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BACKGROUND PAPER

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# INTERCONNECTED, INTER-DEPENDENT RISKS

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# Introduction

Among risk managers, there seems to be a growing recognition that risk management has not sufficiently advanced to address the complexity and the unknown, cascading features of emerging disaster risks. It is has been acknowledged that traditional, linear, risk management approaches have over-relied on what risk managers have been familiar with rather than on depicting causal paths that have thus far been unknown. Such approaches have focused on identifying, prioritising, and preparing for individual hazards, ranking them linearly by likelihood of occurrence and severity of impact according to prior identified intensity categorisations (McGee, et al, 2014). Prevention and preparedness planning, and even ex-post lessons learned approaches have looked at actions for existing, single-hazard regulations. The significant limitations of such an approach have been manifested in a number of recent catastrophes. The Great East Japan Earthquake in 2011 and Hurricane Sandy in 2012 are just two examples that highlighted how conventional risk management systems were unable to predict the complex interactions and consequences the two disasters entailed.

Linear risk assessments have largely failed to identify interactions between risks, their potential cascading impacts, and systemic failures that result from chain reactions across different systems. In addition they have failed to recognise the important interdependence of risks and their risk environments. The latter are particularly challenging to monitor, as they are rapidly changing, given their underlying transformative drivers, such as population dynamics, trends in globalisation and urbanisation and environmental changes (Shimizu and Clark, 2014). The United States sub-prime mortgage crisis shows how such cascading impacts were facilitated through open markets (Cavallo and Ireland, 2014).

However, the identification of complex risks and the prediction of their cascading impacts is not a trivial task. Complex risks can have a much greater impact than other types of risks, over much broader areas of the socio-economic environment, through interrelated, complex networks. In the past they were often characterised by a low probability of occurrence and high economic and social impacts, such as described in "Black Swan" events (Taleb, 2010), however recent disasters have shown that their frequency may rather increase in the future. Since information ex-ante is often scarce, existing methods that could deal with complexities and the analysis of uncertainty and interdependencies, such as Bayesian methods (Ruggeri, et al., 2005), cannot be fully exploited. As a consequence, complex risks are often only understood in hindsight (De Rosa, et al., 2008)

This paper seeks to take stock of what has been done to address complex risks in risk management systems. Its intention is to highlight what is known and what risk managers can already do to better address complex risks. It will equally underline the key challenges that need to be addressed in the future.

In the following, we will first clarify the concept of "complex" risks and suggest a typology to categorise different types of complex risks. The term complex risk will be used as a synonym for inter-dependent or inter-connected risks. The paper will then turn to analyse the emergence of complex risks and identify potential drivers that can help risk managers in better detecting and monitoring them. We will then turn to look at the implications of complex risks for modern risk management systems.

## Understanding complex risks

### What are complex risks

To determine complex risks, it is useful to start first from a definition of risk in general. A widely accepted definition has been developed that dissects risk in essentially two factors: the probability of occurrence and the associated degree of vulnerability (OECD, 2003). For example, factors like climate change have contributed to an increase in the probability of extreme natural events and socio-economic trends such as accelerated urbanisation has made societies more vulnerable to disasters. To emphasise the interaction of risks with their risk environment, some authors have used the term systemic risks to describe for example natural events that were partially altered and amplified by human activity (such as the emission of greenhouse gases) and whose impacts are characterised by the economic, social and technological developments of the environments where they occur (Renn and Klinke, 2004). System risks also describe situations where unexpected synergies develop between otherwise independent risks, magnifying the consequences of a disaster (Helm, 2014).

With regard to complex risks, such a single most accepted definition is more difficult to find. Instead, one comes across a wide range of terms and definitions to describe the concept of complex risks. Compound risks, inter-dependent or inter-connected risks, hyper-risks or complex risks are all terms that have been used either interchangeably or to describe similar phenomena. For example, Kawata (2011) defines compound disasters as ones that are extensive, compound and prolonged that affect a wide area of damage and thereby cause recovery to be prolonged. Ray-Bennett et al. (2014) use the term hyper-risks to describe an event or process that triggers another event or a series of unpredictable events with a likelihood of trans-border cascading effects. According to Beck (2009) hyper risks are hybrid in that they entail a number of features that may have previously been regarded as mutually exclusive. McGee et al. (2014) define cascading effects more closely by a breakdown or failure of infrastructure systems or networks that result in subsequent breakdowns or failures of additional infrastructure systems or networks due to the dependencies between them. Similar expressions for cascading effects can be found in the terms cascading disaster spreading or cascading failures (Buzna, et al., 2007), cascading infrastructure failures (Rose, 2009) or cascading disasters (Haavisto, et al., 2013). This wide array of terminology is, among other factors, a result of the number of different disciplines that have studied the concept of complex risks.

The working definition that will be used in this report is based on an OECD definition set out in *Future Global Shocks* (OECD, 2011), whereby:

> *"Complex risks are rapid onset events with severely disruptive consequences potentially spreading across administrative or national borders, while producing secondary, knock-on effects across sometimes global infrastructure networks and economic sectors."*

The specific dimension highlighted in the above definition is the geographic one that assumes that complex risks are rarely contained to one country or one continent and that their impacts propagate directly or indirectly across national or continental frontiers.

Table 1 demonstrates that even across international institutions working on similar policy issues of complex risks, different terminology and definitions have been used, whereby some deviations in the definitions also define different types of complex risks, such as mega-disasters, global or compound risks.

*Table 1 Terminology for complex risks across International Organisations*

| Terminology | Definition or characteristics | Source |
|---|---|---|
| Compound Risks | Multiple sequential disaster events that produce more serious damage than individual disasters occurring independently. | Asian Development Bank (ADB, 2013) |
| Emerging risk | Describes the risk of extremely low probability disasters associated with new patterns of hazard and vulnerability. Geomagnetic storms, for example, have always occurred, but the associated risks are now magnified by the growing dependence of modern societies on vulnerable energy and telecommunications networks. | UN International Strategy for Disaster Reduction (UNISDR, 2013) |
| Mega-disasters | High-impact event with low probability of occurrence, highly complex phenomenon with cascading effects on sensitive facilities, damages which rocket through supply chains. | World Bank Institute (WBI, 2012) |
| Global Risks | Risks that spread across and affect multiple countries and generations. This risk becomes a global public good whose benefits also transcend boundaries, providing a central rationale for collective action by an international community. | World Bank (World Bank, 2013) |
| | In an increasingly interdependent and hyper-connected world, one nation's failure to address a global risk can have a ripple effect on others. Resilience to global risks – incorporating the ability to withstand, adapt and recover from shocks – is, therefore, becoming more critical. | World Economic Forum (WEF, 2013) |
| Future Global Shocks | A rapid onset event with severely disruptive consequences covering at least two continents while producing secondary, knock-on effects across multiple continents. | Organisation for Economic Co-operation and Development (OECD, 2011 ) |
| Systemic Risk | Risk that affects the systems on which society depends – health, environment, telecommunications etc. | Organisation for Economic Co-operation and Development (OECD, 2003 ) |

## Making sense of complex risks

Traditional risk management classifies risks in for example natural, social, technological hazards, or natural and human-induced risks (Hood and Jones, 1996; Beck, 1992), based on which risk management systems are built. In the case of complex risks, such classifications overlap and intersect (David et al., 2007), making their management significantly more challenging. For example the Great East Japan Earthquake was a multi-hit disaster that was triggered by an earthquake initially, was then followed by a tsunami that in turn triggered a technological risk, the nuclear power shutdown in Fukushima. In an attempt to formalise and thereby simplify the processes underlying complex risks, Liu and Huang (2014) dissect the concept of compound disasters: A single disaster D1 has three component causes: (i) occurrence of a hazard (H1), (ii) exposure to it by a community or population (E1), and (iii) vulnerability of them to the hazard (V1). The relationship can henceforth be described as:

$$|Prob\ (d1) = (h1) \times\ Prob\ (e1|h1)\ \ \times Prob\ \langle v1|e1|h1\rangle$$

In the above equation the precipitation by one disaster event of another can happen at the level of hazard, when the occurrence of one hazard triggers another, or because the impacts of the first disaster, due to high exposure and poor vulnerability to h1, increases the exposure and vulnerability of the communities subject to a second hazard.

In the following table (Table 2) we summarised key past complex risk events. The table does not attempt to be exhaustive, but rather help distinguish complex risks by establishing categories or groups. Events are distinguished by their cascading characteristics, i.e. natural disasters that trigger either (i) other natural disasters or (ii) technological disasters or (iii) biological disasters. However, the categories are not mutually exclusive. For example, the Great East Japan Earthquake at first was a natural disaster (earthquake) that sparked another natural disaster (tsunami) that in turn triggered a technological disaster.

*Table 2 Examples of past complex risk events*

| Category | Events | Description |
|---|---|---|
| Natural ☐ Natural | • Kanto 1923 | • Earthquake caused subsequent fire (high vulnerability since city was built by wood and earthquake damaged roads preventing effective fire-fighting) |
| Natural ☐ Technological[1] | • Taiwan 1999 | • Earthquake triggered landslides that caused electricity transmission tower to collapse, forcing the temporary shutdowns of three nuclear power plants |
| | • Turkey Kocaeli Earthquake 1999 | • The earthquake led to a significant release of hazardous material through the collapse of a concrete stack at an oil refinery that triggered fires in the refinery's naphtha tank farms. |
| | • Europe Floods 2002 | • During the floods 400 kg of chlorine were resealed from a Chemical Works Company in the Czech Republic leading to serious health warnings in the region |
| | • Sichuan 2008 | • Earthquake caused landslides that in turn caused rivers to block, and caused lakes to form and dams eventually to burst resulting in major flash floods |
| | • Great East Japan Earthquake 2011 | • Earthquake caused tsunami caused nuclear power plant disaster |
| Natural ☐ Biological | • Haiti 2010 | • Earthquake led to cholera due to damages to sanitary and public health infrastructure, whereby the epidemic affected 6 percent of the population and caused around 8000 of the 220,000 casualties |

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[1] Also referred to as NATECHs. NATECHs can be defined as a technological disaster triggered by any type of natural disaster. The technological disaster can include damage to industrial facilities housing hazardous materials, gas and oil pipelines, and lifeline systems which results in significant adverse effects to the health of people, property, and/or the environment (Cruz, et al., 2004).

*Source*: Liu, M. and Huang, M. (2014), "Compound disasters and compounding processes – Implications for Disaster Risk Management", Input Paper for the Global Assessment Report on Disaster Risk Reduction 2014, Geneva: UNISDR Liu and Huang (2004); European Commission (2002), "Floods in Czech Republic, Information Sheet No. 5", Directorate General Environment, Civil Protection Unit, Brussels; Cruz et al. (2004), "State of the Art in Natech Risk Management", Ispra: Report EUR 21292 EN; Cruz, A. and L. Steinberg (2005), "Industry preparedness for earthquakes and earthquake-triggered hazmat accidents during the Kocaeli earthquake in 1999: A Survey", Earthquake Spectra, 21(2), pp. 285–303.

The above categorisation does not distinguish phenomena such as multiple lagging natural disasters that should equally be taken into account of complex risk management. For example, in 2013, Mexico was hit simultaneously by two hurricanes: hurricane Ingrid hit the Gulf Coast and Manuel the Pacific coast triggering landslides and flooding. By the time the second hurricane struck the resources for preparedness and response were significantly diminished due to their engagement in typhoon Manuel. Similar phenomena go some time back in history. For example, the Great Ansei Earthquake, or also referred to as Edo earthquake, struck the Kanto region in Japan in 1856 and caused considerable damages as a result of the shock itself, and as result of the subsequent fires and minor tsunamis. A year later, while recovery from the earthquake was still ongoing, a strong typhoon hit the same region causing severe flooding and destroying 10 times as many houses as the earthquake in the previous year. The heightened vulnerability was, among other factors, a result of the defence structures against the typhoon that were destroyed during the previous disaster (Liu and Huang, 2014).

The above categorisation does also not take into account actions that influence the cascading impacts during a complex risk event. For example: if one looks at forest fire, whether and how it continues to strike a community beyond the first hit depends on how communities respond to it, hence on agents' risk management strategies (Heal and Kunreuther, 2003). If a forest fire is not contained during the first hit, the second hit may strike a community potentially even worse (Liu and Huang, 2014). The Sichuan earthquake in 2008 saw a complex disaster whose cascading impacts were decreased as a course of action was taken while the impacts unfolded. The earthquake did trigger landslides and caused rivers to block, but before this could result in a dam burst, authorities evacuated potentially affected areas and thereby avoided major loss of life as a result. Just as there are many potential ways for one disaster event to lead to another, there are also many ways to potentially reduce or even eliminate cascading consequences resulting from such linkages (Liu and Huang, 2014).

## Drivers and potential future trends of complex risks

The intensity of impacts observed in recent complex risk events, including the Great East Japan Earthquake and Hurricane Sandy, has been driven by underlying socio-economic (including demographic), technological and environmental dynamics that have altered the way hazard events can spread and generate cascading reactions (OECD, 2004). Understanding such driving forces is therefore of key importance to inform better management of complex risks and strategic foresight capacity for the identification of complex risks:

## Socio-economic drivers

When looking at socio-economic drivers, we need to distinguish different trends related to population dynamics, urbanisation and global economic development trends. They all constitute factors that have influenced and explained a heightened potential for turning previously linear one-off events into complex disasters:

### Population dynamics

A larger total population and a larger share of more vulnerable people will continue contributing to driving future complex risks. The world population of currently 7.2 billion is set to reach nearly 10 billion by 2050 (UN DESA, 2013). All OECD countries are confronted with an increasing share of elderly people (Chart 1), a group that are more vulnerable to disaster risk events and have special needs in emergency situations. They tend to be less well-off and hence more often located in areas exposed to risks. Recent risk events testify to that: 71 percent of fatalities during Hurricane Katrina were above 60 years old, half of the victims that died during Hurricane Sandy were above 65 years old (Parry, 2013), and most of the fatalities caused by a heat wave in 2003 in Europe were counted among the elderly.

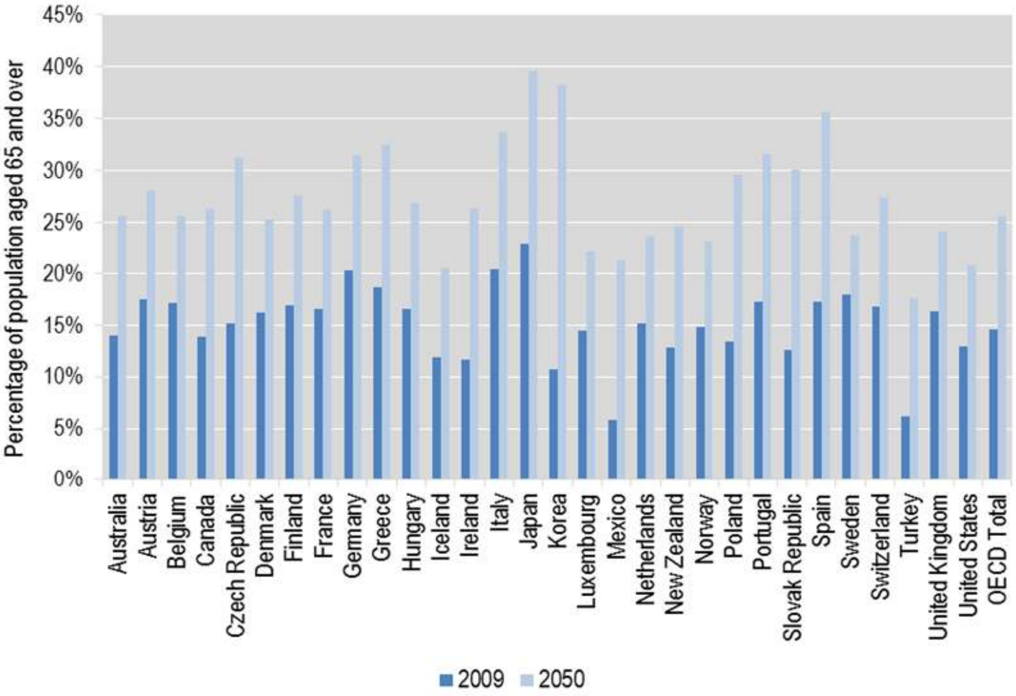


*Chart 1 Percentage of population aged 65 and over across OECD countries*

*Note:* Population data for Estonia, Chile, Israel and Slovenia missing
*Source*: OECD (2009), "OECD Factbook 2009: Economic, Environmental and Social Statistics", OECD Publishing, Paris, pp. 167-192

### Urbanisation trends:

Much of the growth of the world's population and its share of vulnerable groups will occur in highly vulnerable, less developed countries, but furthermore in increasingly dense urban areas (Chart 2), often along coastal areas threatened by climate changes. Urban areas are characterised not only by a high concentration and interdependence of population, but also of buildings and services. Inadequate construction materials and waste and waste water treatment infrastructure could drive the vulnerability to complex risks of urban areas. Growing pressure on food and food safety, water and energy supply could have an eroding and harmful impact on the environment, with new health-related risks occurring for example through the construction of dams and irrigation systems that facilitate diseases such as malaria and parasitic diseases. Furthermore, urban centres will continue to expand, potentially into hazard-prone areas or closer to environmental hazards (such as toxic disposal sites etc.). The need for expansion may also produce compound hazards through simultaneous land-uses in close proximity, such as for example residential areas near key transport axes. Apart from contributing to the driving forces of complexity of future risks, urban areas can be increasingly sources of risks as well. For example, new risks can arise through fires or lightening through electrical equipment on top of buildings or landslides through constructing buildings on watersheds, which in turn modifies hydraulic regimes and destabilises slopes (Wamsler and Brink, 2014).

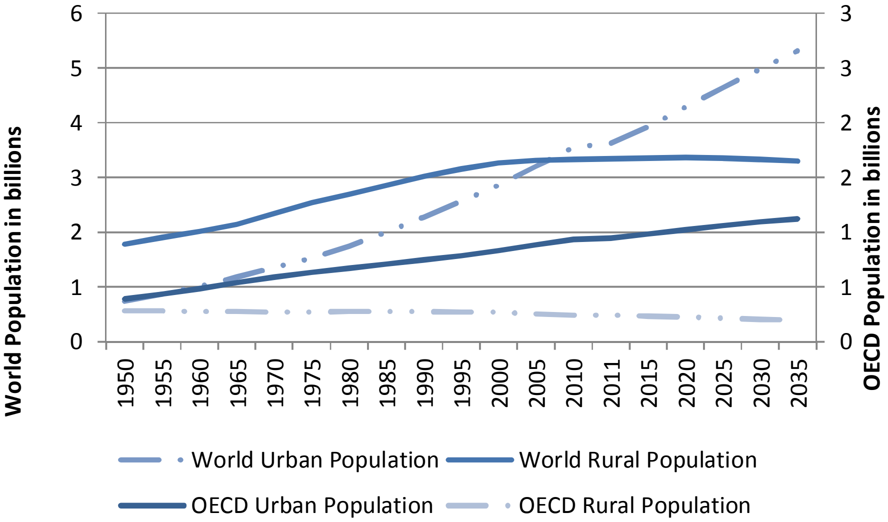


*Chart 2 Urban and Rural Population, 1950-2030*

*Note:* Population data for Korea missing, absolute numbers
*Source*: Calculations based on UN DESA (2013), "World Population Prospects: The 2012 Revision, Highlights and Advance Tables", United Nations Department of Economic and Social Affairs, Population Division Working Paper No. ESA/P/WP.228, http://esa.un.org/unpd/wpp/Documentation/pdf/WPP2012_HIGHLIGHTS.pdf

## Global Economic Development:

Global economic trends have contributed to increasing risk exposure and vulnerability, including the geographic concentration and the global integration of economic activities. The increased geographic accumulation of economic activities (such as for example in Europe depicted in Chart 3) has been motivated by gains in for example transport and financial transaction efficiency. In a drive for optimisation in an increasingly competitive environment buffers and margins are often minimised for short-term financial gains (Becker 2012). As a consequence, a major complex risk for example in the core economic area of the East Coast in the United States could lead to a disruption in the entire country (OECD, 2011).

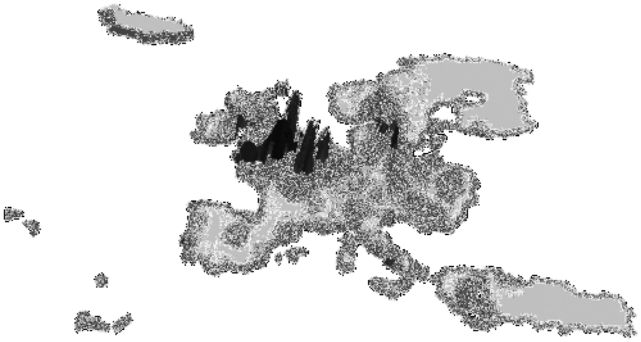


*Chart 3 Economic Density in Europe at TL3 Level (GDP per km2) in 2005*

*Source*: OECD/China Development Research Foundation (2010), *Trends in Urbanization and Urban Policies in OECD countries: What lessons for China?*, OECD Publishing, doi: *10.1787/9789264092259-en*

In addition to economic concentration global integration of value has been amplifying the potential propagating impacts of complex risks (Box 1), especially across national boundaries. Chart 4 depicts the share of foreign inputs in domestic exports added to the share of exports used as inputs in other countries. The higher this share and the more it is concentrated in certain places, the higher the vulnerability of a country's export economy. The chart demonstrates that relatively small countries show a higher participation in global value chains, for example Belgium, Finland and Austria. The increase in global inter-connectedness through supply chains has been driven by outsourcing, offshoring, product and network complexity, single sourcing or buffer stock reduction. These factors create vulnerabilities in themselves, such as for example a reliance on multiple players in diverse locations reduces visibility in monitoring systems. On the other hand single sourcing creates the risks of fewer alternatives in case of disruptions (WEF, 2012).

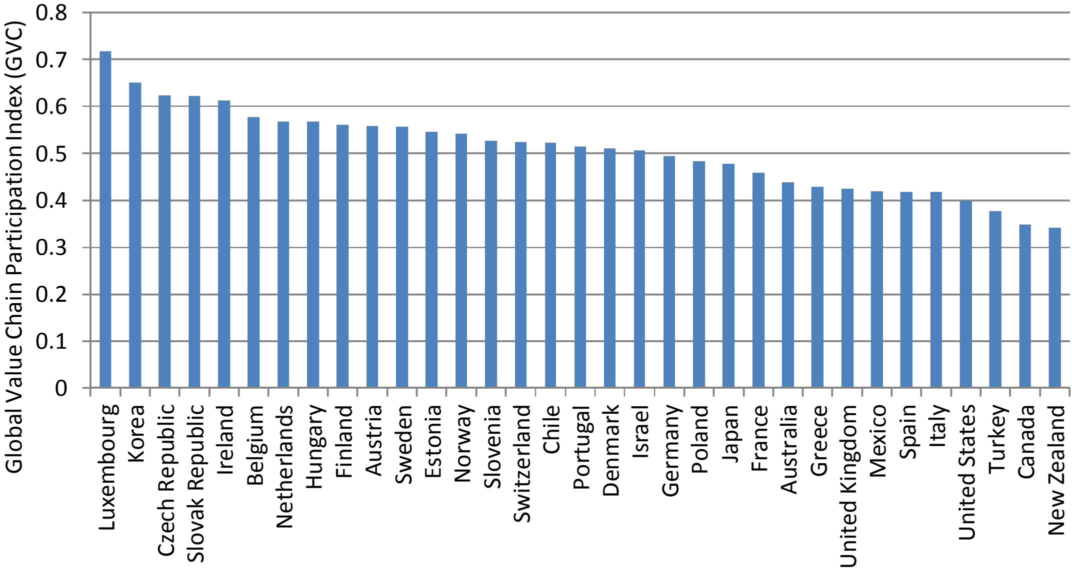


*Chart 4 Global Value Chain participation index in OECD countries, 2009*

*Source*: Mirdoudot, S. and K. De Backer (2013a), "Mapping Global Value Chains", Working Paper presented to the Working Party of the Trade Committee, OECD Publishing

**Box 1: Global value chains as vectors for propagating risks**

An example of how local disruptive shocks can have cascading effects globally is demonstrated by global value chains. The Great East Japanese Earthquake, the Thailand Floods and droughts suffered in the United States have recently demonstrated how such shocks can indirectly, but rapidly and significantly have impacts globally:

- The Great East Japanese Earthquake in 2011 caused disastrous impacts not only in Japan, it led to slowdowns in the global automotive and electronics industries relying on Japan for inputs to their value chain. For example, in the car industry in Detroit, despite the fact that manufacturers sourced microchip controllers from different suppliers, ultimately the supplier was a single producer in Japan, called Renesas, whose production was halted due the destruction of its factory. Single sourcing was equally at the root cause of a global halt on supply of car paint due to a factory that was destroyed and its production suspended in North East Japan. The supplier supplied 100% of global car paint demand, leading to major disruptions in car supply chains worldwide.
- A relatively small eruption of the Eyjafjallajökull Volcano in 2010 in Iceland led to the development of an ash cloud that grounded 100,000 commercial and cargo airliners across Europe for several days, leaving more than 10 million passengers stranded. The estimated loss for aviation firms was EUR 2.5 billion whereas this cost estimation not including the indirect damages suffered by trade relationships all around the world.
- The floods that affected the Bangkok metropolitan area in Thailand in 2011 hit a particularly industrialised part of the city, where more than 1000 factories were affected. 45 % of the world's manufacturing capacity of computer hard disk drives are produced in the affected area. It is estimated that global hard drive supply saw a decrease of 30% in that year.
- The Chi-Chi earthquake in Taiwan in 1999 disrupted the global computer manufacturing industry, by halting the production of semiconductors. The Science Industrial Park in Hsinchu, which was located about 110km from the epicenter, and which housed a significant percentage of the world's semiconductor manufacturing and silicon processing companies, suffered major damages resulting in the closure of the park for two weeks. Subsequently, wholesalers started to hoard memory chips which increased the spot price by 4 to 5 times. Taiwan's central government estimated that indirect business interruption costs reached $2 to $3 billion.
- The Niigata-Chuetsu Oki earthquake in 2007 brought car production in Japan to a halt by cutting the supply off for an engine piston ring. The Riken production facility is responsible for manufacturing 40 percent of all piston rings in the Japanese automobile industry. Riken suffered significant equipment damage due to inadequate anchorage, which led to the closure of the plant for two weeks. At that time Riken was the sole-source supplier of piston rings and transmission seals for major automobile companies such as Toyota and Honda. Toyota alone forewent the production of 120,000 cars in the first weeks after the earthquake. The impact to the automobile industry was attenuated due to the automobile industry assisting Riken restore its production rates two weeks after the earthquake.
- The severe and prolonged drought in the United States that is estimated to have started in 2012 and that is lasting until 2013 has had severe economic impacts. The low water levels in the Mississippi River, for example, where USD 180 billion worth of goods are moved every year, forced barges to reduce the amount of cargo they can carry by two-thirds of their usual load.

*Source*: OECD (2014). Boosting Resilience through Innovative Risk Governance. OECD Publishing, Paris.

During the last decades OECD countries consistently increased their proportion of offshored intermediaries (Chart 5), which reflects the increasing dependency between OECD countries themselves and of OECD and non-OECD countries with respect to the production of end-consumer products. Generally speaking, small economies such as Belgium and the Slovak Republic are much more reliant on global supply chains than others.

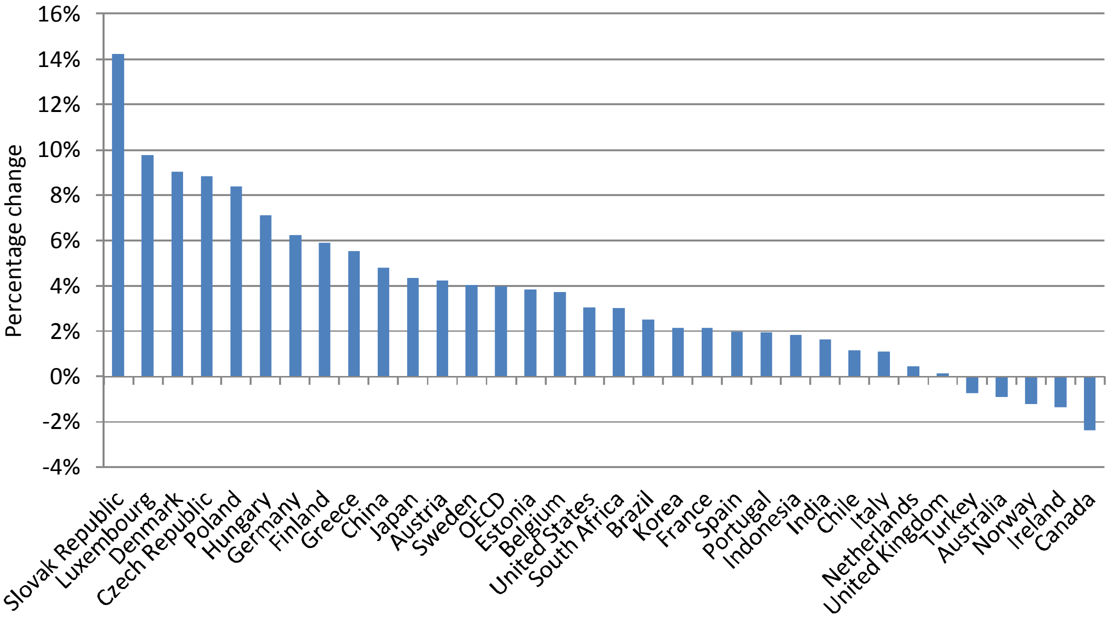


*Chart 5 Percent change in offshoring, 1995-2005*

*Source*: OECD (2010), Measuring Globalisation: OECD Economic Globalisation Indicators 2010, OECD Publishing, doi: 10.1787/9789264084360-en

Global value chains depend on logistical and transportation nodes such as ports. Port cities, an important economic life artery for global value chains, also demonstrate key driving forces for future risks. Miami in the United States, for example, is expected to see an increase in economic assets from USD 416 billion in 20005 to USD 3,513 billion in 2070 (Nicholls, et al., 2008; UNISDR, 2013). Port cities are at particular risk due to their proximity to the sea, subject to uncertain climate change impacts, as well as human-induced risk factors, such as the environmental deterioration around ports stemming from intense economic activities (OECD, 2013b).

Optimisation of supply chains and reliance on lower tier suppliers improved systemic efficiencies in the global economy but at the same time increased rapidity, scope and vulnerability to shock events. Surveys among companies indicated that they may have limited preventive or mitigating capacity regarding supply chain disruptions (OECD 2013a). Shimizu and Clark (2014) highlight that the major shortcoming among globally operating businesses and their supply chain management lies in business continuity planning. There is an incomplete understanding of structure and vulnerabilities inherent in the dependency of thousands of SMEs, in particular second and third tier suppliers that make up the core of corporate supply chains. The focus on cost optimization has highlighted the tension between cost elimination and network robustness – with the removal of traditional buffers such as safety stock and excess capacity. These developments have shifted risk distributions. For example during the Great East Japan Earthquake Honda only realised when it actually happened that the car paint supplier they used from Fukushima was the only existing supplier (Shimizu and Clark, 2004).

As organizations look for efficiencies and cost reduction opportunities in supply chain and transport processes, they need to be aware of the potential impact on their risk profile. For example, Southwest Airlines' strategic decision to operate a uniform aircraft type enables the company to reduce costs associated with maintenance, spare parts and training. However, when a hole appeared in the roof of one aircraft in April 2011, the airline had to ground the entire fleet of 79 aircraft and cancel 300 flights while the fault was investigated. It is critical for both the public and private sectors to understand and mitigate risks at every juncture of supply chain and transport networks (WEF, 2012).

## Technological Drivers

Technological developments in information, communication, space and transport that have facilitated economic development and cooperation on a global scale thereby also act as drivers cascading impacts of complex risks. Chart 6 shows the rapid expansion in internet users in the past 10 years. In OECD countries a rise of 550 per cent was observed in internet users from 1997-2011 (OECD, 2011). Cyber risk is potentially a significant risk because of low barriers to entry and large propagating impacts, fears of which may impede the transition of many financial and other transactions to much cheaper online platforms.

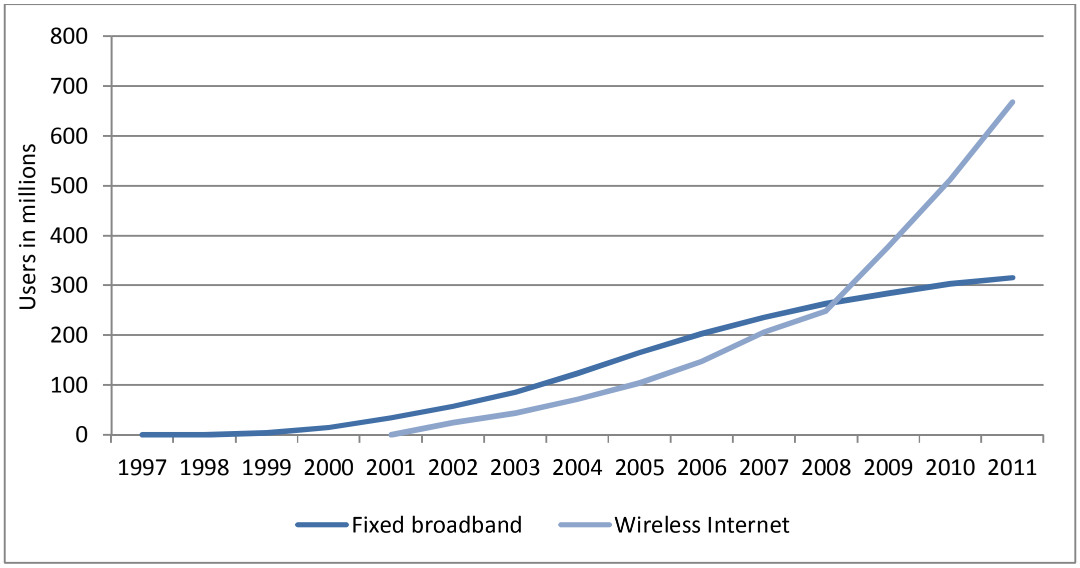


*Chart 6 OECD Internet Users 1997-2011 (in million)*

*Source*: OECD (2012), OECD Internet Economy Outlook 2012, OECD Publishing, doi: 10.1787/9789264086463-en

Similar trends can be seen in people having access to global aviation, and mobile technology through the expansion of satellite dishes. On the one hand they have increased resilience as technology makes hazard analysis, modelling and mapping, early warning, emergency communication and other tasks more easily manageable, but on the other hand they also act as a channel for propagating risks and diseases, potentially transforming humans and their environment.

## Environmental Drivers

Expected climatic changes may be one of the environmental factors driving an increased frequency and intensity of future complex risks. Experts expect that climate change may result in an increase in heavy rainfall, and hence floods, maximum wind speeds, triggering cyclones, and length, frequency and intensity of warm spells, leading to heat waves and droughts. An associated mean sea level rise, glacial retreat and permafrost degradation may increase coastal flooding, slope instabilities, mass movements, glacial lake outburst floods and so on (IPCC 2007). According to Swiss Re (2013) flood risk threatens more people than any other natural catastrophe, since most major cities developed along the sea or waterways. Without any adaption measures, mean annual losses are predicted to reach more than USD 1 trillion in 2050 (Hallegate, et al., 2013). For example, according to the Greater London Authority (2009) 15% of Greater London has some extent of known tidal and/or fluvial flood risk.

## The role of critical infrastructure and systemic risk drivers

The rise of large-scale infrastructure networks is an important driver of complex risks that can have cascading impacts across multiple sectors of the economy. Several critical infrastructure networks have grown to become the backbone of modern economies, such as information and communication technologies (ICTs) Critical infrastructures are interconnected in complex ways, for example ICT's depend crucially on electrical power for their operation (OECD, 2011). Hurricane Katrina highlighted such critical vulnerability caused by the interdependency of water and electricity supply. Despite the fact that the water supply system would have withstood the storm, the power failure led to severe water contamination due to the purification and wastewater treatment plants seizing to function. Contamination, water shortage and health threads leading to several fatalities were the consequence. The associated economic costs were estimated at over USD 2 billion (IRGC, 2006). A similar interconnected risk between urban water systems and electricity supply arose during Hurricane Sandy where drinking water was also contaminated due to black-outs in purification plants. Electric power systems, and also gas supply, urban water supply and waste treatment, rail transport and communication systems are considered critical infrastructure because the functioning of other key critical services depend on it. The degree of criticality is high as the impact of a failure, loss or unavailability is high in scope (potentially international), magnitude (major) and effects of time (immediate). During the Great East Japan Earthquake the regional airport could not be accessed and ground transport was limited due to a gas shortage leading to food and water shortages. Critical communications were also cut due to power, phone and internet disruptions leading to misleading information dissemination and delays in response (Shimizu and Clark, 2014). It is important to articulate dependencies before disasters arise so as to minimise disruptions and establish coordination schemes for different public and private stakeholders to address these problems beyond traditional geographic or expert boundaries.

## Factors driving complex, infectious diseases

The complexity of infectious diseases has been driven by similar factors as other complex risks originating in natural or man-made hazards. For example, global mobility facilitated through global transport networks has largely contributed to a higher risk of the global spreading of infectious diseases. The Dengue and Chikungunya outbreaks in the 1990's were facilitated by global trade in used tires (Table 3). However, the spread of infectious diseases is also interlinked with other sectors such as tourism, energy, civil protection, transport, and agriculture. For example, the outbreak of SARS in 2002 originated in wildlife markets and restaurants in southern China. The risk of global spreading of such diseases further aggravates if control measures do not function, which in turn is often the case in areas where socio-economic inequalities are persistent, resources are lacking or accidents or conflicts have occurred. Global environmental change and land use patterns (agriculture, irrigation, hunting, deforestation) have all contributed to an increase in zoonotic and food- and water-borne diseases (Karesh, et al., 2014; Patz, et al., 2004). Migration and climate have facilitated vector-borne diseases (IPCC, 2012, 2013; Hansen, et al., 2012) and social and demographic factors (such as aging, migration, unemployment) have at times contributed to disease outbreaks, like for example the recent HIV outbreak in Greece due to an increase in people injecting drugs (Paraskevis, et al., 2014; Pharris, et al., 2011). Finally, public health spending can have an influence on the vulnerability to infectious diseases. Health care delivery, vaccines, antivirals and antibiotics are all key investments to fight infectious disease. Budget cuts in those domains can have detrimental public health outcomes (Suk et al., 2014)

*Table 3 Drivers of infectious diseases*

| Disease | Location and date of occurrence | Drivers |
|---|---|---|
| SARS | China 2002-2004 | Wildlife markets and restaurants in southern China |
| Dengue and Chikungunya | Global, starting 1990 | Facilitated by global trade in used tires; mosquito species was secondary vector of disease that spread across the world; Dengue transmitted by the same mosquito and now documented in France and Croatia |
| Measels | Bulgaria | Driven by poor education, poor work opportunities, worsening living conditions connected to broader cultural, demographic and economic risks; despite availability 95% of Bulgarian Romans not immunised against measles-mumps-rubella |
| HIV | Greece | Spread among Greeks injecting drugs, rose especially during economic crisis – increase by 1600%, driven by income disparities, homelessness and introduced by migrant communities |
| Avian Influenza | China, 2013 | Birds are transmitter, virus detected in poultry; drivers have been population density and proximity between humans and animals, live bird markets and human consumption patterns of poultry |
| Polio | Syria 2013 | Outbreak as spread of refugees, many of whom with unvaccinated children |

*Source*: Suk, J. et al. (2014), "The Interconnected and cross-border nature of risks posed by infectious diseases", Input Paper for the Global Assessment Report on Disaster Risk Reduction 2014, Geneva: UNISDR

## Identifying, assessing and managing complex risks – the need for integrative approaches

### A new paradigm for managing complex risks?

Even though it has proven challenging to develop a single most optimal new risk management system that is adapted to the reality of complex risks and its underlying drivers, consensus seems to emerge that any new paradigm has to depart from and complement traditional, linear risk management approaches (Cavallo and Ireland, 2014; Hood and Jones, 1996;). When dealing with complex risks, national governments are advised to improve overall resilience in society, as the efficacy of traditional mitigation measures may be limited (Chart 7). It is paramount for complex risks to be aware of cognitive biases and not expect the future to be like the past (OECD, 2011).

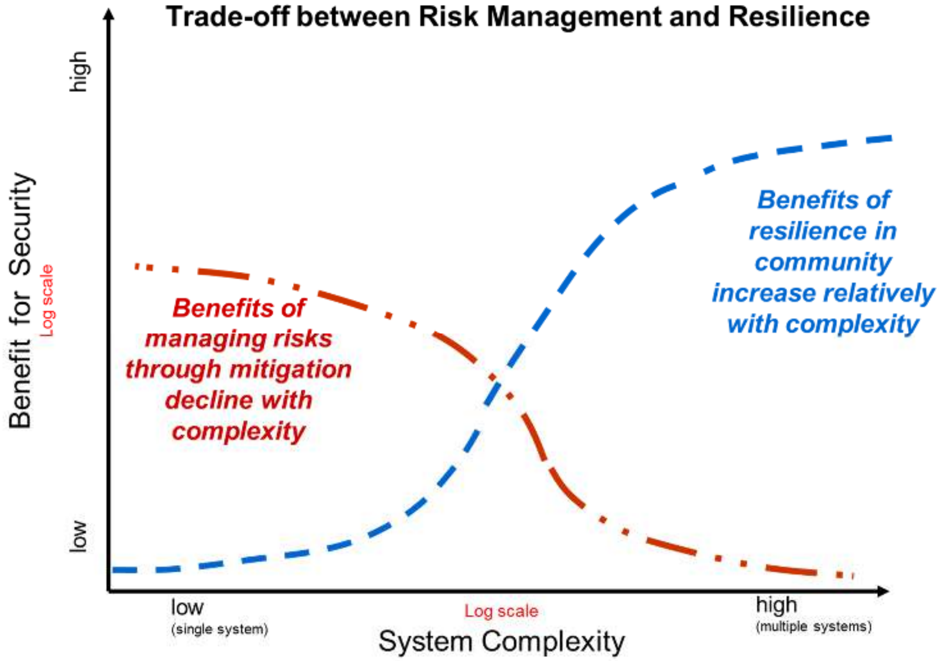


*Chart 7 Trade-off between risk management and resilience*

*Source: Helm, P. (2012). "Risk & Resilience: A Systems Approach to National Security", Keynote Presentation held at the OECD High Level Risk Forum, 13.12.2013, Paris.*

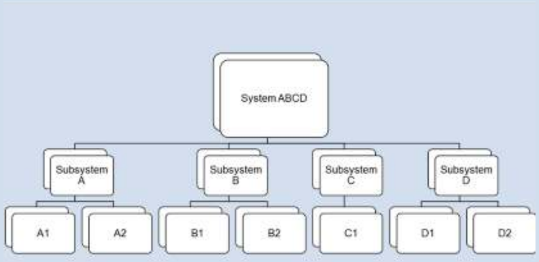
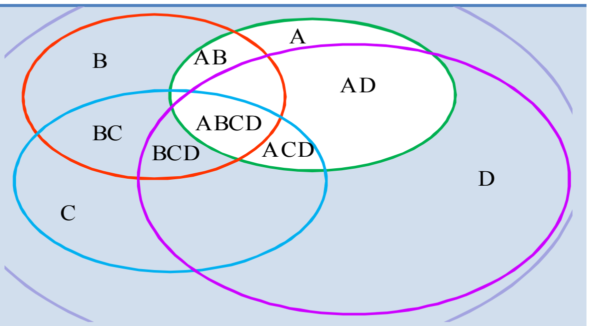
To address this challenge, Cavallo and Ireland (2014) distinguish a *general* resilience approach that is to complement the traditional *specified resilience* approach (Table 4). The later focuses on managing *known* risks, whose consequences have been observed before and whose action plans are reductionist in that plans are being broken down into more manageable components addressed individually. In this approach risk assessments depend on linear cause-effect relationships and the risk management strategy follows a "sense and respond" principle.

In contrast to the traditional approach, general resilience in Table 4 refers to the ability of communities to face *unknown* shocks. The approach emphasises the two-way exchange between governments and communities, i.e. governments need to inform communities about emergency management arrangements and at the same time collect feedback on communities' assets and deficiencies to assess their self-organization capabilities. The general approach is therefore based on a "probe, sense and respond" approach, where risks and solutions often come from programs and institutions that do not appear in DRM plans, such as community gathering programs. In the general approach one cannot specify the threat from which to protect communities, hence its focus should be on what would be critical in any large-scale emergency (e.g. hospitals, essential goods and services). At the end risk management aims at maintaining a safe operating space.

The distinction in table 4 is useful as it attempts at conceptualizing complex risks and in thinking of how they can be approached and managed, which is more obvious for specifically identified risks as opposed to complex, potentially unknown risks.

In order to identify unknown risks Ray-Bennett et al. (2014) propose reflective response approaches that are a combination of individual, organised and critical reflections embedded in an organisation's context. The approach promotes learning at the individual, collective as well as organisational level that focuses on analysis based on considering alternatives and on seeing things from different perspectives to better understand the complexity of risks. Taking the Great East Japan Earthquake as an example, the authors explain that the event showcased an historical reactive approach to managing risks in Japan. The basic law introduced in 1961 was a result of lessons learnt from past disasters, rather than an attempt to prepare for future unknown risks. The establishment of the Nuclear Safety Commission in 1978 was similarly a reaction to the Mutsu accident in 1974. The consequences of this traditionally reactive approach revealed significant shortcomings in assessing and preparing for the potential tsunami knock-on effects.

*Table 4 Specified versus general resilience management approaches*

| Specified Resilience | General Resilience |
|---|---|
|  |  |
| Reductionist | Abductive |
| System of subsystems (SoSS) | System of systems (SoS) |
| Identified risks | Unforeseen, unanticipated risks or unprepared community |

| Linear thinking | System thinking |
|---|---|
| Sense and Respond | Probe, Sense and Respond |
| Mitigate Risk of Negative Events | Keep a Safe Operating Space |

*Source*: adapted from Cavallo and Ireland (2014) "Preparing for complex interdependent risks: A System of systems approach to building disaster resilience", Input Paper for the Global Assessment Report on Disaster Risk Reduction 2014, Geneva: UNISDR

The new approaches to managing complex risks suggested here are challenging for governmental and non-governmental organisations with regard to time, bureaucracy and traditional decision making processes, all of which underpin power, politics and authority. These practices can bring some of the nuances of messy business and power dynamics to the fore through lack of awareness and in-actions (Fook, 2004).

## The importance of critical infrastructures in new approaches to managing complex risks

As mentioned in the previous section, critical infrastructure is a key source and also compounding driver of complex risks, and hence should be addressed explicitly in new risk management approaches. Hurricane Sandy for example caused power utilities and petroleum infrastructures to collapse triggering failures in health care, public transportation, the supply of necessities, and emergency facilities in New York (Haraguchi and Kim, 2014).

Mapping and modelling critical infrastructure networks enables policy makers to address hazards and their economic cascading impacts that do no travel linear pathways. Mapping complex systems is useful to identify hubs that are likely propagating pathways for large-scale disruptions to economic activity (OECD, 2011). It is of paramount importance to study the nature and characteristics of the possible compounding processes that can be caused by critical infrastructure. Risk managers need to be vigilant to the wide range of interactions between disasters and technologies, and to minimise the chances of single natural disasters turning into a wider technological disaster (McGee et al. 2014; Liu and Huang, 2014). Good maps should include various system elements, such as interdependencies, nodes, hubs, scope, pathways, external factors and gaps. Maps that identify all those elements of complex risks are scarce, because it is challenging to map the sheer number of components and interconnections. It may however also be a result of a lack of knowledge about those inputs. In addition, mapping requires detailed knowledge from various disciplines. Finally, mapping necessitates a sustained effort since the dynamics and components contained in them change over time (OECD, 2011).

To improve our understanding of such compounding effects through mapping and modelling McGee et al. (2014) propose to map critical infrastructure in Causal-Loop-Diagrams (CLD) that can portray high level relationships across key critical infrastructure sectors. They form the basis of feedback dynamics at work in critical infrastructure operations indicating when and why cascading effects may be triggered by a disruptive incident. Chart 8 depicts the example of critical infrastructure failures on businesses. They range from disruptions in critical services, such as energy supply, information and telecommunication services, but also include damages to infrastructure such as roads and negative impacts felt by citizens, such as loss of life or injuries.

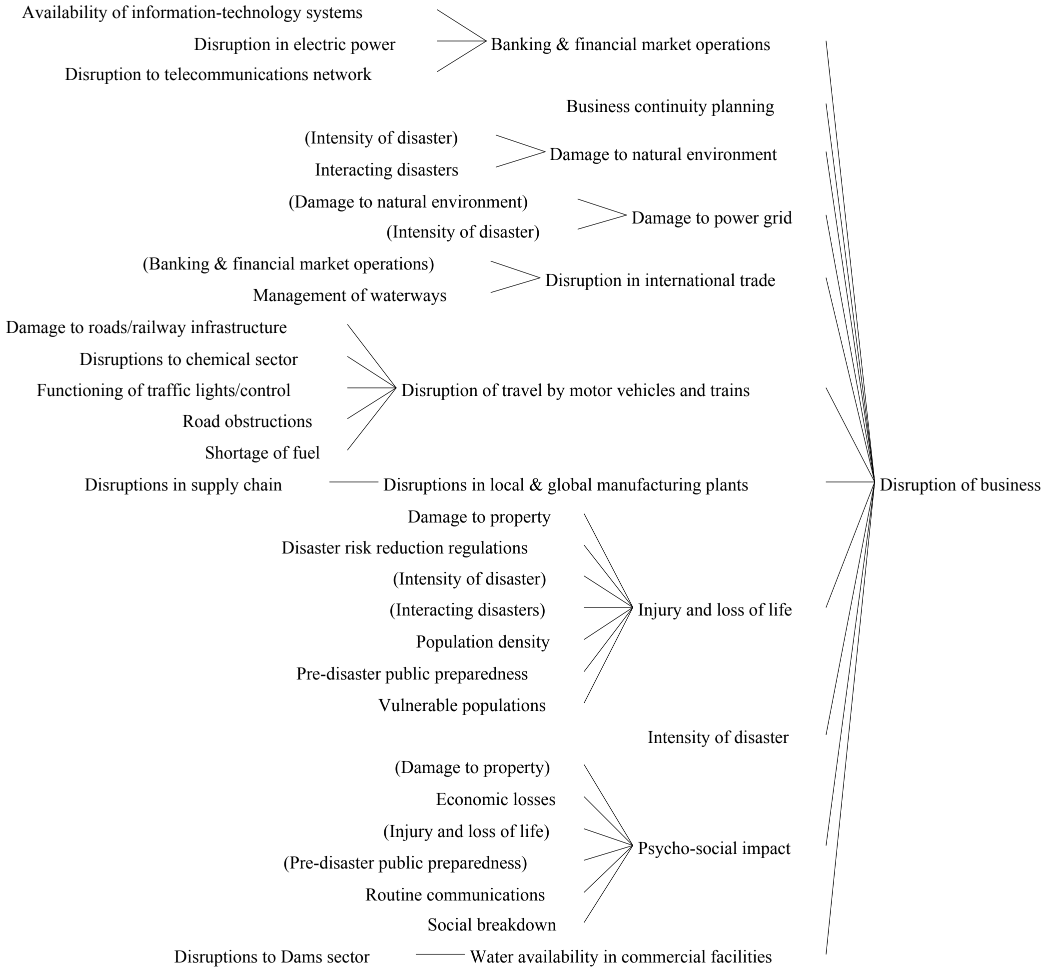


*Chart 8 Cascading Effect of Critical Infrastructure Failures on Businesses*

*Source*: McGee, S. et al. (2014), "Risk Relationships and Cascading Effects in Critical Infrastructures: Implications for the Hyogo Framework", Input Paper for the Global Assessment Report on Disaster Risk Reduction 2014, Geneva: UNISDR

Socio-economic dynamics of localities strongly interact with critical infrastructure failures. Vulnerable populations exacerbate the negative impact of critical infrastructure failures, whereby post-disaster fatalities can be a consequence of the interruption of medical services, disruption of water and wastewater systems. Critical infrastructure failure in one locality may cause relatively minor inconveniences in one place, whereas in other places it may have more serious ramifications (McGee et al., 2014).

Chart 9 depicts another CLD example, this time applied to the Great East Japan Earthquake: the loss of electric power as a result of the earthquake was compounded by the ensuing tsunami that washed the backup generators out and as a consequence disabled the entire cooling system for the nuclear reactors. This in turn caused explosions and meltdown and release of significant levels of radioactive materials, which complicated the overall response with radiation having ramifications for wildlife and food chains as well as long-term population migration and inhabitation trends in the impacted area. Finally, the Japanese government compensated for the loss of power generated by nuclear energy by importing oil which led to a record trade deficit in the order of US$ 78 billion in 2012 (Ferris and Solis, 2013).

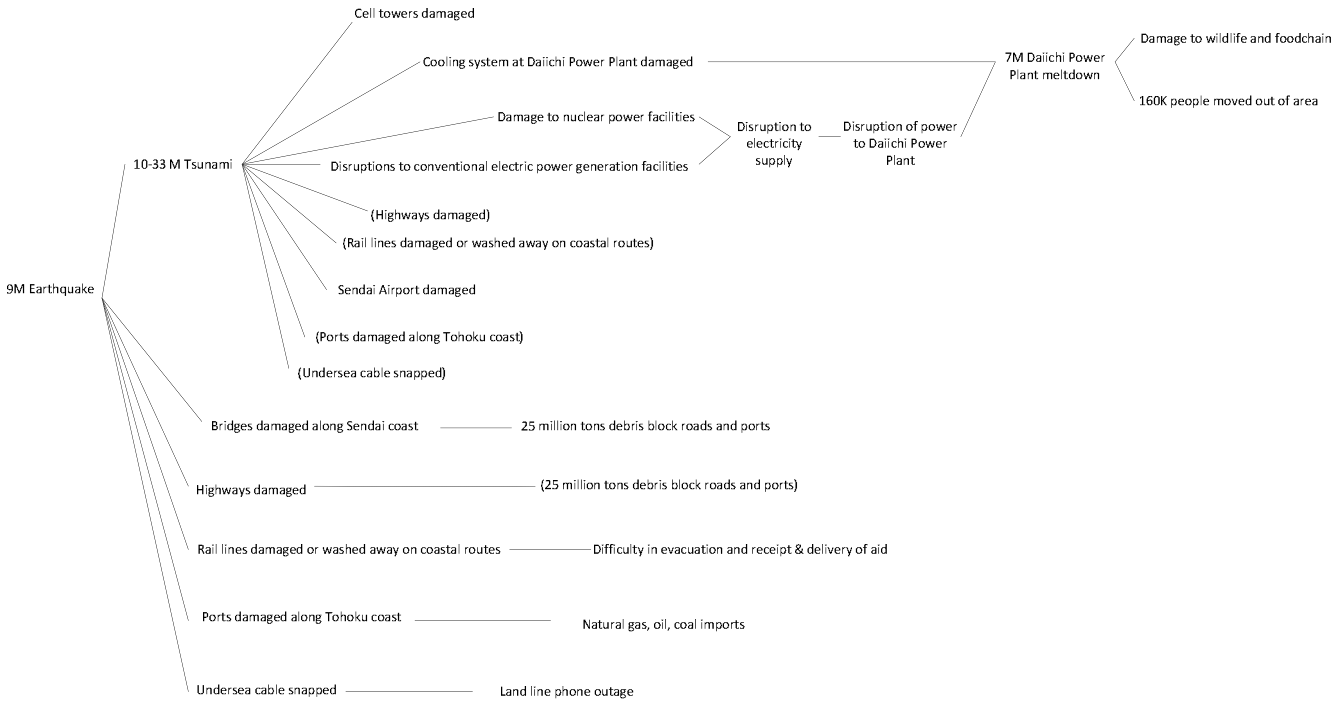


*Chart 9 Critical Infrastructure Failure and its Cascading Impacts during the Great East Japan Earthquake*

*Source*: McGee, S. et al. (2014), "Risk Relationships and Cascading Effects in Critical Infrastructures: Implications for the Hyogo Framework", Input Paper for the Global Assessment Report on Disaster Risk Reduction 2014, Geneva: UNISDR

It seems straightforward to depict the cascading impacts through infrastructure failures ex-post of a disaster. But if failures were not identified ex-post, we have little idea about how close infrastructures were to break down (Shimizu and Clark, 2014). Hence, the regulated level of safety may or may not exist. When failure does not occur these assumptions are reinforced with the result that safety margins are often reduced on the basis that the system has not failed in the event of a disaster. The incentive of measurable financial benefits from reduced safety precautions (e.g. inspections, testing, maintenance etc.) against an unmeasurable level of safety usually drives decision-making for critical infrastructure regulation. Once this determines organisational culture it is very difficult to implement alternative courses of action. The lesson to learn from this analysis is that infrastructures are first and foremost designed to be productive (Shimizu and Clark, 2014).

## Policy recommendations

Given the occurrence of past inter-connected, compound disaster events and their underlying driving forces causing future uncertainty, countries need to address existing shortcomings in the management of such complex risks. It is key to integrate aspects of complex risks in all phases of the disaster risk management cycle, in particular in (a) risk assessments; (b) in the evaluation of underlying driving forces, and (c) in the adaptation of preparedness and response mechanisms. Since complex disasters have shown to be caused by a wide range of different factors and spread across localities, countries, as well as sectoral activities (d) coordination and cooperation across administrative levels, sectors and countries has to become part of the new operating principles.

### Disaster risk assessment

There is a need to more fully define and understand complex, interconnected risks and the structure and diverse impacts of resulting cascading disasters. To accomplish this requires a whole-of-society approach to risk and vulnerability assessments. This is particularly true for large complex development or agglomeration areas, such as was the case of the Great East Japan Earthquake or Hurricane Sandy in New York, where economic activities, industries as well as communities exist closely intertwined with and dependent on interconnected critical infrastructure (Shimizu and Clark, 2014; OECD, 2014). As a preventive measure, Iwama et al. (2014) suggest to make an interconnected risk assessment obligatory for any new larger scale infrastructure development, most similar to conducting standard Environmental Impact Assessments in the planning process of large-scale infrastructure. Such assessments would identify the creation of potentially harmful or vulnerable interconnections for which precautionary measures have to be built into the systems.

For infectious diseases there is a similar need to improve risk assessments towards a better understanding of their interconnected nature. This involves creating tools and methods that allow for predictive modelling as well as assessing countries' preparedness capacity, a crucial factor determining the interconnected vulnerability occurring through the spread of infectious diseases. Finally, future risk assessments need to better understand and identify the interdependencies between infectious diseases and other sectors (Suk et al., 2014).

In terms of using maps and models to improve complex risk assessment policy makers should promote the availability and accessibility of data needed to develop good maps and make use of the technological instruments that exist, but cannot be exploited due to data insufficiency. Government support is crucial for improving mapping and modelling to ensure continuity, validation and refinement over time (OECD, 2011).

### Disaster risk drivers

As was shown in the present paper, the occurrence of complex risks has very much been driven and amplified by underlying risk factors, including the interconnectedness of global economies through global information and communication technologies, global mobility and transport and so on. Therefore, complex risk assessments have to be closely linked with a monitoring and evaluation process of underlying risk drivers. The challenge for this will be to not only assess the breath of factors and linkages between critical infrastructure, but to update them regularly enough in risk assessments so as to adapt disaster risk preparedness and response measures (Wamsler and Brink, 2014).

### Disaster risk preparedness and response

An explicit and strengthened perspective on inter-disaster linkages also implies that timely and adequate responses to one disaster may be the key to preventing another. Thus disaster responses are not simply "responses" to the aftermath of a prior disaster. They are also, and should be, treated as an integral part of any disaster prevention policy. Adequate actions can cut the chain of cascading impacts. For example, if adequate measures were taken after the tsunami following the Great East Japan Earthquake, it has been suggested that the power plant disaster could have been contained or at least better controlled. It is unlikely that such timely and adequate responses can all be pre-planned. Much will rest on the ability to respond flexibly and effectively under a fluid post-disaster situation, and sometimes improvise, which does not mean complete passivity. An experience and knowledge of the range of possibilities, and the ability to anticipate and react based on this experience and knowledge would be especially important (Liu and Huang, 2014).

### Coordination and cooperation

Interconnected, complex risks require cross-sectoral engagement and collaboration. For example during the Great East Japan Earthquake a whole range of policy domains was affected including disaster management, environment, energy, public health, local economy and industry and international relations. To deal with complex risks, previously specialised agencies need to participate in multi-sectoral policy formulation and coordination processes. Complex disasters require more and more effective co-knowledge production that includes systematically accumulating, synthesising and integrating key information, experience, data and lessons learned beyond conventional expertise, organisational or geographical boundaries to produce actionable policies. Coordination is therefore not only important across sectors, but also across governmental levels and across countries' borders. In addition, it is key to coordinate and collaborate with non-governmental stakeholders, including the private sector as many of the actions are also destined for and depend on the cooperation of such actors. The OECD Recommendation on Governance of Critical Risks provides detailed propositions for policy makers to make an engagement with all stakeholders nationally and internationally happen (OECD, 2014)

## Implications for the Hyogo Framework for Action (HFA)

The adoption of the HFA in 2005 remained mostly mute on the topic of complex risk. Nevertheless some countries, such as the United States, Germany, Bulgaria, and Australia have recognised the importance of the interconnected risks and critical system failures (Haraguchi and Kim, 2014). The future HFA post 2015 therefore needs to be strengthened with regards to this in its evaluation and objective setting framework (Liu and Huang, 2014). To do so, the future HFA could:

- identify interdependencies across critical infrastructures and prioritize critical infrastructure recovery operations;
- include the assessment of complex, interconnected disasters in national and regional risk assessments;

- address private sector’s need to identify business and critical infrastructure interdependencies and establish robust continuity plans that account for critical infrastructure failures;
- address risk-benefit decisions when planning communities and critical infrastructure facilities;
- guide the prioritisation of key sectors from a protection and recovery standpoint.

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