decision- making.

Learning and experimentation: the capacity of a system to test the effects of system change under controlled settings, and identify policies or goals to achieve positive change.

Lock-in: an arrangement where a system is increasingly obliged to operate under a certain series of principles, resources, or realities that makes it less nimble to transition in the face of adversity.

Niches: denoting or relating to products, services, or interests that appeal to a small, specialised section of the population.

Regime: the prevailing contextual environment and structure of systems that determines the normal expected behaviour of such systems.

Regime shift: large, abrupt, persistent changes in the structure and function of a system.

Resilience: the ability of a system to plan, prepare for, absorb, recover from, and adapt in the aftermath of systemic threats.

Risk governance: the totality of actors, rules, conventions, processes and mechanisms concerned with how relevant risk information is collected, analysed and communicated and management decisions are taken.

Risk management: the design and implementation of the actions and remedies required to avoid, reduce, transfer or retain the risks.

Scenarios: plausible storylines, developed by organisations, about how the future might unfold and how this might affect an issue that confronts them or challenge their status as an ongoing concern. Scenarios can be developed qualitatively, quantitatively, or both.

Self-organisation: a process where some form of overall order arises from local interactions between parts of an initially disordered system. These systems arise organically, as opposed to via structured interventions by decision makers.

Slow-developing catastrophic risks: risks that develop slowly, but which can ultimately lead to sudden, catastrophic and often irreversible changes in complex social, economic and ecological systems.

Socio-ecological systems: a system that is defined at several spatial, temporal, and organisational scales, which may be hierarchically linked.

Socio-technical systems: the interaction between society's complex infrastructures and human behaviour.

System: a regularly interacting or interdependent group of items forming a unified whole.

Systemic risks: the threat that individual failures, accidents, or disruptions present to a system through the process of contagion.

Systems thinking: adopting a perspective where all objects, organisations, and activities in daily life operate within a given system and are comprised of smaller sub-systems.

Tipping point: a point in time where a system is vulnerable to transition into a new form.

Transformation: is a thorough or dramatic change in form or appearance. It involves fundamentally changing the system dynamics, so there are new feedbacks to maintain the system in a new regime or along a new pathway. It is a change towards a future that is fundamentally different from what currently exists.

Transition: long-term, multi-dimensional and fundamental processes of change, based on profound changes in dominant practices, policies and thinking (EEA).

Uncertainty: a lack of clarity or quality of the scientific or technical data.

Wicked problems: a problem that is difficult or impossible to solve because of incomplete, contradictory, and changing requirements that are often difficult to recognise.

Windows of opportunity: periods where systemic transition into a more favourable state is eased due to an amenable resource and/or contextual environment.

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About IRGC

Since 2016, IRGC consists of two distinct and independent entities, which collaborate and support each other:

- The **International Risk Governance Center** (IRGC@EPFL), a transdisciplinary centre at the Ecole polytechnique fédérale de Lausanne. More information on irgc.epfl.ch.
- The **International Risk Governance Council Foundation**. Established in 2003 at the initiative of the Swiss government, the IRGC Foundation is based at EPFL in Lausanne, Switzerland, with network partners in Europe, the US and Asia. More information on irgc.org.

Both work together towards improving the governance of risk issues marked by complexity, uncertainty and ambiguity. As a neutral platform for dialogue about emerging risks as well as opportunities and risks related to new technologies, IRGC works to help improve the understanding and management of risks and opportunities by providing insight into emerging and systemic risks that have impacts on human health and safety, on the environment, on the economy and on society at large.

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