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Extreme Events, Critical Infrastructures, Human Vulnerability and Strategic Planning: Emerging Research Issues

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The importance of critical infrastructures and strategic planning in the context of extreme events, climate change and urbanization has been underscored recently in international policy frameworks, such as the Sustainable Development Goals (SDGs), the Sendai Framework for Disaster Risk Reduction 2015–2030 (UNISDR (United Nations/International Strategy for Disaster Risk Reduction) 2015), and the new Paris climate agreement (UNFCCC (United Nations — Framework Convention on Climate Change) 2015) as well as the New Urban Agenda (UN-HABITAT 2016). This paper outlines key research challenges in addressing the nexus between extreme weather events, critical infrastructure resilience, human vulnerability and strategic planning. Using a structured expert dialogue approach (particularly based on a roundtable discussion funded by the German National Science Foundation (DFG)), the paper outlines emerging research issues in the context of extreme events, critical infrastructures, human vulnerability and strategic planning, providing perspectives for inter- and transdisciplinary research on this important nexus. The main contribution of the paper is a compilation of identified research gaps and needs from an interdisciplinary perspective including the lack of integration across subjects and mismatches between different concepts and schools of thought.

Keywords: Critical infrastructure; urban planning; spatial planning; risk management; climate change; extreme events; cascading effects.

1. Introduction

The rise in economic losses due to natural hazards and climate-related extreme events is increased significantly when critical infrastructures (such as energy, water supply, information and communication systems, transportation systems, or health facilities) fail to operate or operate sporadically. Such disruptions affect local areas most severely, but they can have global ramifications and significance. For example, the Fukushima nuclear power plant failure after the Tohoku earthquake and subsequent tsunami illustrated the connection between natural processes and technological systems failures (see Pescaroli and Kelman 2016; The Guardian 2016) and the spatial extent of contamination and loss (land degradation, health impairment, livelihood loss, economic loss). The event had important consequences for energy policies in countries not directly affected, far beyond the direct impacts of the failure of the nuclear power plant. For example, it marked an important step towards the nuclear phase-out (transformation of the energy sector) in Germany. There are other examples of such cascading events at the national and local level that do not attract global media attention. All of these disruptions of critical infrastructures (CI) within or after extreme events demonstrate that failures of such systems have the ability to multiply human suffering, economic losses, and environmental degradation well beyond the initiating event.

Currently, we observe a significant transformation of industrial production through the merging of digital technology and manufacturing processes (supply, production, distribution and the product itself) often called industry 4.0 (see European Parliament 2015). Through this merging various services of manufacturing systems are highly connected and interlinked with digital processes and respective IT infrastructures. Thus, the shift toward industry 4.0 is likely to increase the dependency of the industry on the functioning of CI.

Despite the increasing international awareness about the importance of critical infrastructure dependencies and the need for disaster resilience, most programs and research initiatives continue to focus on individual systems or the technical interrelations of coupled CI, such as the linkages between energy and water supply systems.

Overall, research in the area of CI remains sector specific and also fragmented in terms of the approaches on how to deal with the nexus between extreme events, critical infrastructures and human vulnerability. McGee *et al.* (2014) argue that the current research has made substantial progress in understanding risk-relationships and cascading effects during disasters. Various publications on robustness and resilience of CI provide important recommendations on how to improve such systems (see overview in Urlainis *et al.* 2014). However, the core focus of these publications is on the technical system itself and potential interrelations with other technical systems of CI. It does not consider the broader human-technical nexus and the different scales where such interrelations manifest themselves. We argue that in order to increase the resilience of cities and CI one has to also address the nexus between extreme events, CI failures, dependency of users on CI services and their vulnerability (user vulnerability) to CI failures, as well as options of strategic planning.

Most contemporary research focuses on the impact of a specific hazard on a CI and respective cascading effects for other infrastructures. Only very few, however, include the analysis of different levels of vulnerability of people dependent on such services or focusing on different city scales and their adaptive capacity to CI failure.

This paper introduces the international context of CI and outlines definitions of what CI are and why they are seen as key elements in international agreements, such as the Sendai Framework for Disaster Risk Reduction (DRR). Using a structured expert dialogue approach within the DFG roundtable and within the International Council of Science — programme on Integrated Research on

Disaster Risk (IRDR) (see IREUS website — DFG-Roundtable 2016) and IRDR website (2016), the paper presents important new drivers that influence the significance and role of critical infrastructure, such as the digitalization and urbanization (Section 3). Using example from Europe and Germany in particular, the significance of CI disruptions due to extreme events are outlined (Section 4), including the structural, functional, technical and community contexts as well as options to address CI within existing regulations and institutional settings of spatial and urban planning (Section 5). Finally, the paper defines research gaps (Section 6) that were identified within the structured expert dialogue and formulates conclusions including future research needs (Section 7). Before exploring new drivers that influence the role of CI, the following section deals with new international agreements and directives that highlight the importance of CI.

2. International Context for Critical Infrastructures

Various international documents, such as the New Urban Agenda (UN-HABITAT III 2016) and the Sendai Framework for DRR (UNISDR 2015) underscore that infrastructures are the backbone of societies, particularly in the Global North and in emerging economies, as well as in urban areas in developing countries. CI play a key role in building resilience and reducing vulnerability of people to natural, natural-technical and human-induced hazards including climate change and extreme events.

According to the European Union Council Directive 2008/114/EC, CI refer to an “asset, system or part thereof (. . .) that is essential for the maintenance of vital societal functions, the health, safety, security, as well as economic and social well-being of people, and where the disruption or destruction of which would have a significant impact in the respective country as a result of the failure to maintain those functions” (European Commission 2008).

The directive and other documents include under CI particularly: (I) energy (electricity, oil and gas), (II) transport (road, rail, air, inland waterways, ocean and short-sea shipping, and ports) and (III) Information and Communication Technologies (ICT).

Infrastructures are often judged to be critical if they have a potential impact to cause (a) casualties, (b) significant economic consequences and (c) negative effects for the public (see Bouchon *et al.* 2008). The operationalization of these criteria is still a research task for different disciplinary perspectives and spatial context conditions (e.g., urban versus rural areas, small and medium sized cities versus big and mega-cities).

The importance and relevance of resilience of CI was highlighted in the last UN World-Conference on DRR in Sendai in March 2015. More than 180 countries agreed that the disruption of CI and basic services were major risk factors. The international consensus concluded that reducing the risk from such infrastructure failures and strengthening infrastructure resilience was so important that it became one of the seven core global targets for DRR between 2015 and 2030:

> "Substantially reduce disaster damage to critical infrastructure and disruption of basic services, among them health and educational facilities, including through developing their resilience by 2030" (UNISDR 2015).

It is interesting to note that the European Commission has issued new directives that promote a stronger consideration of integration of CI designers and operators in strategic environmental and risk assessment and planning approaches at local to national scales. Such directives allow for a more systematic consideration of risks of and vulnerabilities to CI failure within the planning and design of infrastructures.

While there is recognition of CI resilience at international and regional scales, it is important to note that national programs of CI protection have important influences on how risk management and resilience building regarding critical infrastructures is organized and implemented. For example, in the US infrastructure resilience is an important aspect in the national disaster recovery plan (see FEMA 2011). The need to articulate between governance structures (national, regional, international) is an emerging challenge for critical infrastructure resilience.

3. New Influences on CI

The discussion of new influences on CI and particularly the identified research gaps (Section 6) and the recommendations for future research (Section 7) in the conclusion part are based on the DFG roundtable discussion that brought together more than 30 experts from academic institutions (e.g., universities, federal research institutes) and practitioners representing a wide-range of fields and disciplinary backgrounds, such as engineering, geography, sociology, environmental management, spatial and urban planning at the newly established IRDR International Center of Excellence on Critical Infrastructures at the University of Stuttgart (see in detail IREUS website - http://www.uni-stuttgart.de/ireus/forschung/Initiativen/index.en.html).

This roundtable showed that language, definition and scope differences across studies as well as appearance and emergence of new terms and concepts, such as green infrastructure (see Rouse 2014) and social infrastructure (O'Sullivan *et al.* 2013) makes it difficult to attain a comprehensive overview of the CI landscape and the related new influences and risks.

While climate change and urbanization are global megatrends that modify risks of CI and also our dependency on functioning CI services, other issues of CI safety and risk vary widely among countries. For example in the USA the discussion on terrorism threats have influenced the CI safety debate significantly (Moteff 2005). Such nationally - specific influences and discourses can create tensions between infrastructure issues and CI risk assessments at the global and regional scale. However, in contrast to specific national discourses, there are three major global trends influencing CI and human vulnerability to CI failure in the future, namely smart cities and digitalization, the megatrend of urbanization, and decentralized power supply systems.

3.1. *The vision of smart cities and digitalization*

Challenges regarding the failure of CIs and particularly the nexus between extreme events, CI, human vulnerability and strategic planning are also influenced by the trend of digitalization of various processes and the vision of the so-called "Smart City". Concepts of "Smart City" often include applied technologies that help humans live, work and commute in urban environments. These concepts encompass smart grids, smart meter or smart infrastructure systems for electricity, water supply and waste management as well as mobility and ICT (Siemens website 2016). A digital future city and its infrastructures raise new questions regarding the robustness and resilience of these systems to extreme events as well as the increasing dependency and vulnerability of people on CI. In particular, the relationship between increasing user dependencies on CI and their services during and after extreme events has not been well researched at present. Also lacking is a critical revision of the enhancement of interdependencies of critical infrastructures and CI sectors as a function of the implementation of smart city concepts.

In the past decade, resilience of CI (services) has received increasing attention because more and more people are living in complex urban structures (Batty 2013; Bettencourt 2013) that cannot function without these services. However, most research focused on the direct impact of a hazard on a CI (e.g., regarding railway infrastructure see Kellermann *et al.* 2015, 2016), rather than examining different levels of vulnerability of people dependent on such services or focusing on different city scales and their adaptive capacity to CI failure.

3.2. *Urbanization*

The number of people in urban areas is expected to increase by 2.5 billion in 2050, and approximately 35% of this growth will take place in China, India and Nigeria according to new statistics of UN DESA (2014). Resilience challenges will be found in rapidly growing small and medium-sized cities that are characterized by an already high vulnerability of the urban population, such as in medium-sized cities in Africa and Asia in particular (Birkmann *et al.* 2016). Against this background it is essential to better understand how specific strategies of robustness and resilience of CI are linked to differential user dependencies and also to variable types of cities and urban agglomerations.

In addition to knowledge about the resilience of technical systems there is a need to develop an in-depth understanding about operation and use of the system. This requires improved knowledge about the varying vulnerability and dependency of people on CI (e.g., elderly and/or hospitalized people, marginalized communities, etc.) and potential changes of these dependencies over time and across space (e.g., demographic change) in the future.

3.3. *Decentralized power supply systems*

In Germany and in many other countries, there is a shift in power supply systems ("Energiewende") due to the increasing integration of renewable energies. For some municipalities and counties, this means a shift from centralized to decentralized energy systems and networks. As a consequence of the widespread introduction of renewable energy sources, the emergence of many decentralized power generation methods (wind, solar, geothermal and biomass) is projected for the near future. This results in a reduction of base supply capacity by the big utilities and a higher reliance on the networks that distribute power to industrial and private customers with such networks of growing complexity.

While power generation decreases in centralization, the power transmission increases the degree of interconnectedness. The distribution systems are often the most fragile parts of the system. Most failures occur due to damages of these distribution systems and networks. So-called smart grid solutions aim to make such decentralized networks more effective and more resilient though the introduction and use of information technology. By implementing technology that allows for localized control, power networks can take advantage of several opportunities: (1) grow from the bottom up in a modular way — complement the existing structure without needing to replace it, (2) different modules can continue to function whether connected to the main grid or not, (3) disruptions can be isolated from the rest of the system to reduce cascading failures, (4) unused energy can be fed back into the system to better balance demand between peak and off-peak hours and (5) renewable energy sources can be connected more easily (Farhangi 2010). However, the induced smartification of power grids goes hand in hand with new issues: the lack of robust standards for new technologies, and the associated difficulty with interfacing new and old technologies. Cost is also an issue, as is governmental support, and the potential for cybersecurity is of increasing concern as more control is brought online, particularly with growing complexity and less human oversight (Holmukhe and Hegde 2015). Finally, the dependency between power supply and IT infrastructure is increased.

4. Extreme Events and Failures of CI

Hydro-meteorological disasters do have the potential of significant distortion of CI functionality, which was revealed during Hurricane Sandy in New York (Hurricane Sandy Rebuilding Task Force 2013), Hurricane Katrina in New Orleans, and weather-related events in Europe. For example, in November 2005, Münsterland in Germany was without power for several days up to weeks as many electrical towers collapsed due to ice load (Klinger *et al.* 2011). In this case, the combination of an outdated infrastructure and severe weather conditions acted as the driving force. Winter storm Kyrill (2007) also resulted in hundreds of damaged electric towers, cut-off power line, and extended power losses (see e.g., GDV 2007; Fink *et al.* 2009). Prior to this event the winter storm Lothar (1999) caused wide-spread loss of power in France; in some communities services were interrupted for up to 2 weeks (see e.g., DKKV 2007; MunichRe 2002). Losses during the German floods in 2002 accumulated to 50 million Euros for the Deutsche Bahn (DB 2002: p. 4). The floods of June 2013 lead to damage of the tracks of the bullet train between Hannover and Berlin, an outage that lasted until November 2013 and left the Deutsche Bahn (German railway company) with 100 million Euros of direct and indirect economic losses (see e.g., DB 2013: p. 42; Thieken *et al.* 2016; DKKV 2015). Another example of a technical failure is the fire at the railway operation center at Mühlheim (Ruhr) main station in October 2015. Due to this fire the train station was inaccessible for several days and the main rail connection Duisburg–Essen–Dortmund was shut down for several days as well as delays (see WELT–website accessed 2016).

The vulnerability of CI systems to extreme events will most likely rise in the future due to the increased complexity and interconnectivity of CI systems. Key drivers of this development are among others digitalization, urbanization and the introduction of smart grids as discussed in Section 3. The increasing interdependencies within CI (e.g., due to the increasing role of ICT in steering CIs) is a growing field of research and requires integrated and coherent assessment approaches and models that contain detailed low-level models of (sub)-systems as well as high-level models that capture all hierarchical levels of infrastructures involved. The research regarding the analysis of interlinked systems of infrastructures is often summarized under the heading of systems of systems (Eusgeld *et al.* 2011).

A challenge identified in the structured expert dialogue in Stuttgart is that the criticality of an infrastructure system is determined by the various structural, functional and technical settings and elements within the overall system. This systemic configuration often requires an assessment of criticality by examining the entire network of an infrastructure (e.g., electricity) and its potential cascading effects on other infrastructure systems once it is hit by an extreme event.

4.1. *Blind spots in the area of extreme events, natural hazards and CI*

Apart from the observed large losses of the past we see emerging phenomena that have not been sufficiently studied and deserve increased attention. In 2013, for instance, the hail storms Andreas and Bernd caused extremely high losses in Germany (4.5 billion Euros) as the event affected urbanized areas (see ERGO Group website 2015). An interesting, but little-explored type of disaster is the combination of extreme temperatures with extreme precipitation (drought plus heat or heavy precipitation with cold). Past extreme events may not be indicative of potential future scenarios under climate change conditions. A hypothetical winter storm with the high gust velocities of Lothar (1999) with 172 km/h maximum and the large storm field of Kyrill (2007) could be much more devastating compared to what we have seen so far (see also Fink *et al.* 2009; DKKV 2007). The interaction of a low probability high impact event (such as Lothar) with rather frequent adverse conditions (snowfall) can significantly delay infrastructure restoration times and thus affect the resilience of CI for the whole city or region.

4.2. *Multi-hazard-complexes*

Multiple hazards such as the simultaneous and/or consecutive occurrence of different hazards plays a role when very long return periods are considered as it is the case with nuclear power plant safety. Multi-hazard risk modeling became a topic of recent research (Grünthal *et al.* 2006, Schmidt *et al.* 2011; Kappes *et al.* 2012; Marzocchi *et al.* 2012; Mignan *et al.* 2014). However, the cases experienced so far indicate that large losses, including failures of infrastructures, are triggered by single extreme hazards. Nevertheless, it is likely that multi-hazard conditions are increasing due to climate change and climate variability. Also it can be argued that the design and planning of critical infrastructure and its consideration in spatial and urban planning has to take into account multi-hazard conditions and scenarios.

5. Strategic and Adaptive Planning within the Context of Spatial and Urban Planning

Opportunities to reduce risks and vulnerabilities of interdependent CIs to extreme events have also to take into account the specific geographic setting and the spatial context in which the CI is embedded, e.g., urban agglomerations, peri-urban areas versus rural areas. Actors and agencies for strategic and long-term planning (urban and spatial planning, including infrastructure and environmental planning, etc.) are not sufficiently involved in systematic strategies to deal with the resilience of CI. Up to now mainly disaster management agencies and private companies who operate CI consider these issues in one way or another. A strong link between individual infrastructure designers, developers and operators, and urban and spatial planners is often missing according to the expert discussions conducted. Therefore, this section explores the role of strategic and adaptive planning for increasing the resilience of CI.

5.1. *Spatial planning*

Spatial and urban planning make decisions regarding “if” and “how” certain spaces or areas will be used. That means spatial and urban planning are space and area-oriented. Particularly, spatial planning influences the vulnerability in cases of geographically relevant natural and technological hazards (floods, accidents in chemical plants, etc.); however, a planning authority is primarily responsible for its own territory. In general, goals of a regional plan or a local land-use plan for a specific area have to be justified against other competing land-use interest for the same area. Consequently goals of spatial planning often need to be linked to specific areas (e.g., areas where new urban development should take place versus green belts should protect the open space for different environmental functions (e.g., protection of space for cold air flows to reduce the urban heat island effect in cities for example).

CI networks and failures might influence and operate on very different spatial scales, thus mismatches between conventional spatial planning approaches and systemic risks of CI are evident. Impacts of a disruption or a collapse of CI might be global (as proved by the 2011 floods in Thailand), but the areas, directly affected by a disaster have only local to regional dimensions.

The structured expert dialogue in Stuttgart revealed that many administrative units and boundaries do not match the spatial scale of interconnected CI systems.

That means the goal of considering the entire network of an interdependent CI might create a mismatch in praxis with spatial and urban planning that is all too often focused on a specific administratively defined territory linked to the specific responsibility of a city or municipality or urban agglomeration. However, this might explain why spatial and urban planning up to now often focuses solely on the susceptibility of the physical dimension of CI and not examined functions and interdependencies.

Hence, the protection of CI and the management of disruptive effects and failures of CIs due to natural hazards or extreme events are not only a problem of horizontal and vertical interaction, but also a problem of scale (especially spatial and functional scale mismatches). This necessitates interdisciplinary and transdisciplinary research focusing on individual elements of infrastructures as well as on entire networks and systems. Part of the horizontal approach is linked to spatial questions — different geographical settings also define for example the exposure of infrastructures to specific hazards, such as floods, earthquakes or fires. At the same time spatial patterns of settlement determine aspects of human vulnerability to the failure of CIs. The vertical approach looks at interactions between different sectors of CIs, coupling and cascading effects or buffering options, as well as the governance frameworks. Riegel (2015) developed an approach to identify spatial and functional vulnerabilities and to measure the effects of disruptive events using the transport, energy and water sectors as examples. Despite limited efforts, the effects of coupling and cascading risks within CI have to be addressed through further research.

5.2. *Strategic and adaptive planning*

In the light of the necessity to increase the resilience of cities and infrastructures to extreme events two approaches to planning in general, and spatial planning in particular are being discussed: strategic planning and adaptive planning. The concept of adaptive planning focuses on the question of how uncertainty and different future development pathways including changes in environmental conditions (e.g., climate change), and societal structures, (e.g., demographic change and migration) can be better infused into formal and informal planning tools (including planning objectives) and processes (Birkmann *et al.* 2010). The term adaptive planning has close linkages to the discourse of strategic planning. Both approaches, the adaptive planning and the strategic planning approach, emerged as a counter strategy to a purely prescriptive planning concept that operates primarily with current legal thresholds (e.g., thresholds for noise, air pollution, building density) or legal instruments.

Both adaptive and strategic planning refer to how and to what extent long-term planning is feasible and appropriate in highly dynamic environments (Wiechmann 2008). The adaptive model is used when the planning problem is characterized by greater complexity and the planning actors have limited expertise about the structure of the problem. In contrast to the paradigm of linear strategy development (analysis, conception/plan development and implementation) with a totally rational planning approach, strategic and adaptive planning concepts account for the bounded rationality of actors and the emergence of alternative strategies. In this regard, the process of collective learning is emphasized and a greater autonomy of the actors involved is assumed. Following the logic of adaptive and strategic planning it is not the implementation of planning goals that is in the focus, which Faludi (1997) describes as the conformance principle, but rather whether the planning process or plan had a positive influence on decisions taken on the basis of the planning thereafter. Hence, the focus shifts from the "conformance principle" to the "performance principle" of planning (Faludi 1989). Translated to the nexus of extreme events, CI and human vulnerability, strategic planning it is the key to better understand how risks (e.g., CI risks and human vulnerability) are defined as relevant and how they are examined, communicated and further dealt within risk management approaches in spatial and urban planning as well as in infrastructure design (see Renn and Graham 2006: p. 80; Renn 2008: p. 289; Greiving and Fleischhauer 2008; Greiving *et al.* 2013). Climate change governance and earth system governance provide additional insights for concepts of adaptive and strategic planning, such as the consideration of the importance of different spatial, temporal and functional scales (Biermann 2007; Fröhlich *et al.* 2011). However, the development of appropriate assessment methods for considering and measuring risks and resilience of coupled and interconnected infrastructures along different temporal and spatial scales is still a challenge (see also Bach *et al.* 2013).

5.3. *Critical infrastructures and spatial planning*

One important principle of spatial planning — in Germany but also in various other countries — is the planning principle of concentrating infrastructures spatially along axes to safeguard green and open spaces. Whether this principle has to be revised under the question of risk prevention for CI is still controversial. In this regard, it becomes necessary to measure spatial criticality (Riegel 2015; Fekete 2011) and then incorporate information about the assessment of the resilience and vulnerability of CI and differential dependencies of people on these CI services into spatial/urban planning and evaluation processes. This information could be further enhanced through data on temporal criticality and the quality of services provided by CI (Fekete 2011).

Fortunately, the recent amendment of the Environmental Impact Assessment (EIA) directive (Directive 2014/52/EU – see European Parliament 2014) establishes a link between EIA and risk management:

> "The environmental impact assessment shall identify, describe and assess [. . .] the direct and indirect significant effects of a project on the following factors: (e) exposure, vulnerability and resilience of the factors referred to in points (a), (b) and (c), to natural and man-made disaster risks." (European Commission 2013)

The guidance documents on integrating climate change and biodiversity into EIA and Strategic Environmental Assessment (SEA) argue: "In addition to climate scenarios, it is important to consider socio-economic scenarios as this will help to assess future vulnerability to climate change." (European Commission 2013: p. 39). Furthermore, the impacts of climate change on the assessment results through so-called "Evolving baseline trends" (European Commission 2013: p. 39) have to be considered. However, the consideration of socio-economic scenarios within future vulnerability assessments to climate change in EIA is not very advanced. It remains to be seen how these scenarios will be applied in practice in such assessments in the future.

Overall, the amendment of the EIA Directive (Art 3. § 2 directive 2014/52/EU [European Parliament 2014]) calls for precautionary actions that need to be taken into account for projects which, because of their vulnerability to major accidents, and/or natural hazards (such as flooding, sea level rise or earthquakes), are likely to have significant adverse effects on the environment. Even though different project types within the EIA are considered by different countries, it is noteworthy that various large scale CI projects require an EIA inside and outside of the European Union. Consequently, the EIA can be an important vehicle for integrating knowledge regarding the robustness, resilience and vulnerability of CI to extreme events into different (spatial) planning processes in the future.

6. Research Gaps

Against the backdrop of the importance of CI in recent international agreements, the new influences that modify CIs, the dependency of people on CI services, the discourse of CI failure and extreme events, and the importance of strategic planning and assessment many research and science gaps become apparent. These research gaps outlined below are core results of the structured expert dialogues particularly the outcome of the DFG roundtable discussion conducted at the IREUS University of Stuttgart.

The research on the resilience of CIs is still fragmented and often not integrative or interdisciplinary. While risks of single CIs to specific hazards, such as floods or tsunamis, are well explored, major gaps still exist in terms of the knowledge and understanding of the complex interactions and interdependencies between extreme events (multi-hazard context), CI resilience, human security and strategic planning approaches before and after crises. Additionally, potential amplification of CI damage due to cascading hazards like landslides triggered by floods or earthquakes, or tsunamis triggered by earthquake is required to be incorporated into resilience of CIs.

6.1. *Coherence of assessments, standards and norms*

Significant knowledge gaps exist in the appropriate process for defining specific protection standards for CI resilience. Although important frameworks for addressing and operationalizing resilience within infrastructure systems to extreme events have been developed (McDaniels *et al.* 2008; Andrijcic *et al.* 2013), there is limited knowledge on the development of protection standards (Fekete *et al.* 2012) for complex and interwoven CI for entire cities or regions — instead of individual infrastructures (dam/reservoir operators, electricity companies, railway operators) operated or controlled by specific organizations. For example, norms and standards applied within the EIA process are often based on sectoral laws and focus primarily on how the infrastructure might impact (negatively) different environmental protection goods, e.g., water, soil, humans, biodiversity, etc. The EIA also requires that vulnerability of the infrastructure to climate change and disasters have to be assessed in the future. In contrast, norms and standards applied in the Euro-Codes (see EN 1991-1-7) predominantly deal with the individual elements of a CI and the security of e.g., steel or concrete structures. Even though this is necessary for the design of the individual infrastructure, it is also important to assess the criticality of the infrastructure of a city or an entire region, which is often not done. Overall, integrated management approaches for enhancing resilience (including aspects of cost effectiveness and redundancy, rapidity, resourcefulness, reliability and robustness) would require a strong link between the various (security) standards applied in different planning and assessment tools. How these different assessment methods, standards and norms can be linked is still an open research area.

6.2. *North-South dimension of CI often neglected*

Until now, it is typically hypothesized that CI failure is a challenge primarily to industrialized countries in the Global North, given the greater level of infrastructure. However, there is less understanding of the extent to which CI failure is also an emerging risk in developing and transition countries. Even when CI is being discussed in developing countries, questions of applicability and context conditions are largely neglected. CI concepts and systems are, for instance, increasingly transferred from the Global North to the Global South, often within the context of development aid or even austerity. However, apart from transferring the technology as such, insufficient attention is being paid to how institutional arrangements of risk management have to be adapted in order to embed the technical infrastructure solutions and make them workable in-country. Resilient solutions demand a co-evolution of technological advances, organizational changes, adequate and effective governance structures, and adaptive behavior of users. Hence, wider questions of adaptive governance and adaptive planning, including the adjustment of planning procedures and respective institutions, need to be addressed in order to allow for context-specific configurations of CI.

Further, experiences with critical infrastructure resilience and failure are not sufficiently shared between developed and developing countries. International agencies, like UN institutions, but also the European Union, propagate the transfer of knowledge and best practice between (local) governments. However, the technology transfer particularly in the context of North-South cooperation often lacks local adaptation and capacity to implement and therefore can result in negative impacts on the ground. How new transnational co-learning and knowledge transfer mechanism (Ley *et al.* 2015) can support such local adaptation processes need to be further explored.

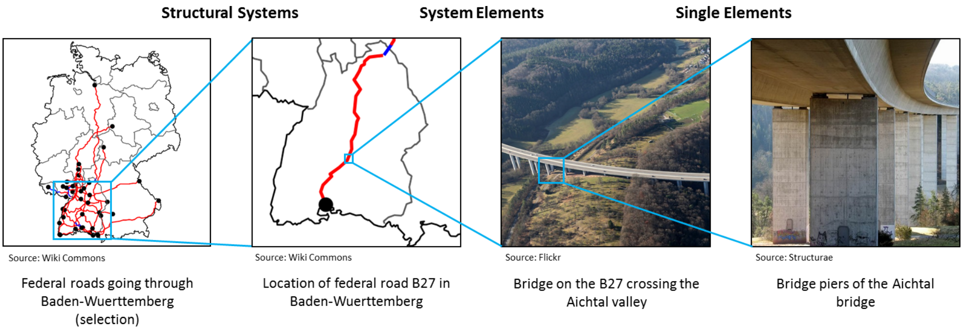
6.3. *Risk cascades and interdependencies*

One notable characteristic of CI is interdependency that can lead to cascading effects once a specific CI is hit by an extreme event. Cascading effects might be consequences of one failure or impairment in one infrastructure leading to further consequences in other infrastructures or secondary hazards and consequences of multiple types. Such additional effects to a given disaster situation are one hallmark of infrastructure crises and disaster effects that have a specific quality and dimension. Dependencies exist between almost all CI, and in many cases, there are mutual interdependencies with feedback effects (see e.g., Rinaldi *et al*. 2001). In modern societies, such interrelations increase and dependencies on energy and information technologies as well as transport availability result in significant service interruptions that can hinder disaster response and recovery as well as being the source of severe health impacts or social unrest. The increasing dependency of societies on CI services has also contributed to risk accumulation and the threat of cascading risks once a hazard event (flood, drought, heat wave, earthquake, human management failure, etc.) impacts such facilities and services. The integrated modeling of higher societal dependencies on CI services on one hand, and the likelihood of different types of failures of CI services due to extreme events on the other hand needs further development. The consideration of indirect losses and harm (e.g., on ecosystems) is still not very advanced. Also the experiences of different people and communities should be taken into account in order to strengthen the co-production of knowledge about risk and risk management responses.

6.4. *Different perspectives: Resilience of CI-elements, -systems versus community resilience*

Disaster resilience has many definitions, but it is generally considered to provide a means of representing a system's ability to rebound from a disaster and to keep up key system functions despite hazard perturbations (Folke 2006). A lot of work has been done on characterizing the inherent characteristics of communities that support resilient behavior (Cutter *et al.* 2014), but it is also important to look at the system's behavior in response to a particular event — where are the crucial points of failure, when do different actors have opportunities to influence losses, how much loss is occurring — when and where —, and what does the failure of service mean for different groups, e.g., in the context of increasing urban inequality. In addition, the speed of recovery is an important issue for the severity of the failure. Finally, it is essential to better understand how to reduce losses and how to speed up recovery, or both, so that the time remaining in a state of loss is minimized. The most obvious indicator is the physical system, i.e., the ability to resist or to recover from an actual physical disruption. However, the impact of this disruption on the economy or society is also a crucial issue. In most cases, it is not only the physical system of a CI that needs to recover, but also the interrelated supportive networks.

In this context, the assessment of vulnerability and risk of a CI raises questions about the appropriate spatial focus of the analysis. The assessment of vulnerability and risk in large scale structural dependent systems such as federal highway or road networks often requires a different model and conceptualization of vulnerability and risk criteria compared to the analysis of a single infrastructure, such as a bridge, within the network (see Figure 1). However, specific structural design criteria to strengthen the robustness of an individual infrastructure element, such as a bridge, might have significant consequences for the entire infrastructure and the structural system. Consequently, the analysis of the robustness and resiliency of infrastructure requires the consideration of multi-scale interactions that are often difficult to capture and model.



Structural Systems

System Elements

Single Elements

Source: Wiki Commons

Federal roads going through Baden-Wuerttemberg (selection)

Source: Wiki Commons

Location of federal road B27 in Baden-Wuerttemberg

Source: Flickr

Bridge on the B27 crossing the Aichtal valley

Source: Structurae

Bridge piers of the Aichtal bridge

Figure 1. Multi-Scale Perspectives on Robustness and Resilience of CI-elements and Systems
Source: Author's own figure, photos from A. Pfaender

Robustness is also an important aspect of CI-resilience, so that the infrastructure does not suffer from a loss in the first place (see also McDaniels *et al.* 2008). Concepts to develop robustness for specific structures through engineering design have been defined for example with regard to accidental events in Eurocodes, such as the EN 1990 and EN 1991-1-7 (see CEN European Committee for Standardization and Figure 2). The strategies to enhance the robustness of infrastructures through their design focus on two different aspects: (a) strategies to deal with identified hazard or accidental action; and (b) strategies on limiting the extent of localized failure which include issues of redundancy (see Vogel *et al.* 2014; Kuhlmann *et al.* 2009).

Hazard and risk reduction is also fundamental, such as burying power lines underground. Preparedness helps as well with resilience by pre-positioning resources in the run-up to a storm (e.g., replacement equipment, technical personnel, etc.), in order to ensure that they can be mobilized more quickly. Because

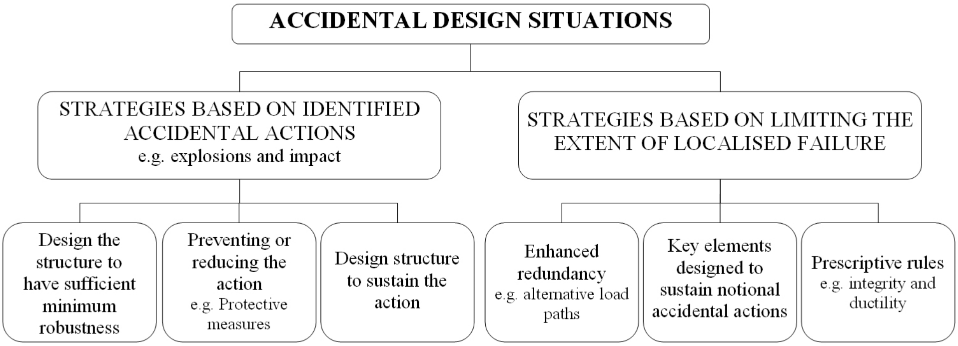


Figure 2. Strategies to Deal with Accidental Situations through Engineering Design based on the EN 1991-1-7

of the uncertainty of occurrence (earthquake, landslide and tsunami) and of the impact (hurricane, winter storm) associated with different types of events, the ability to change plans and adapt as needs become more apparent is also critical according to the expert dialogue conducted. Redundancy provides flexibility, however, redundant systems might also increase the costs particularly for those companies that run such infrastructures. Consequently, it is an open research question whether and to what extent the vision of redundant CI systems creates tensions with other goals of companies that operate such systems (reduction of costs). Apart from redundancy, other parameters such as rapidity and resourcefulness as well as cost-efficiency have to be addressed within interdisciplinary frameworks and research on resilience (Bruneau *et al.* 2003).

6.5. *Improving stress testing methodology and learning across case studies*

Stress testing is a procedure applied to determine the stability of a system or entity. It involves the testing of a system or an entity beyond normal operational capacity, often to a breaking point, to observe the performance/reaction of the system to a pre-defined internal or external pressure/force. Stress tests have also been used for many years in air traffic safety, in particular for airplanes and helicopters. In recent years, stress testing has often been associated with the methodologies to assess the vulnerability of a financial system or components of it, such as banks. A number of analytical tools have been developed in this area and have been frequently used since the late 1990s (Borio *et al.* 2012).

More recently, stress testing has been applied to the comprehensive safety and risk assessment of nuclear power plants, in particular in the aftermath of the 2011 Fukushima Dai-ichi accident. Many aspects of the accident devastating the Fukushima Dai-ichi nuclear power plant are still unknown, and it will probably take several years before lessons can be drawn from the sequence of events that caused the release of large doses of radioactive material from the plant. Still, present knowledge has already led nuclear regulators, experts and operators throughout the world to some important conclusions regarding the improvement of nuclear power plant safety. In particular, the accident highlighted three potential areas of weakness in existing safety approaches: (a) inadequacy of safety margins in the face of extreme external events (in particular natural hazards); (b) lack of robustness with regards to events that exceed the design basis; (c) ineffectiveness of current emergency management under highly unfavorable conditions. The lack of stress tests for CIs is a deficit that should be overcome by interdisciplinary research.

6.6. *Spatial and cross-cutting issues*

Currently, there is much focus on resilient cities and especially megacities due to the concentration of humans and human values exposed to natural perils as well as human-made risks, and infrastructure concentration, and the relationship between the two. Place-based assessments, however, must also put more focus on small- and medium-sized cities and rural settlements which are often neglected by an increased public and political focus on megacities (Birkmann *et al.* 2016; Fekete 2016). Financing risk reduction primarily in big cities can impair other cities and rural communities around such a megacity. Not only must those settlements attract more attention, also the interrelations of the city to the hinterland, and in general urban–rural connections must be assessed under the CI focus more prominently. Place-based assessments and spatial planning serve to integrate several disciplines and CIs can serve as a cross-cutting issue to instigate novel collaborations and research. New developments of infrastructure systems like the national grid expansion activities for overlaying high voltage connections in Germany can be considered as case studies in order to investigate and assess how critical infrastructure resilience is implemented in spatial and technical planning processes.

Overall, the discussion of the structure expert dialogues underscores that there are still important demands to and research gaps that need to be addressed through the scientific community and have to receive more attention by decision makers at different levels.

7. Conclusions and Outlook

The following section summarizes findings of the structured expert dialogues and particularly formulates an outlook that also stresses future research needs in the field of extreme events, critical infrastructures, human vulnerability and strategic planning.

One core conclusion from the expert dialogue is that various risk management approaches for CI to natural hazards and extreme events still focus on an individual infrastructure rather than on the interconnectivities of such systems of systems in specific places and regions. Mismatches and synergies between different norms and standards applied in the planning, design and management of CI are poorly understood and often detached from the assessment of human vulnerability and the role of the CI for the entire city or region. Against this background the following five research needs can be formulated. These points do not intend to be comprehensive, however, they might provide some interesting food for thought:

1. Even though new international agreements call for building resilience of CI systems, concepts for such systems have been mostly developed for specific infrastructures. A more comprehensive assessment of resilience of CI will require more research on how to link the various norms embedded in different existing assessment methodologies across scales, such as Euro-Codes (for individual structures) and EIA (for infrastructure systems). Consequently, future research has to explore different methods on how to link these methods and assessments, including the consideration on how affected people can be part of such a process.
2. In this context, new and more systematic knowledge about the criticality of different CI is essential. That means, future research is needed on how to better account for the changes within CI systems (e.g., decentralization, increasing interdependencies between CI-systems, governance of CI, etc.) and the dynamics of human vulnerability (e.g., aging population) that both heavily determine the criticality and resilience of CI.
3. Against the experience that CI can fail (Section 4), research is required on what various society or different societal groups are willing to accept (failure of service) as well as to invest building resilience. It is important to identify and evaluate different options for resilience building focusing on interdependent infrastructure systems and processes in order to optimize the allocation of limited funds, including options to reduce human vulnerability to CI failure. This also requires research on how to define and set up protection standards for CI services considering the different actors, such as operators of CI, emergency management, spatial and environmental planning, communities themselves and civil society organizations, etc.
4. Impacts of extreme events on CI have been observed in the past with severe negative consequences. However, a systematic review and evaluation of the different reconstruction processes of CI after extreme events and the methods to document lessons learned is still missing. Consequently, inter- and transdisciplinary research is needed in order to develop guidelines on how to document lessons learned from past failures and disasters. This could also encompass recommendations on how to document institutional learning.
5. New infrastructure developments, such as smart grids or smart city concepts, need to be further explored in terms of additional risks that they might imply as well as their opportunity to enhance resilience due to the establishment of new infrastructures (information clouds, new technologies for communication between systems and users, etc.). In this regard, also the issue of uncertainty has to play a prominent role.

6. New research needs also exist in terms of the transferability of CI systems and CI resilience concepts from the Global North to the Global South and vice versa. Recently an increased role of adaptation networks and city networks (encompassing experts and laypersons) can be observed that exchange experience and knowledge on innovative policies and best practices. The role of these networks for promoting CI resilience should be an emerging research issue.

Even though the research needs outlined above are not intended to formulate a coherent research programme, they are however, important ingredients that should be taken into account in the development of future research programmes at the international and national level on the issue of extreme events and CI. In order to be able to address these research needs different types of knowledge and expertise need to be brought together. In this regard, the collaboration of scientists from different backgrounds and disciplines as well as the integration of practitioners in developing these research recommendations (as done within the DFG roundtable discussion) might be one step into the right direction.

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